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Image characteristics of deep seismics in Calabria (S. Italy) using tomography and ray-tracing

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Abstract: *The seismic characteristics of the lower crust of Serre Mountains, South Calabria (Southern Italy) were investigated by a Deep Seismic Sounding experiment along the main profile of about 30 km long. In this profile, 31 dynamite shots (10-95 kg) recorded by five recording units and three-component receivers. For the upper 2 km of the sections, the first breaks were used as input for tomographic inversion calculations. Modeling evaluations were based on the shot gathers. Both these and velocity data for deeper layers, were used for the ray-tracing modeling. Later, the section was extended to obtain 3D models and ray-tracing was again performed using actual geophone and shot positions. The shot gather ray-tracing was conducted on these models. Field and synthetic sections show good correlations with the seven layers such as low velocity zone, the Hercynian lower crust reflections, the strongly reflective Calabrian crust and the crust-Moho boundary. The Moho, which dips to the south, can be seen between 6.5 and 8 s corresponding to the depths of 19-24 km. A low velocity zone probably marks the contact between the Hercynian lower crust and the upper crust in the region (1.5-4.5 s). The gravity modeling also confirmed these layers evidently.*

Key Words: *Deep Seismic Experiment, Tomography, 3-D Ray-Tracing Modeling.*

INTRODUCTION

Ray-tracing is an important way to model 2D and 3D geologic structures and consists of finding the path of seismic energy from a source to a receiver and computing traveltimes and amplitudes along these paths. The ray method was firstly applied to propagation studies of the high-frequency elastic waves by Babich (1956), Babich and Alexeyev (1958) and independently by Karal and Keller (1959). It has been used in 3D modeling studies, because it is quite simple, applicable, easy to understand and does not require much computer memory (Julian and Gubbins, 1977). Ray-tracing has many applications in the solution of both direct and inverse seismological problems of laterally varying 2 or 3D layered media. Therefore, it also plays a very important role on many inversion techniques (seismic tomography). Ray-tracing is a flexible approach to seismic modeling and has been used in most of methods to interpret seismic waves, both in structural seismology and in seismic source studies using the principles of the ray method (Cerveny, 1986).

An accurate crustal seismic study can provide the necessary link between seismic in-situ properties and laboratory measurements on rock samples and petrology. The objectives of the experiment were:

(1) Study the Transmission properties of seismic P- and S- waves (velocities, Poisson-ratio, anisotropy).

(2) Study the Reflectivity characteristics of P- and S-waves for each exposed boundary.

(3) Determination of structure using a combined analysis of the refraction and reflection data.

The first objective has been discussed before (Cernobori et al., 1990; Luschen et al., 1991; Çifçi, et al., 1993). The second but mostly third objectives are the subjects of this paper. For these purposes, a complete refraction-reflection seismic profile was obtained in southern Calabria (Italy) as vertical, radial, transversal components. The seismic characteristics of the lower crust were investigated by this Deep Seismic Sounding. A tomographic study depending on a velocity model parameterized in terms of Cubic B-splines given by Michelini and Mc Evilly (1991) was also performed using first breaks for uppermost part of the crust (first 2 km). A very good geometrical correlation was found between tomographic P velocity model and the velocities from laboratory tests, geological and geophysical interpretation (Michelini *et al*., 1992).

The results of tomography were used in the ray-tracing modeling. The earth model obtained by interpretation of the seismic sections was incorporated into the seismic model and these were compared with the actual seismic section. The differences allowed us to change the earth model and to alter the interpretation, thereby obtaining a better interpretation. A complete section of the continental upper and lower crust gave us the opportunity to combine deep seismic exploration with the modeling techniques of tomography and ray-tracing. Gravity modeling was also carried out using seismic data.

GEOLOGY OF THE CALABRIA

Calabria is a continental margin above a subduction zone and is characterized by granulite-facies metamorphism and crustal differentiation. Figure 1 shows the major geological elements of the region. Metamorphism was accompanied by magmatism and subsequent tectonic uplift. This may have been caused by a continent-continent collision (Schenk, 1984, 1989, 1990). Southern Calabria may represent a continuous crustal profile (Schenk, 1984, 1989). Petrological and isotopic age data indicate the two important tectonic events during which the lower crustal section was uplifted and tilted. The first uplift occurred during the Hercynian and the last uplift and tilting occurred in the Apenninic orogenic cycle. The position of the Southern Calabria is in the sharp bend of the Alpine-Apennine mountain system. The Calabrian massif is considered a piece of pre-Alpine crust. Later the Alpine mountain system was dismembered due to movements of microplates in the Western Mediterranean region (Alvarez, 1976).

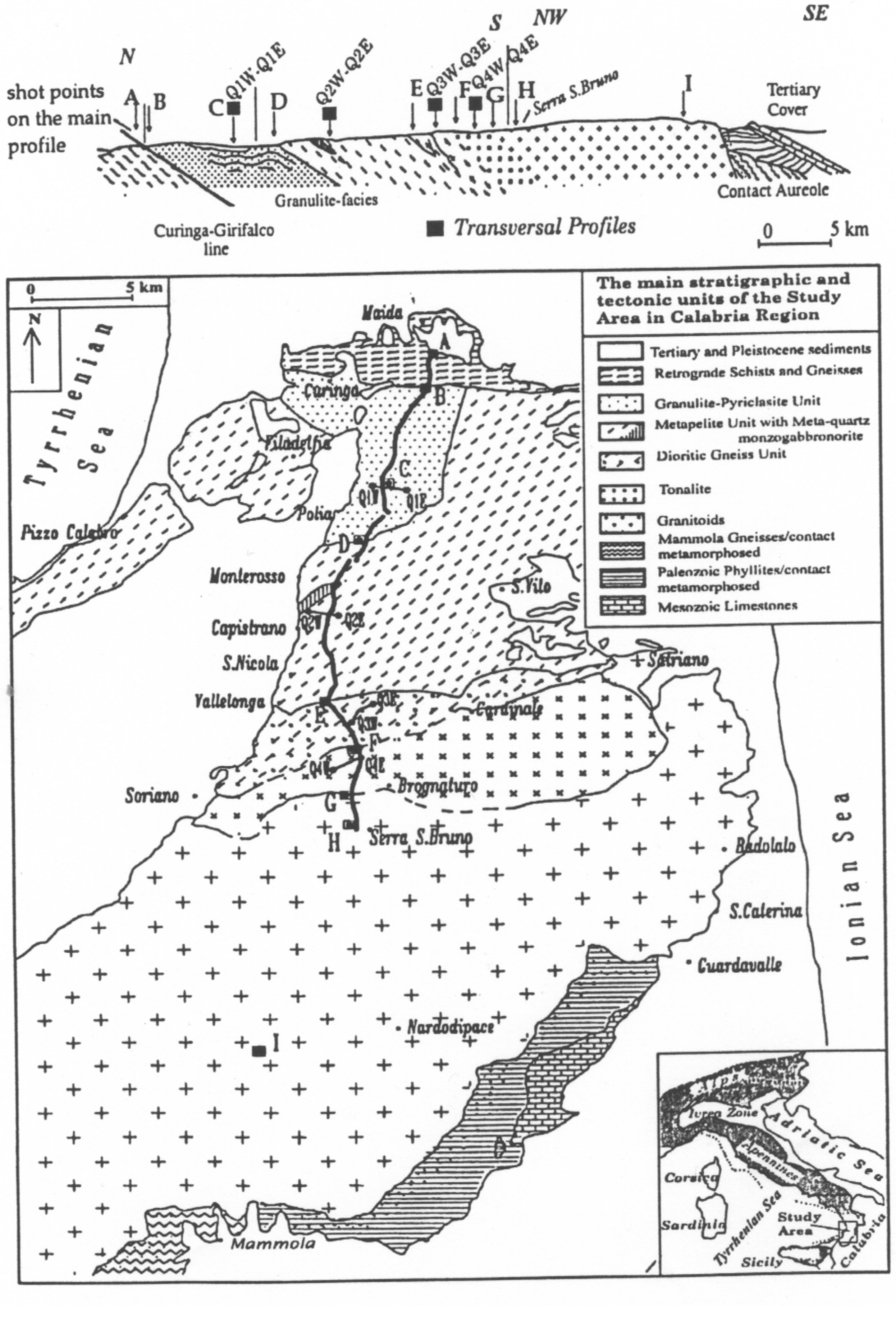


FIG. 1. The position of the seismic profiles on a simplified geological section and map through Serre of southern Calabria (after Schenk, 1980, 1984). The Calabrian crustal section can be followed over a distance of about 50 km by a rock sequence that ranges from granulite-grade through granitoids and amphibolite-facies gneisses into unmetamorphosed Paleozoic and younger sediments.

From a geodynamical point of view, the Italian peninsula could be divided into the North-Central Apennines and Calabrian arc regions (Bousquet and Philip, 1976). The Calabrian arc is the region of Italy characterized by the most intense geodynamic activity, as can be deduced from the historical seismic data, the neotectonic movements and the general structural setting (Ghisetti and Vezzani, 1979; De Vivo et al., 1979). Seismic refraction studies revealed a doubling of the crustal thickness in Calabria and along the whole plate boundary with respect to the adjoining Tyrrhenian and Adriatic crusts (Schütte, 1978; Giesse and Reutter, 1978). The Calabrian crustal section can be followed over a distance of about 50 km by a rock sequence that ranges from granulite-grade through granitoids and amphibolite-facies gneisses into unmetamorphosed Paleozoic and younger sediments. In southern Calabria, granulite-facies rocks are exposed over an area of about 400 km^2.

SEISMIC DATA COLLECTION

A complete deep refraction and reflection seismic data was acquired in southern Calabria. A main profile in NS direction was about 30 km. The data were recorded using three component stations (vertical, longitudinal and transversal), with 80 m spacing between two stations, and 9 shot points (shot point A, B, C, D, E, F, G, H, I) with a maximum offset of 43 km. All the 384 receiver positions were occupied by three component geophones, each comprising 6 geophone strings. For each trace, 12 vertical and 12 horizontal (6 transversal and 6 radial) geophones were utilized. The recording length was 30 s and the sampling interval was 2 ms. In this profile 31 dynamite shots have been recorded on three different layouts by five recording units. Also four shorter (about 1 km) profiles, perpendicular to the main profile have been recorded. Each of these transversal profiles was placed on different and homogeneous lithological units. The positions of receivers and shotpoints are shown on a simplified geological section on Fig. 1. The procedure adopted for the field layouts was to deploy a fixed array with all available channels and to fire shots along the line of geophones. The fixed spread was then moved to the next location and the nine shots repeated.

The following data processing sequence was applied to all of the seismic sections: demultiplexing, geometry definition, sorting into common-shotpoint gathers (CSP) according to the field layout, data editing and a datum plane correction. Signal enhancement was attempted using different filtering and scaling techniques, spectral analysis, filter tests, gain function test, deconvolution tests and trace mixing test. High cut-off frequency during recording was 128 Hz. Interactive frequency analysis made on graphic screens have revealed relatively high P wave frequencies (up to 70 Hz) and a wide spectral bandwidth. This provides unusual high resolution, which is determined by the dominant wavelength. P waves have frequencies in the range from 10-50 Hz. Only few records required a notch filter of 50 Hz. Various filters have also been used depending on offset.

SEISMIC TOMOGRAPHY APPLICATION TO CALABRIA SEISMIC DATA

For the upper 2 km of the section, the first breaks of the refraction data were used as input for tomographic inversion calculations. Some of the velocity data for the upper layers were determined by the refraction tomographic inversion processes. Velocity analysis with cubic B-spline interpolation method has been used in the tomography study. The method is applied as an inversion based on a model parameterization in terms of beta-splines (Michelini et al., 1992). This simultaneous inversion method of seismic wave arrival times for velocity structure minimizes travel-time residuals in a least-squares sense for the coupled elastic velocity model. Since the problem is non-linear and a solution is found by linearizing the problem locally, solving for parameter adjustments in a least-squares sense given an initial model and then iterating. The cubic B-splines method imposes the correlations directly in the parameterization of the velocity model (Çifçi and Michelini, 1994). The method adopted in the study of Michellini and McEvilly (1991) parameterizes the velocity model in terms of cubic B-splines, which results in a velocity model that is continuous everywhere up to the second derivative.

Figure 2 shows the result on the upper velocity field. The velocity model starts from shot point H and ends at shot point A. The main features of the model are in a good agreement with the geological section in Fig. 1. Shot point B is near the Curinga-Girifalco fault (CF), which is seen on the surface, and the Hercynian lower crust (HCLC) outcropped at the surface. The P-model displays an abrupt velocity change near the surface at this point with lower velocities (4 km/s) to the north. The P-velocity between shot points B and D is lower than in other parts of the section. This part of the section has been inferred by Schenk (1989) as being made up of mainly metabasic rocks with minor felsic granulites (the lower Granulite-Pyriclasite unit). Shot point D lies at the bottom of the Metapelite unit consisting of migmatic paragneisses with minor metabasic and metacarbonate rocks. Between shot points D and E lower velocities were resolved at the surface but higher velocities at greater depths (around 1 km depth, the strong vertical velocity gradient near the contour of 5.7 km/s). Finally, the contact between the Metapelite and the bottom of the Dioritic gneisses unit is marked by the velocity section (5.1 and 5.6 km/s contours).

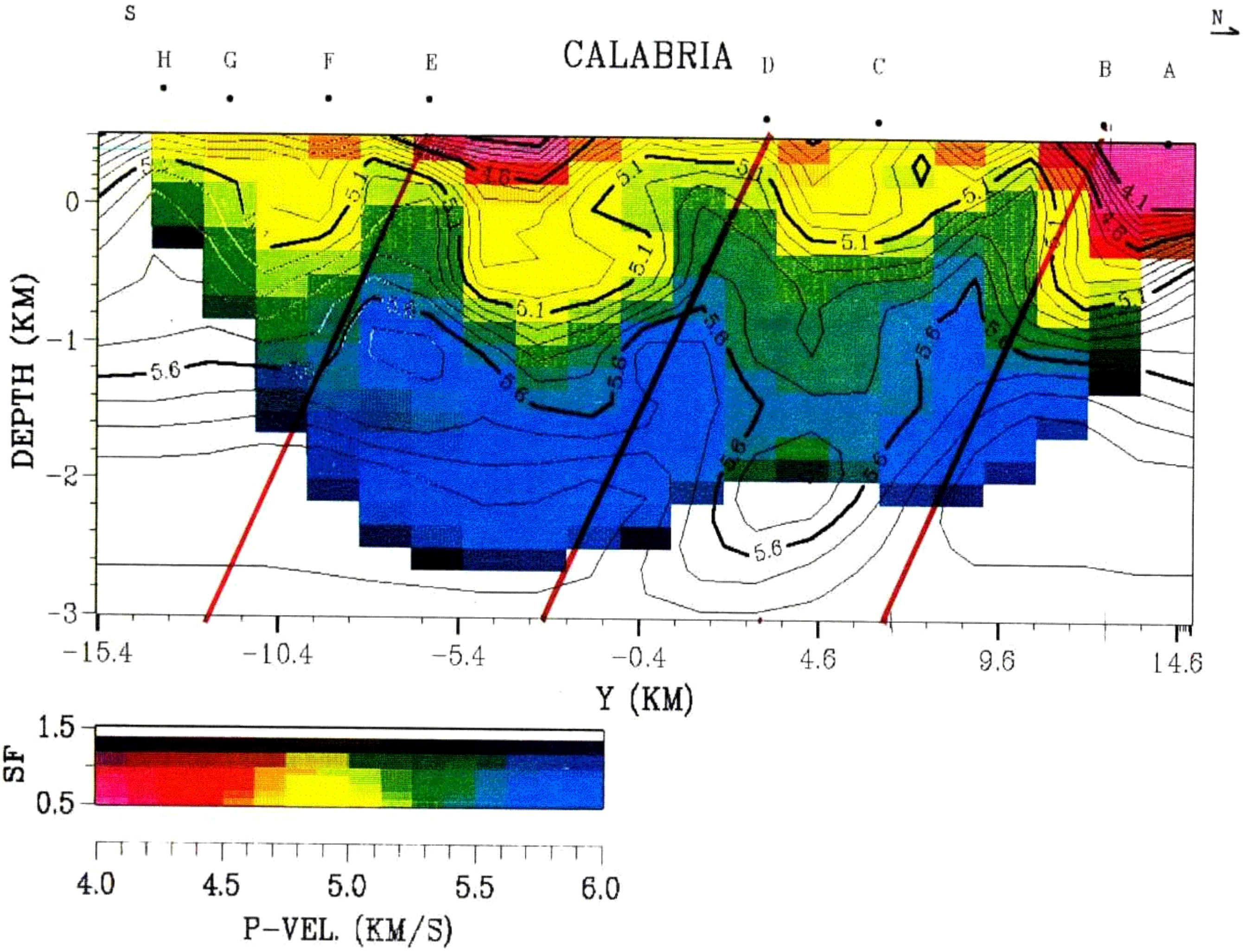


FIG. 2. The result of the tomographic inversion on the upper velocity field (after Michelini *et al*., 1992).

The geometrical correlation between the P-model and the inferred geological cross-section (Fig. 1) does not have, however, a good correspondence in terms of absolute velocity values. In fact, the overall velocity values are substantially lower than those determined in laboratory experiment by Kern and Schenk (1988) for samples of the same units. This discrepancy should be probably attributed to various reasons, such as the level macroscopic fracturing, presence of fluids and the low overburden pressure.

RAY TRACING MODES

The ray-tracing method is a typical representation of the approximate high-frequency or asymptotic method in the seismic wave propagation. Seismic data can be modeled using different ray-tracing modes. Figure 3 shows specific ray-tracing modes associated with the data types resulting from the seismic processing flow. Shot and CMP gathers are modeled with variable incidence rays in which rays reflect off model surfaces at varying angles. The stacked section is represented by normal incidence rays, which reflect only at right angles from model horizons. The time-migrated section is represented by image ray being normal to the ground surface but bend across model horizons, whereas depth-migrated section is represented by vertical incidence rays which extend from the ground surface to model horizons without bending. Vertical incidence ray-tracing modeling is not used for modeling but for depth-to-time conversions or vice versa (Fagin, 1991).

The ray-tracing problem is stated as follows: given a model of subsurface structure and velocities, source and receiver location, one can find the raypath that reflects from a particular model surface and leads from the source to the receiver. In general, it is not easy to derive the raypath for a given subsurface structure. This process is achieved iteratively and generally two types of ray-tracing modeling are performed: offset and zero-offset ray-tracing modeling.

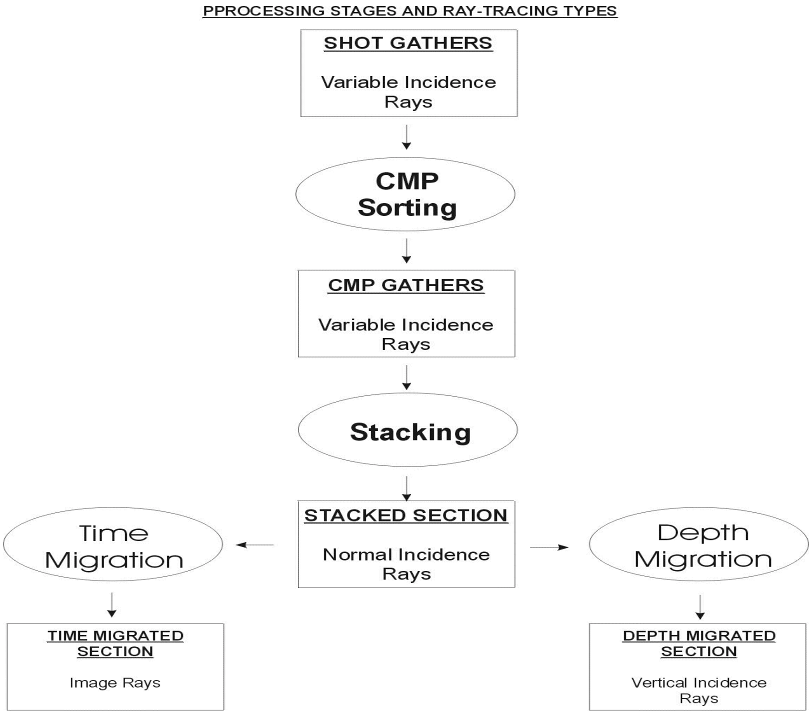
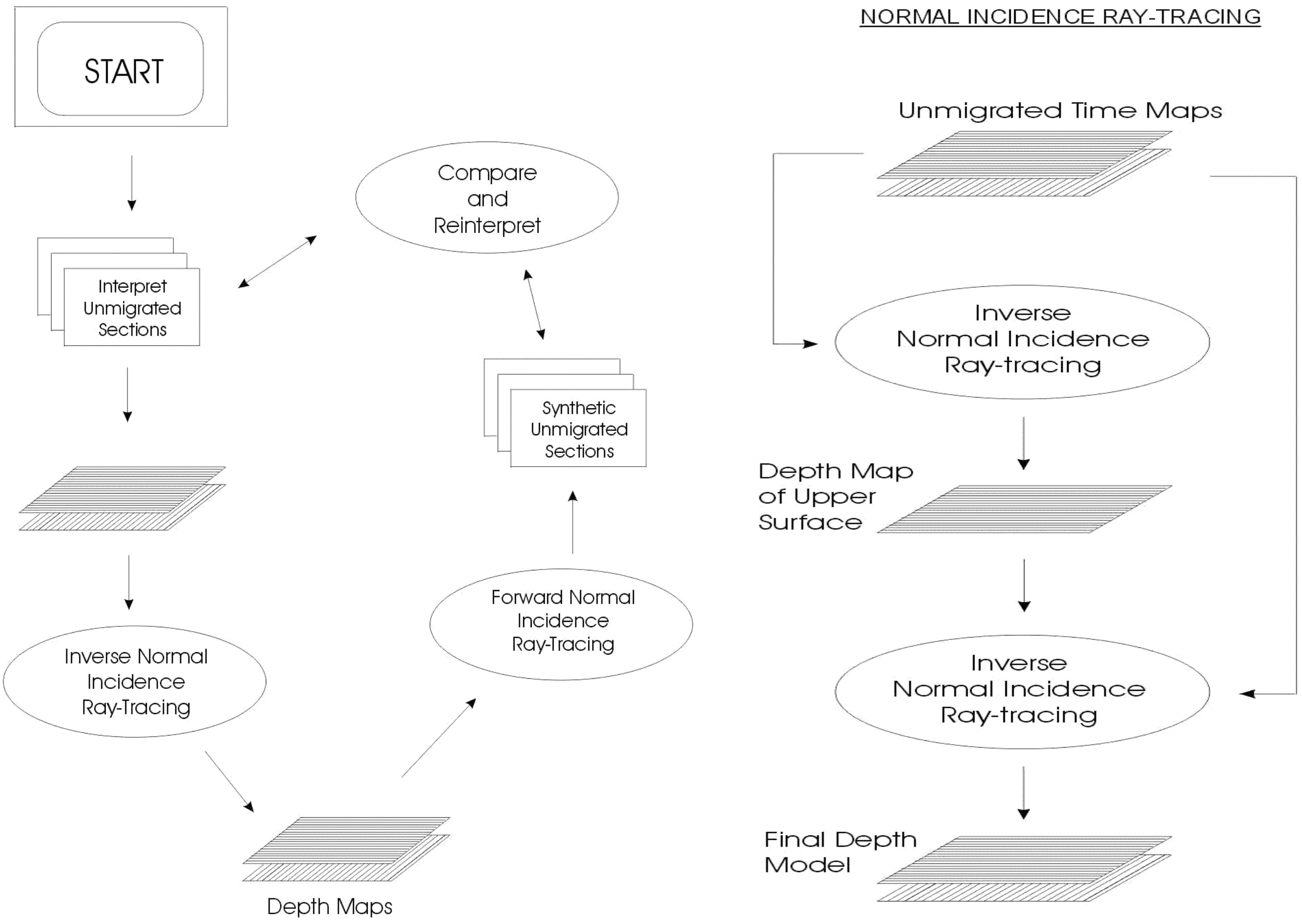


FIG. 3. Different ray-tracing modes corresponding to data processing stages (after Fagin, 1991).



a) b)

FIG. 4. (a) The unmigrated time section as simulated by normal-incidence ray-tracing, (b) Stages of the depth migration in converting the reflection structure to the depth maps. Forward modeling served as a guide to interpreting reflection structure (Fagin, 1991).

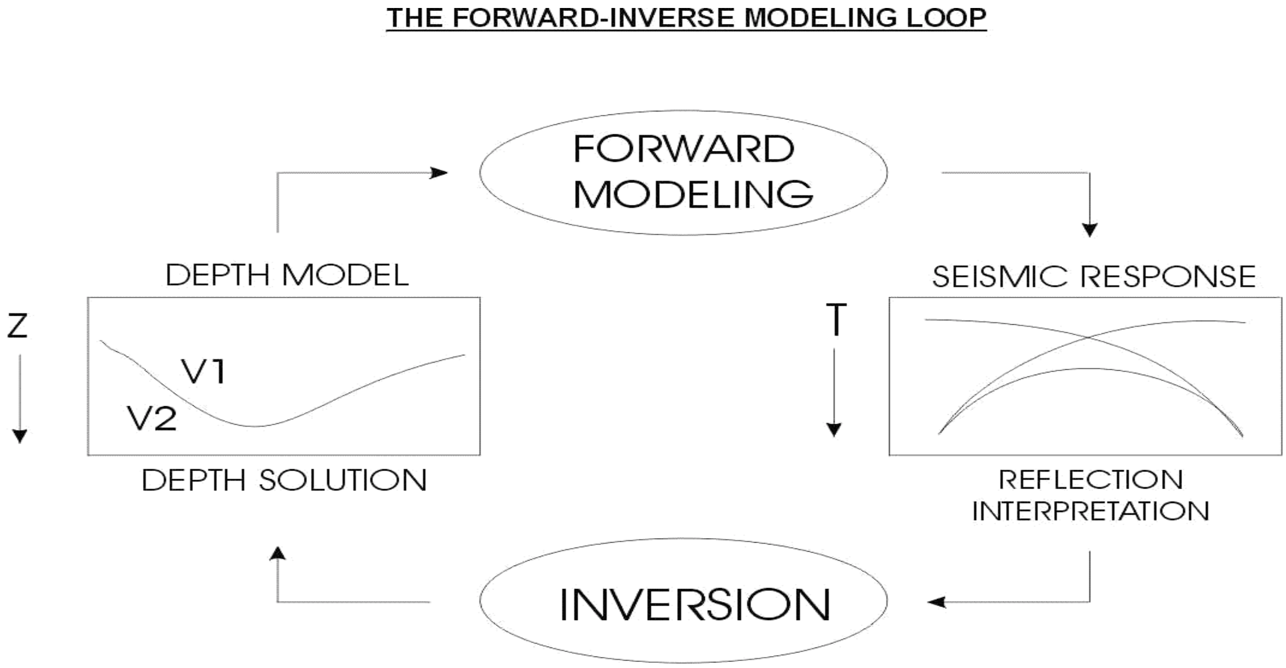


FIG. 5. The forward and inverse modeling. Inputs and outputs of the two processes are reversed.

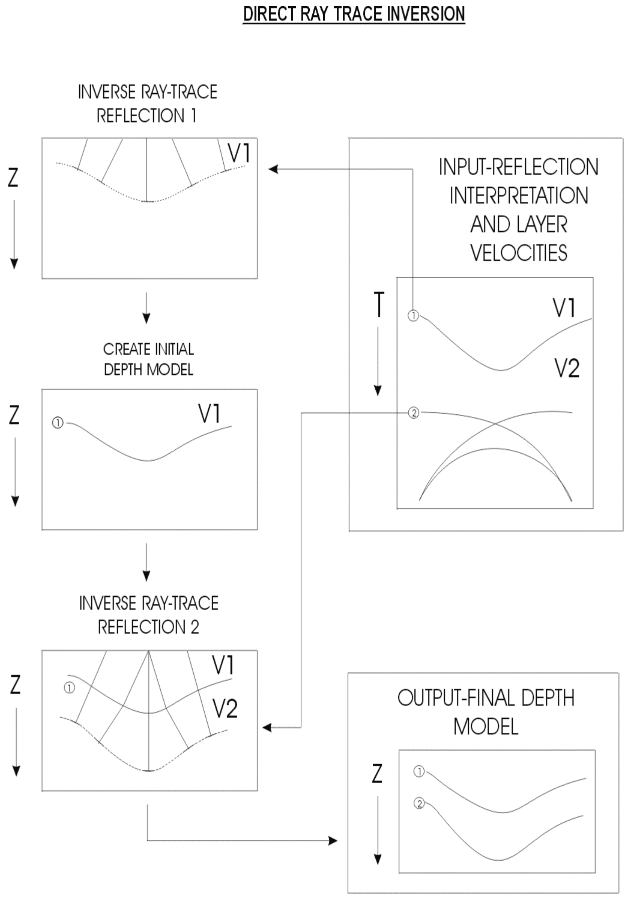


FIG. 6. Direct ray-tracing inversion. The input is in two parts. One part is an interpretation of reflection structure and the second one is layer velocities adopted from the velocity analysis. The output is a depth solution. In this two-surface example, reflection 2 from the second surface is a multi-valued bow-tie reflection.

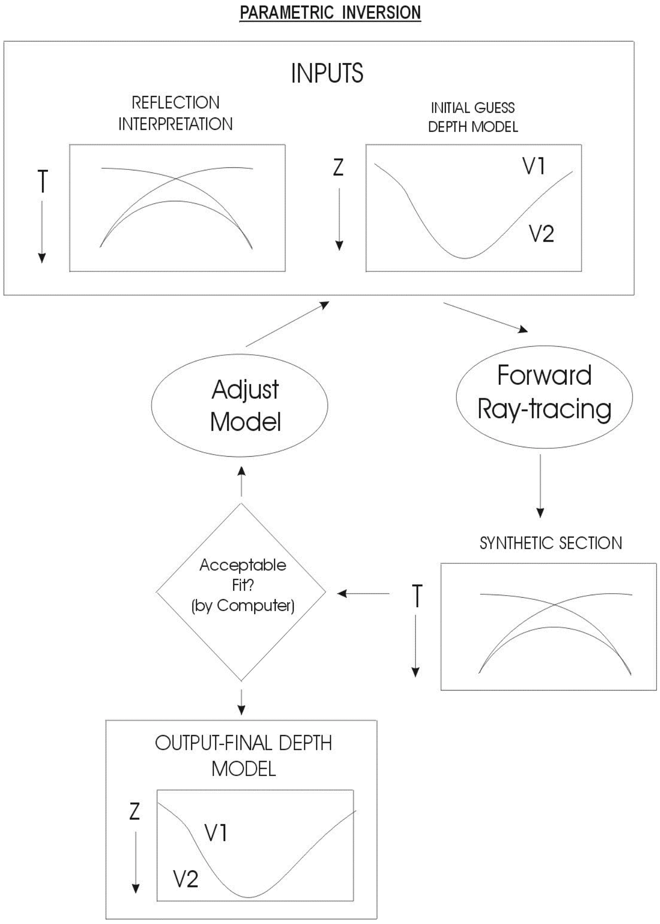


FIG. 7. Schematic diagram showing parametric inversion.

The offset ray-tracing problem is to find the raypath of a reflected ray extending from a source to a receiver. Raypaths for a shot gather are determined by searching for a ray that leads from the source to a subsurface reflection point and to a receiver. Shot gather modeling is used for data processing steps such as dip filtering and prestack migration. In zero-offset ray-tracing modeling, considering a model in which the source and the receiver are located at the same point, the raypath from source to reflection point must be identical to that from reflection point to receiver because of reciprocity. Therefore, only the upgoing or downgoing raypath needs to be traced. In addition, the raypath must be normal to the reflecting surface since the raypaths are identical and the incidence and reflection angles must be equal. Therefore, zero-offset ray-tracing is also called "normal incidence ray-tracing". Because the ray is normal to the reflector, it can be initiated at the reflector and traced upward. The unmigrated time section is simulated by normal-incidence ray-tracing (Fig. 4a). When time and velocity maps are defined to the satisfaction, they can be converted to depth maps using depth migration. The map migration process allowed the following: defining time maps for migration, defining velocity fields and performing the ray-tracing migration (Fig. 4b).

It is possible for ray-tracing to define the structure of an unmigrated reflection in time and derive the subsurface structure of the reflector in depth. This process is referred to as inverse problem (May and Cavey, 1981). Figure 5 shows the relationship between forward and inverse problems. The input of the ray-tracing inversion is a reflection structure in either 2D or 3D, which means reflector shape in a stacked or migrated section, or reflection shape in a gather. Because it involves the transformation of seismic observations to a depth model, ray-tracing inversion is often referred to as migration. Two main ray-tracing inversion types are direct ray-tracing inversion and ray-tracing parametric inversion. Direct ray-tracing inversion is shown in Fig. 6. The input for the inversion is unmigrated reflection structure and layer velocities. The structure of each reflector is successively derived and used for raypath bending. In direct inverse ray-tracing, the ray is initiated from ground surface and continued downward since the depth structure is not known. The departure angle of this ray is the angle at which the wavefront impinged upon the ground surface at receiver location. In inversion, when the ray is traced back into the subsurface, this emergence angle becomes the departure angle. After the departure angle is derived, the raypath length is defined as the arrival time recorded at the point of departure. For such a raypath, the coordinates at the base of the ray are used to derive reflecting surface being normal to the ray at its terminus (Fagin, 1991).

Parametric inversion is described in Figure 7. In ray-tracing parametric inversion, the comparison between reflection interpretation and the synthetic data is made automatically. This procedure also includes a forward modeling step. The adjustment of the depth model obtained is from the synthetic/real data comparison. An initial estimate of the subsurface is required for the first iteration. Fig. 7 describes the inversion of zero-offset data. Parametric inversion aimed at inverting offset arrivals is termed tomography (Bregman *et al.*, 1989).

3D OFFSET RAY-TRACING APPLICATION FOR CALABRIA SEISMIC DATA

3D ray-tracing modeling was applied to deep seismic reflection data from Serre Mountains, Calabria. The velocity information required for ray-tracing modeling is acquired from Calabria time-distance graphs using first breaks (Çifçi, 1992). Figure 8 shows final zero-offset unmigrated time section for vertical component along the main profile, with several south-dipping interfaces including low velocity zone (LVZ). The line drawings map obtained from this section is shown in Fig. 9, which was used as a starting point for structural modeling. Numbers in circles show the main layers to be modeled, and locations of the shot points are also given on top of the figure.

Ray-tracing software QUIK, which can perform either 2D or 3D modeling, was used to model 3D shot gathers. It carries out shooting pattern generation, ray generation, ray capture and amplitude computation. QUIK is concerned primarily with geometric reflections, while other types of waves are not calculated (QuikShot, 1990). In ray-tracing modeling, initially zero-offset sections and later shot gathers were simulated. The same steps were also followed during the extension from 2D to 3D, editing the original locations of the acquisition to the modeling programs. Figure10 shows the initial depth model with six layers in 2D, which was used as an input for the ray-tracing modeling in order to obtain the synthetic sections. The reflectors of the depth model were extended horizontally, more similar to 3D model. These reflectors have moderate dips towards to east (from Tyrrhenian to Ionian Sea about 1 km on 10 km, that is the width of the model in E-W direction). This quasi-3D model, which contained the real positions of shots and receivers, was created.

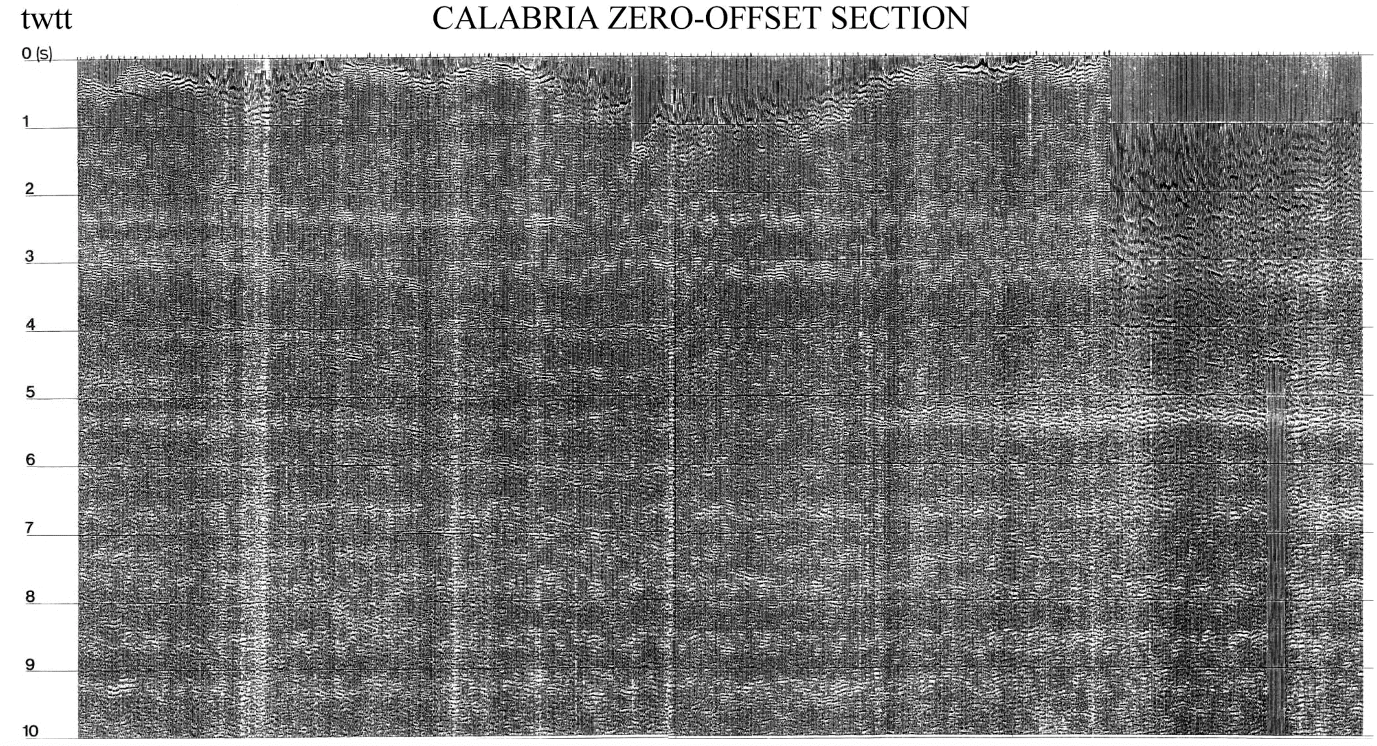


FIG. 8. Final zero-offset time section for vertical component along the main profile.

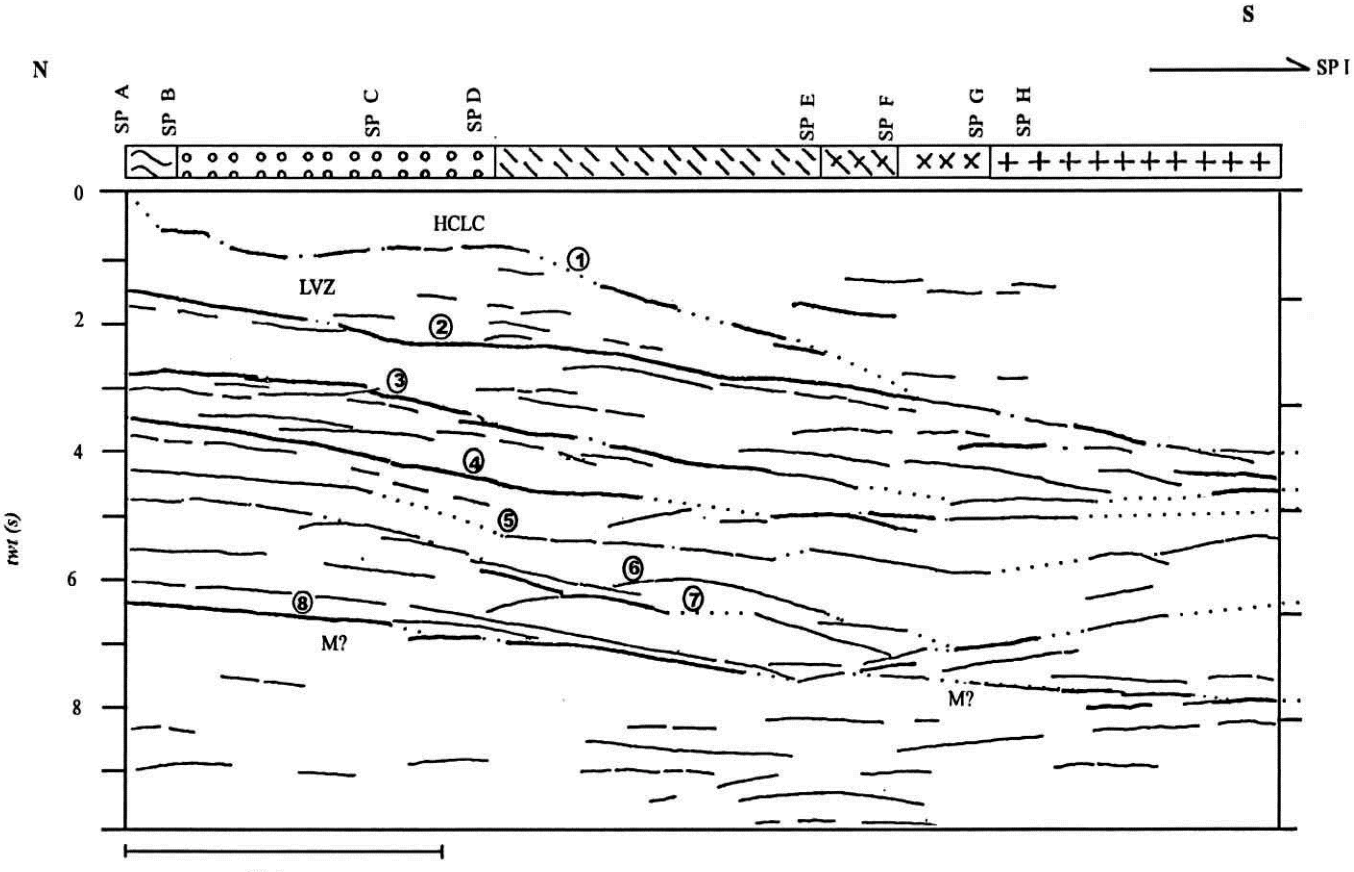


FIG. 9. Line drawings of the final zero-offset section of Calabria deep seismic data. Shot points are allocated on top of the figure. Numbers in the circles indicate the main reflectors, M is Moho reflection, LVZ is low-velocity-zone and HCLC is Hercynian lower crust.

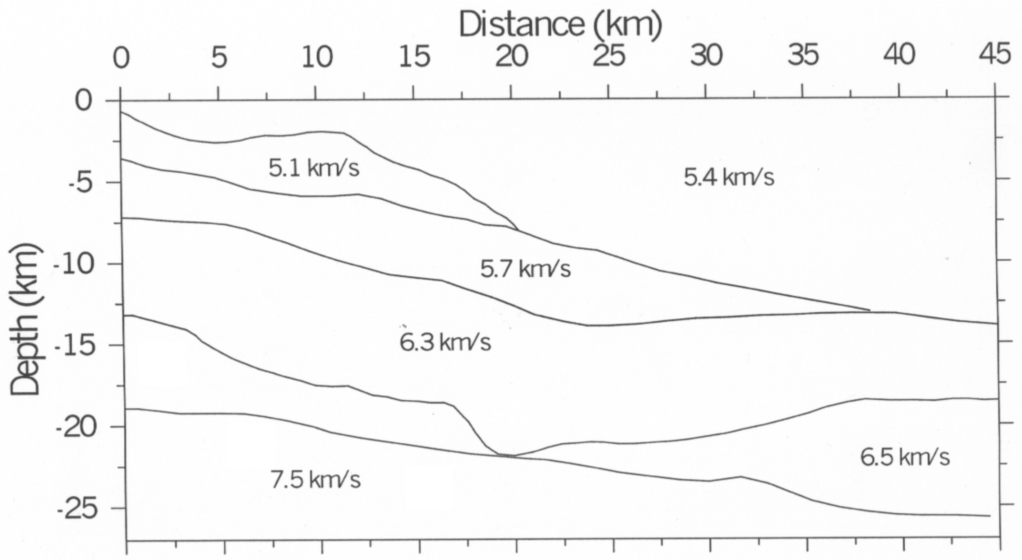
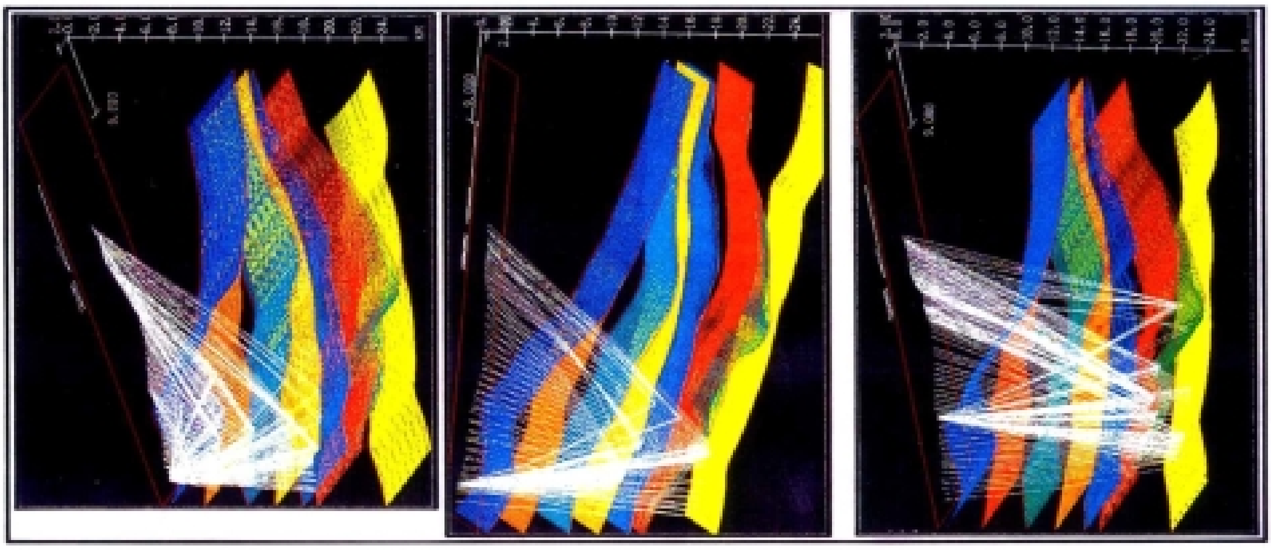


FIG. 10. Initial depth model having 6 layers, used in normal incidence ray-tracing, then shot gather modeling.

a)



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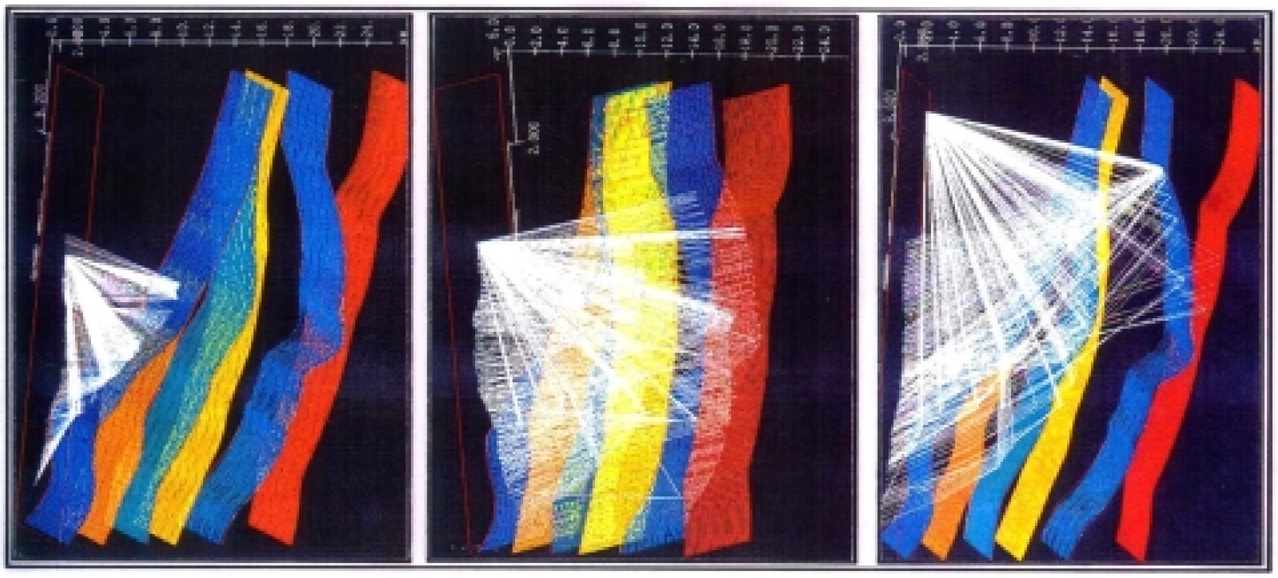

FIG. 11. Views of offset-ray-tracing rays on the quasi-3D model. (a) Rays from shot point A, B and C, (b) Rays from shot point G, H and I respectively.

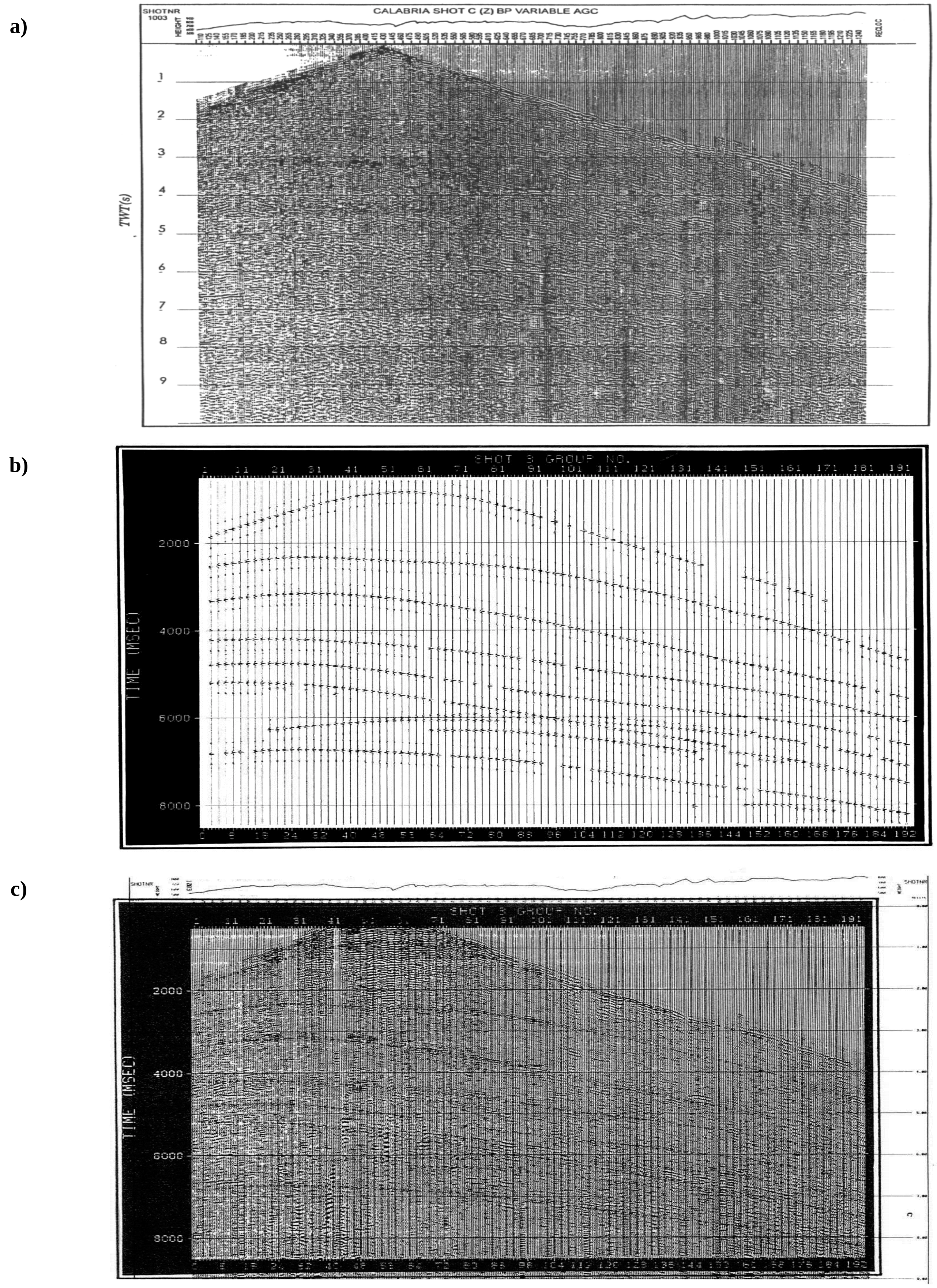

FIG. 12. (a) The vertical component field record from shot C processed with offset-time variable bandpass filter and trace mixing, AGC = 1000 ms, (b) Synthetic section of shot point C on the Calabria quasi-3D model with AGC = 200 ms, (c) Synthetic and field data comparison for shot point C.

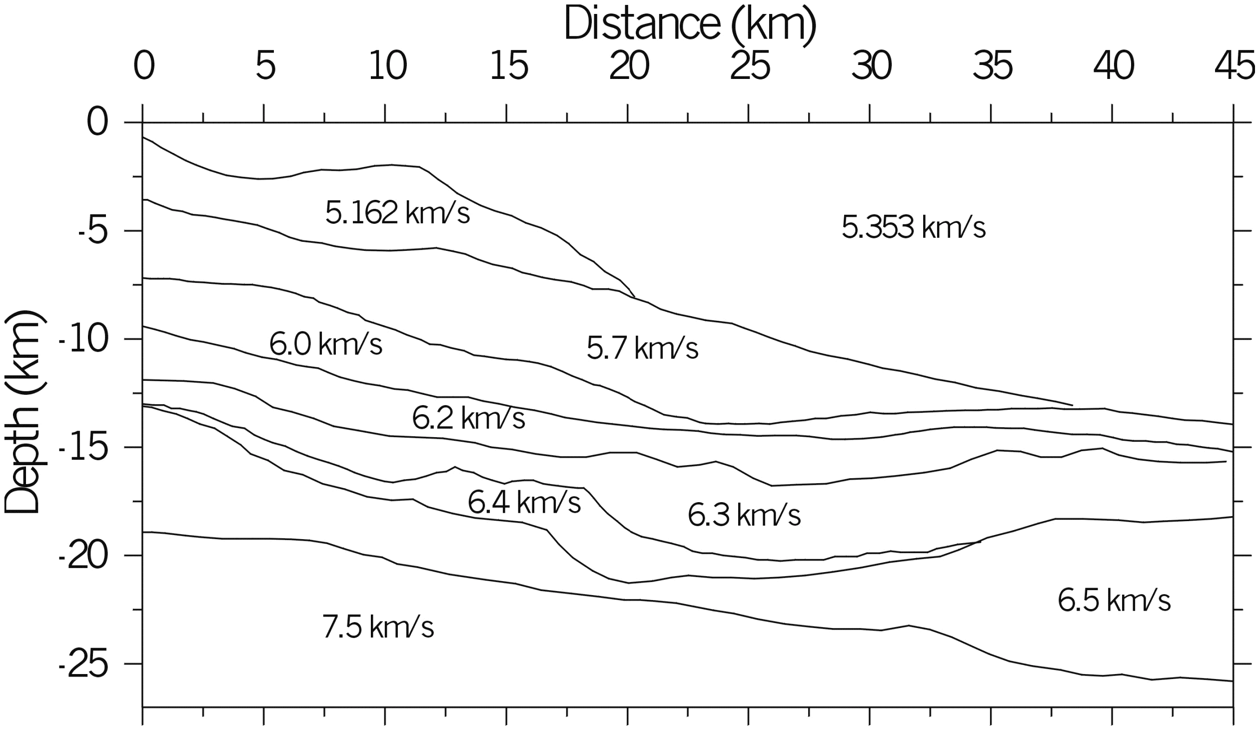

FIG. 13. The final depth model in 2D having 8 layers, after ray-tracing modeling.

After calculating the traveltimes and complex vector amplitudes, program QUIK transforms the traveltime and amplitude data into synthetic shot records in time domain. Afterwards, the wavelet being most suitable for the project is defined and convolved with the spike seismogram. In order to produce correct amplitude and phase of each seismic arrival, both the wavelet and its Hilbert transform is used. The wavelet is convolved with the real part of the seismic amplitude response and the Hilbert transform of the wavelet is convolved with the imaginary part of the amplitude response. The correct amplitude and phase of each arrival are reached by summing these two convolutions.

Initially the structure was 30 km long, but it was extended 45 km artificially in order to get reflections from shot point I. At the beginning, the model contained 3 surfaces; later 6 surfaces and finally 8 surfaces were incorporated. The disadvantages of 3D modeling lie primarily in the considerable additional effort in model building. A modeling project, which was completed in several days in two dimensions, took several weeks in three dimensions. These problems restricted the existing number of surfaces to a maximum of 8. The ray-tracing allowed modeling of laterally varying layers and vertical variation within a layer as well.

Figures 11a and 11b show the rays for offset ray-tracing from shot points A, B, C and G, H, I respectively with different southward-dipping interfaces on Calabria quasi-3D model. The source and the receivers were located at their original positions as in field data. Fig. 12a shows field shot record of the vertical component from shot point C. Result model section of offset ray-tracing for shot point C is shown in Fig. 12b, and synthetic-real data comparison is shown in Fig. 12c for record C.

The interpreted final depth model after ray-tracing modeling is shown in Fig. 13. The number of interfaces is improved to 8 such as Hercynian lower crustal reflections, low-velocity-zone (LVZ), strongly reflective Calabrian crust, Moho etc. The low-velocity-zone lies between 0.5 and 5.3 km depths along the distances of 0-20 km of the section.

GRAVITY MODELING

Deep seismic data of the Calabria region have given information about the lower crust for the limited area because the data were only available on land for short distances. Therefore, two gravity profiles were included in the study and the results of seismic modeling were used in the beginning of Profile 1.

Bouguer gravity anomalies at the northern end of Profile 1 have high values that can be indicated by thinned differentiated Moho (approx. 18-19 km depth) dipping to the South (Fig. 14a). Towards the end of Calabria seismic model, the gravity values decrease. This could be explained by the existence of the layers with density of 2.7 g/cm^3 and the thickening of the layer with a density of 3.0 g/cm^3. Bouguer gravity values around +24 mGal are found in coastal areas at the Profile 2. Decreasing gravity values are probably caused by accumulation of low-density sediments, which were identified by the densities as 2.20, 2.35, 2.40 and 2.62 g/cm^3. Upper crust can be expressed by the mean densities of 2.74 g/cm^3, whereas the lower crust's around 2.82 g/cm^3. A differentiated Moho or a transition zone can be explained by a density of 3.0 g/cm^3. Another point relating to the upper crust is the interpretation of the low-velocity zone. This zone should be a contact between the fossil lower crust and the autochthonous crust. In Profile 1, the low-velocity-zone with 2.55 g/cm^3 density is also well corresponded by the gravity modeling.

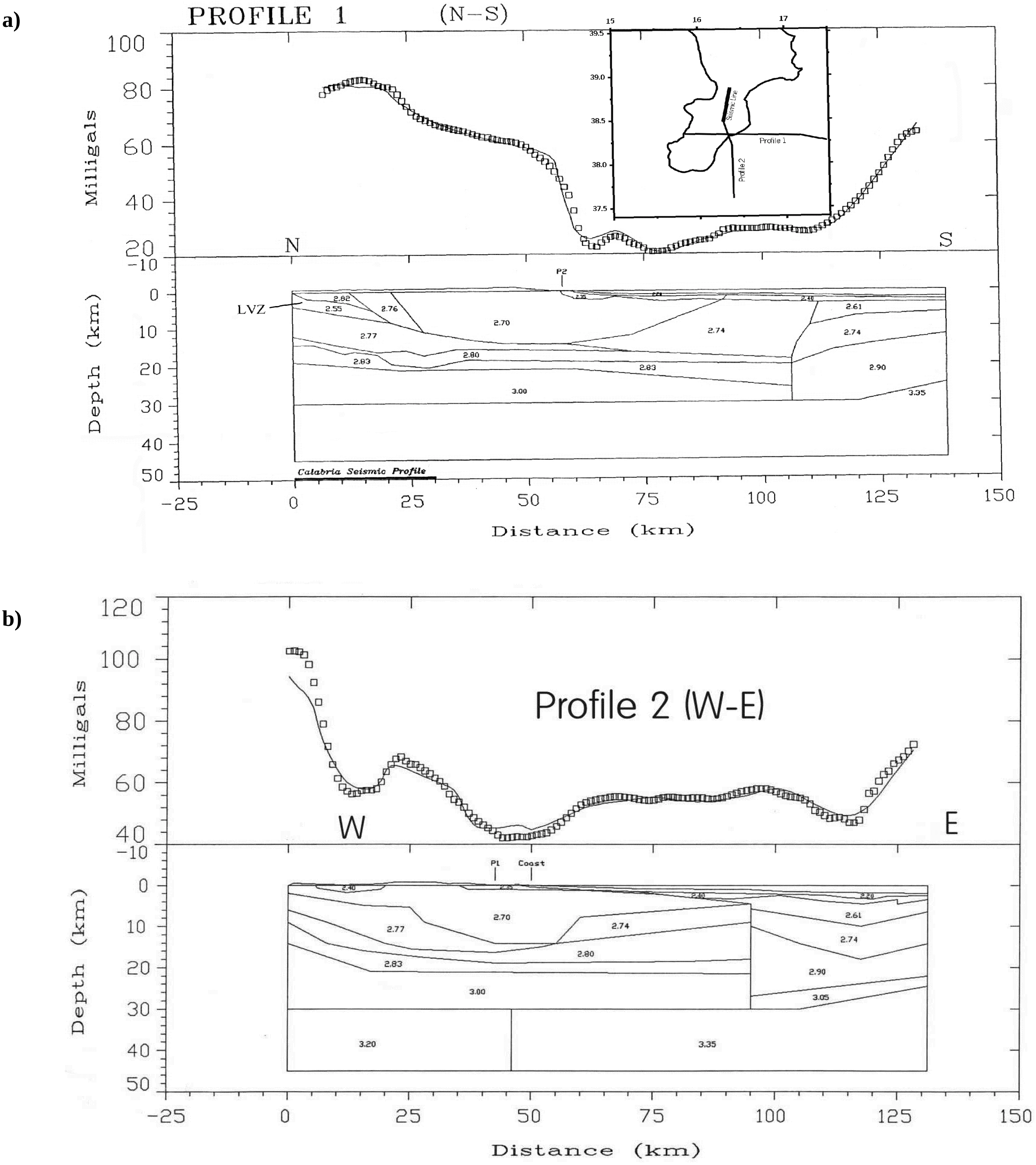

FIG. 14. Observed (square symbols) and calculated (continuous line) Bouguer gravity anomalies, and the model structure (densities are in g/cm^3), (a) Gravity modeling Profile 1 and profile locations, (b) Gravity modeling Profile 2.

The western end of Profile 2 has higher Bouguer gravity values (Fig. 14b). This should be caused of the thin crust, which is known around the Tyrrhenian Sea. Around the Profile 1, the decrease of anomaly is exactly well corresponded with the thinning of the layer of 2.77 g/cm^3 density. The minimum Bouguer gravity anomalies were observed at the border of the coastal area and were approximately +44 mGal. The Calabria seismic model was also used in this part of the Profile 2. The gravity field in this region is controlled by the transition from 3.20 to 3.35 g/cm^3 density. Accumulation of low-density layers with 2.20, 2.40 and 2.61 g/cm^3 is indicated by the lower gravity values towards the East. However at the very end of the Profile 2, the Bouguer gravity values increase sharply.

CONCLUSIONS

The importance of the Serre Mountains, Calabria (S.Italy) area is that it represents nearly outcropped crustal sections. The general geotectonic setting of the Calabria Hercynian granulite-facies metamorphism and crustal differentiation is a continental margin above a subduction zone. This model is based on the occurrence of granulite-facies metamorphism. It was accompanied by magmatism and the subsequent tectonic uplift.

There is high reflectivity in the crustal structures of Calabria. A low velocity zone (LVZ) was detected that outcrops in the north of the section at the base of the fossil lower-crustal unit and dips to the south at about 10 degrees. This LVZ marks the contact between the tectonically uplifted and tilted lower crustal rocks with the actual upper crust. Relatively strong reflections at 6.5-8 s TWT dip to the south.

According to the tomographic inversion calculations, for the upper 2 km of the section, around shotpoint B (the Curinga-Grifalco Fault), the velocity model displays an abrupt change near the surface with low velocities. Between shot points D and E lower velocities were encountered at the surface but higher velocities at greater depths. A good geometrical correlation was found between tomographic P-velocity and the velocities from laboratory tests and geological interpretation. All mapped contacts can be recognized in the resolved tomographic model.

All shot gathers of Calabria deep seismic study were simulated successfully by 3D ray-tracing modeling, but only one example of the synthetic sections is presented as shotpoint C to compare with its field and synthetic time sections of the offset ray-tracing. Field sections and models obtained from 3D ray-tracing modeling show good correlation for seven or eight layers for such interfaces as the Hercynian lower crustal reflections, LVZ, the strongly reflective Calabrian crust and the differentiated mantle. The LVZ zone is the contact between the Hercynian lower crust and strongly reflective Calabrian crust and the underlying Alpine metamorphic units and is about 5-10 km thick. The crust-differentiated Moho boundary, which dips to the south, is in between 19 and 24 km depth. The results of gravity modeling correspond well with observed and calculated values due to the seismic control.

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