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A *P*-wave velocity model of the upper crust of the Sannio region (Southern Apennines, Italy)

Giovanni Iannaccone (1), Luigi Improta (2), Paolo Capuano (1), Aldo Zollo (2), Giancarlo Biella (3), Roberto De Franco (3), Anne Deschamps (4), Massimo Cocco (5), Lorenzo Mirabile (6) and Roberto Romeo (7)

(1) *Osservatorio Vesuviano, Ercolano, Napoli, Italy*
(2) *Dipartimento di Scienze Fisiche, Università di Napoli «Federico II», Napoli, Italy*
(3) *Istituto per le Ricerche sul Rischio Sismico, Milano, Italy*
(4) *Institut de Geodynamique, CNRS, Université de Nice, Sophia-Antipolis, France*
(5) *Istituto Nazionale di Geofisica, Roma, Italy*
(6) *Istituto di Oceanologia, Istituto Universitario Navale, Napoli, Italy*
(7) *Servizio Sismico Nazionale, Roma, Italy*

Abstract
This paper describes the results of a seismic refraction profile conducted in October 1992 in the Sannio region, Southern Italy, to obtain a detailed *P*-wave velocity model of the upper crust. The profile, 75 km long, extended parallel to the Apenninic chain in a region frequently damaged in historical time by strong earthquakes. Six shots were fired at five sites and recorded by a number of seismic stations ranging from 41 to 71 with a spacing of 1-2 km along the recording line. We used a two-dimensional raytracing technique to model travel times and amplitudes of first and second arrivals. The obtained *P*-wave velocity model has a shallow structure with strong lateral variations in the southern portion of the profile. Near surface sediments of the Tertiary age are characterized by seismic velocities in the 3.0-4.1 km/s range. In the northern part of the profile these deposits overlie a layer with a velocity of 4.8 km/s that has been interpreted as a Mesozoic sedimentary succession. A high velocity body, corresponding to the limestones of the Western Carbonate Platform with a velocity of 6 km/s, characterizes the southernmost part of the profile at shallow depths. At a depth of about 4 km the model becomes laterally homogeneous showing a continuous layer with a thickness in the 3-4 km range and a velocity of 6 km/s corresponding to the Meso-Cenozoic limestone succession of the Apulia Carbonate Platform. This platform appears to be layered, as indicated by an increase in seismic velocity from 6 to 6.7 km/s at depths in the 6-8 km range, that has been interpreted as a lithological transition from limestones to Triassic dolomites and anhydrites of the Burano formation. A lower *P*-wave velocity of about 5.0-5.5 km/s is hypothesized at the bottom of the Apulia Platform at depths ranging from 10 km down to 12.5 km; these low velocities could be related to Permo-Triassic siliciclastic deposits of the Verrucano sequence drilled at the bottom of the Apulia Platform in the Apulia Foreland.

Key words *Southern Apennines – upper crustal structure – 2D P-wave velocity model*

Mailing address: Dr. Giovanni Iannaccone, Osservatorio Vesuviano, Via A. Manzoni 249, 80123 Napoli, Italy; e-mail: iannaccone@osve.unina.it

1. Introduction

The Sannio region is a sector of the Southern Apennines (Italy) (fig. 1) that in historical times has been struck by strong earthquakes ($I_0 \geq$ X MCS), as inferred from intensity data. At the present time, the seismicity of this region is characterized by low energy earth-

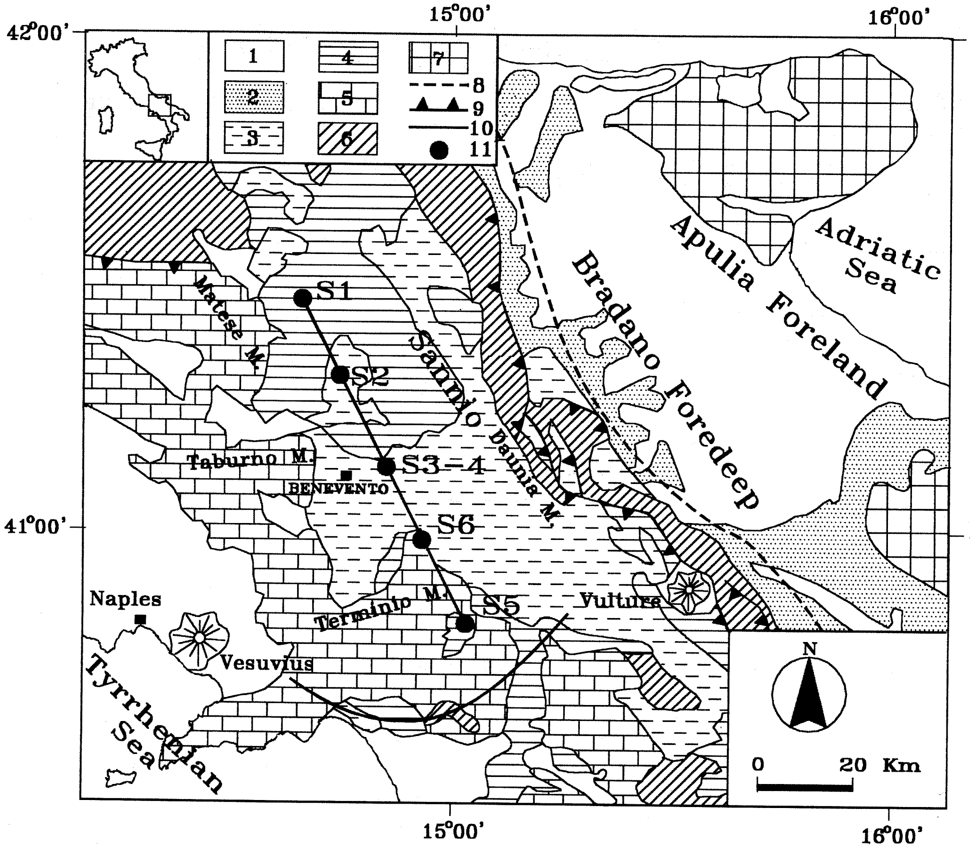

Fig. 1. Simplified geological sketch of the Southern Apennines (modified from Cinque *et al.*, 1993). 1) Middle-Upper Pleistocene and Holocene deposits; 2) Upper Pliocene-Lower Pleistocene deposits; 3) Upper Tortonian to Upper Pliocene thrust-sheets-top deposits; 4) Sannio and Sicilide nappes; 5) Western Carbonate Platform and related marginal areas including unconformable Upper Miocene flysch deposits; 6) Lagonegro and Molise basin sequences; 7) Apulia Carbonate Platform; 8) Buried frontal ramp of the Apennine thrust sheets; 9) Out of sequence thrust; 10) Main seismic refraction profile and fan line; 11) Shot point.

quakes frequently clustered in swarms; these sequences indicate seismic activity occurring at the borders of seismogenetic zones which caused the most energetic earthquakes.

In this context a detailed velocity model is needed to compute accurate hypocentral locations and fault plane solutions in order to understand the relation between tectonics and low magnitude seismicity.

During October 1992 an active seismic experiment involving personnel and instrumentation of several Italian and French institutions was carried out in the Southern Apennines. This experiment was performed in the framework of a multidisciplinary research program supported by the Commission of European Communities to develop a microzonation and hazard methodology to be applied to Benevento, the main town of the region. In fact, Benevento was considered a typical Southern European town and was chosen as a test site for this project (Marcellini *et al.*, 1995a,b).

Thus, the field experiment was designed with two main objectives:

– To determine a velocity model of the upper crust of the Sannio region.
– To test the feasibility of using small amplitude seismic signals for evaluating the site effects in the town of Benevento.

The velocity model was detected performing a seismic refraction survey which consisted of a main profile 75 km long, parallel to the Apenninic chain, and a curved profile (fan) centered at about the middle of the main line (fig. 1).

The evaluation of the seismic amplification effects in Benevento was performed by recording the same shots by a temporary seismic network deployed in the town with the number of stations depending on the distance from the shot (Iannaccone *et al.*, 1995).

In this paper we analyze and interpret data collected along the seismic refraction profile to obtain the *P*-wave velocity structure of the upper crust of a sector of the Southern Apennines.

2. Geological and geophysical setting

The seismic refraction profile analyzed in this paper is located in the Sannio region, in the northern sector of the Southern Apennines that is a Neogene east-verging accretionary wedge developed above a west-dipping subduction of the Apulian-Ionian lithosphere (Doglioni *et al.*, 1996) (fig. 1).

The geological structure of the Sannio region is not clear at present because of the complexity of the paleogeographic domains involved in the mountain chain building. Moreover, compression propagated non-cylindrically and was characterized by the development of out-of-sequence structures (Patacca *et al.*, 1992).

Furthermore, this sector of the chain was not investigated in detail by geophysical methods. The regional gravity and magnetic fields in Central and Southern Italy were used to reconstruct the crustal structure and the top of the carbonatic sedimentary rocks (Corrado and Rapolla, 1981; Fedi and Rapolla, 1990). The only seismic data available in the study area are some refraction and wide angle reflection profiles (DSS) recorded in the seventies (Italian Explosion Seismology Group, 1982). These data provide some indications about the depth of the Moho boundary in the transitional area between the Southern and Central Apennines but do not allow to define a detailed velocity model of the upper crust.

Regional synthesis of the upper crustal structure of a large portion of Southern Italy was realized by jointly interpreting geological studies and well and oil exploration seismic reflection data (Mostardini and Merlini, 1986; Casero *et al.*, 1988; Roure *et al.*, 1991).

In the study area (fig. 1) the accretionary wedge consists of a pile of nappes forming a duplex system orogenically transported over the flexured south-western margin of the Apulia foreland (Patacca and Scandone, 1989; Patacca *et al.*, 1990). The nappes are formed by sediments of Meso-Cenozoic domains, including basins and shelves, of the Apulia continental margin.

The tectonic units underlying the roof-thrust are represented by Meso-Cenozoic deposits of the Apulia Carbonate Platform disconformably overlain by Messinian carbonates and evaporities and Pliocene terrigenous marine deposits. They are involved in the folds and thrusts of a buried thrust belt (Mostardini and Merlini, 1986).

The nappes above the roof-thrust derive from the Lagonegro-Molise basin (originally located between the Apulia Platform and the Western Carbonate Platform) and from the Western Carbonate Platform and related marginal areas (including unconformable Upper Miocene flysch deposits). In the study area the highest unit of the duplex system is the Sannio nappe derived from a more internal basin.

Piggy-back basins, developed on the top of the advancing thrust sheets from Messinian to Late Pliocene-Pleistocene times, have been progessively filled in by different sedimentary sequences at present widely outcropping in the region (Patacca *et al.*, 1990).

During the Middle Pleistocene the Southern Apenninic wedge was uplifted and involved by an extensional tectonic with a NE-SW direction responsible for the historical and present day seismic activity (Anderson and Jackson, 1987).

3. Field procedure

The seismic profile, 75 km long and oriented 150°N, is roughly parallel to the compressive fronts of the Sannio region (fig. 1). Therefore, along this direction the geological structures are almost plane parallel allowing a more constrained interpretation of the seismic data.

Six shots were fired at five sites with about 15 km spacing along the line. Each shot consisted of 4-7 holes drilled to a maximum depth of 45 m and loaded with a charge ranging from 400 to 600 kg of explosives (table I). The shots are numbered from 1 to 6 following the chronological order.

We used a total of 81 portable seismic stations, 60 of them recording in digital form and 21 on analog magnetic tape. 60 stations were equipped with three-component short period geophones with a natural resonance frequency of 1 or 2 Hz and 21 with a vertical component 1 Hz sensor. The sampling rate ranged between 125 and 200 Hz and analog records were subsequently digitized at 125 Hz. The time signal was provided by internal clocks synchronized by radio time signal.

The seismic stations were deployed in a variable configuration according to the two objectives of the experiment. Shots S1, S2 and S6 were recorded by 71 stations along the profile and 10 in Benevento. The closest shot to the town of Benevento (S4) was recorded by 43 stations deployed in the town and the remaining along the profile. The shot S3 fired at the same site as S4 was recorded along the fan. The fan profile was made by putting the seismic stations along an arc with mean radius of about 55 km (fig. 1). The refraction profile was made with one explosion per day and deploying the instruments along the main line with an average spacing of 1 to 2 km.

All the stations and shots were located using 1:25 000 topographic maps with an estimated location accuracy of 25 m.

4. Data analysis and interpretation

The data are shown in the upper panels of figs. 2a-e as record sections plotted with normalized amplitude and reduced time scale, using a velocity reduction of 6 km/s.

In order to improve the signal to noise ratio, a preliminary spectral analysis was performed and then the seismograms were filtered in the frequency band 5-15 Hz using a 36 db zero-phase Butterworth filter.

Impulsive first arrivals are recorded only at close distances from the shot site. Most of the records show a weakly emergent first arrival

Table I. Shot parameters.

Shot name	Lat. N	Long. E	Elevation m a.s.l.	Date m d y	Shot hour h min s.xxx	Holes number and depth N, m	Charge kg
S1	41°25′58″	14°39′54″	515	05 10 92	15 30 06.896	7×42	600
S2	41°18′46″	14°44′10″	348	06 10 92	06 59 59.944	4×45	400
S3	41°08′16″	14°52′18″	148	07 10 92	14 29 59.920	4×45	500
S4	41°08′09″	14°52′09″	146	08 10 92	06 59 59.592	4×45	400
S5	40°51′09″	15°03′40″	512	09 10 92	14 29 59.832	5×45	500
S6	41°01′19″	14°56′30″	219	10 10 92	07 00 00.264	4×45	560

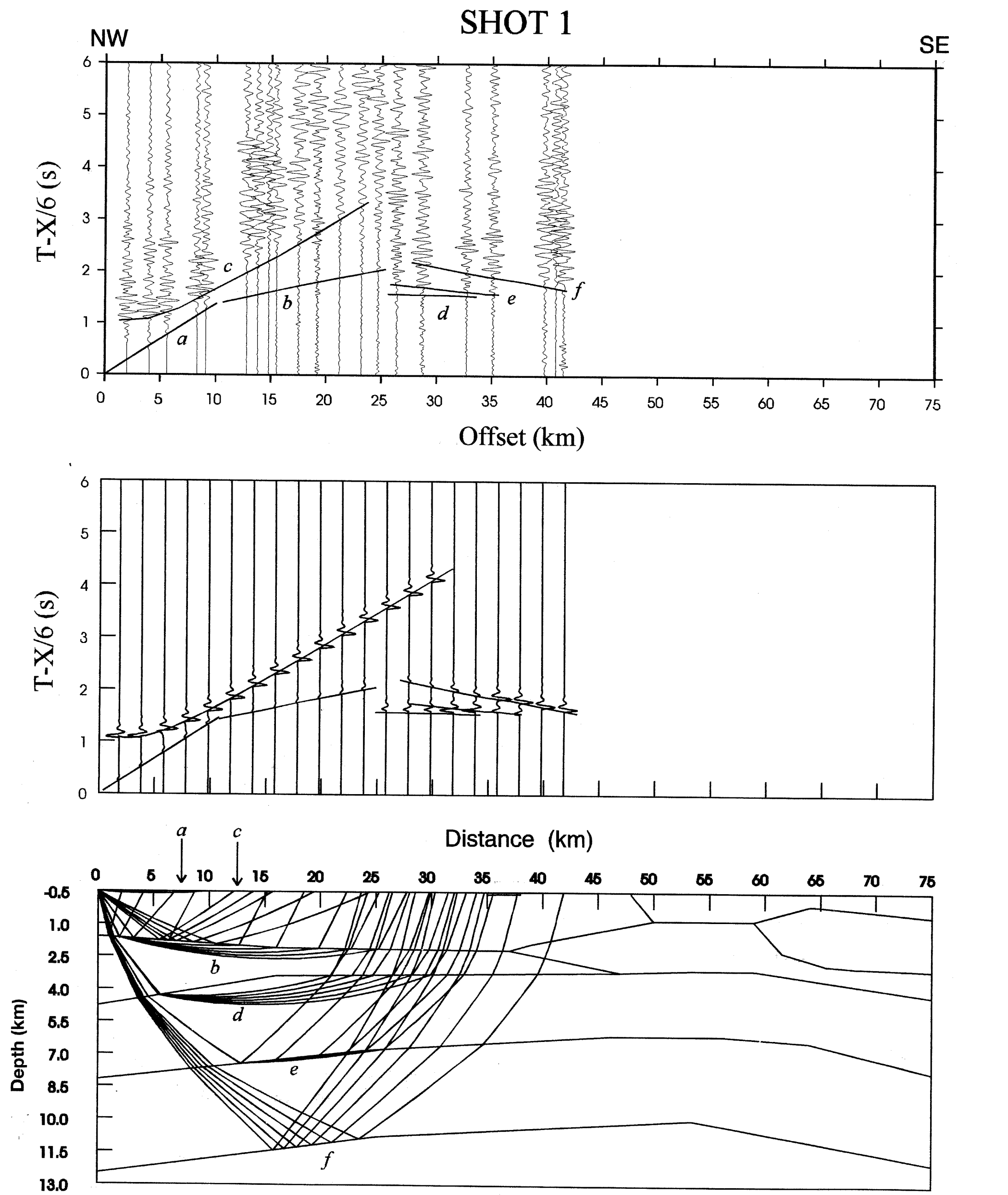

Fig. 2a. Record section for shot 1 (upper panel), theoretical section obtained by dynamical raytracing (middle panel) and seismic model with the indication of ray-path for each analysed phases (bottom panel). Data are plotted with normalized amplitude and reduced time scale, with a velocity reduction of 6 km/s. The small letters in the upper and bottom panel show each analysed phase. Synthetic seismograms are plotted in normalized amplitude and 2 km spaced. The arrival branches overlapped on data and synthetic are computed by ray-tracing. The seismic model is shown with vertical exaggeration close to 2.

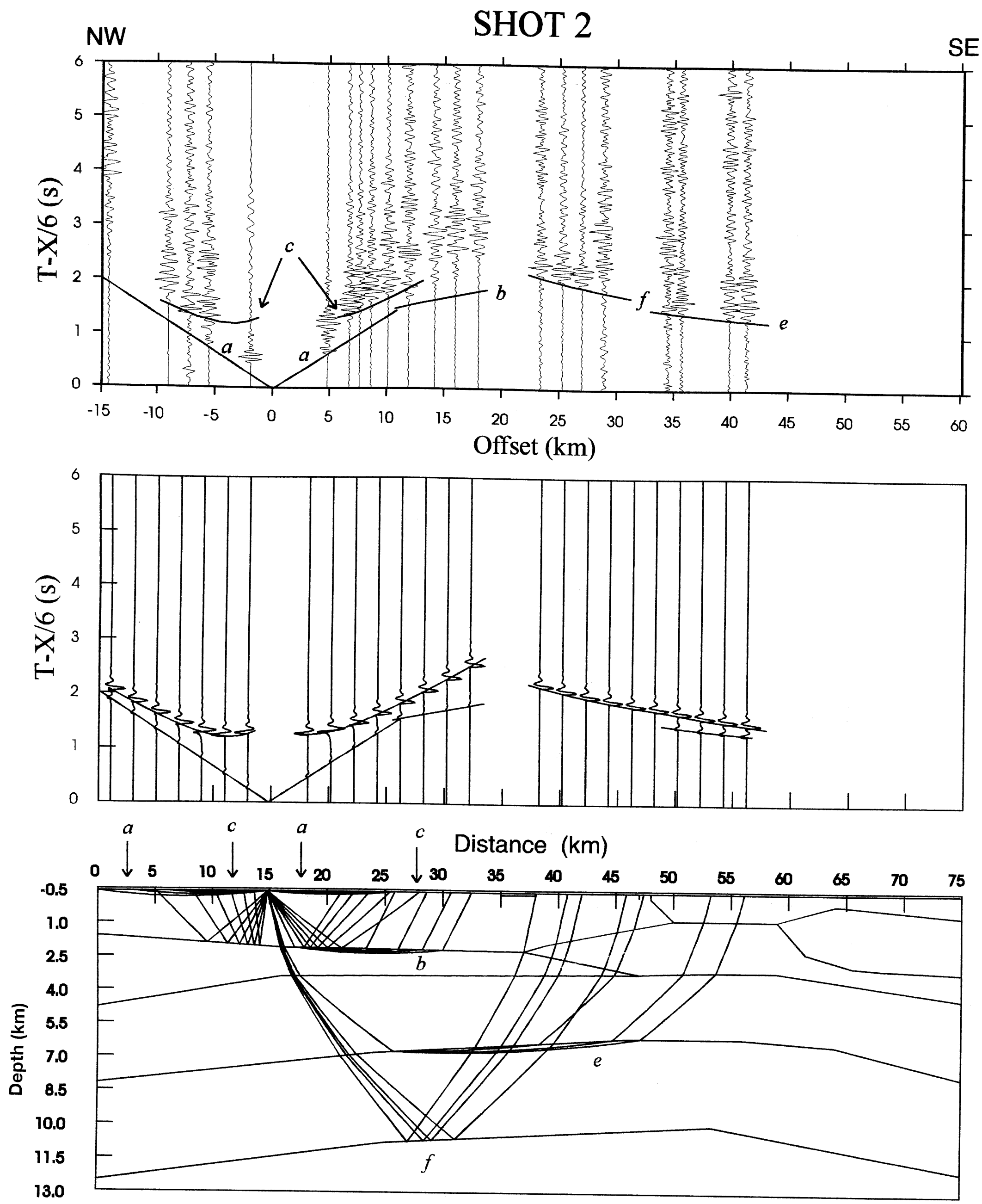

Fig. 2b. Data and interpretation of shot 2. See caption of fig. 2a.

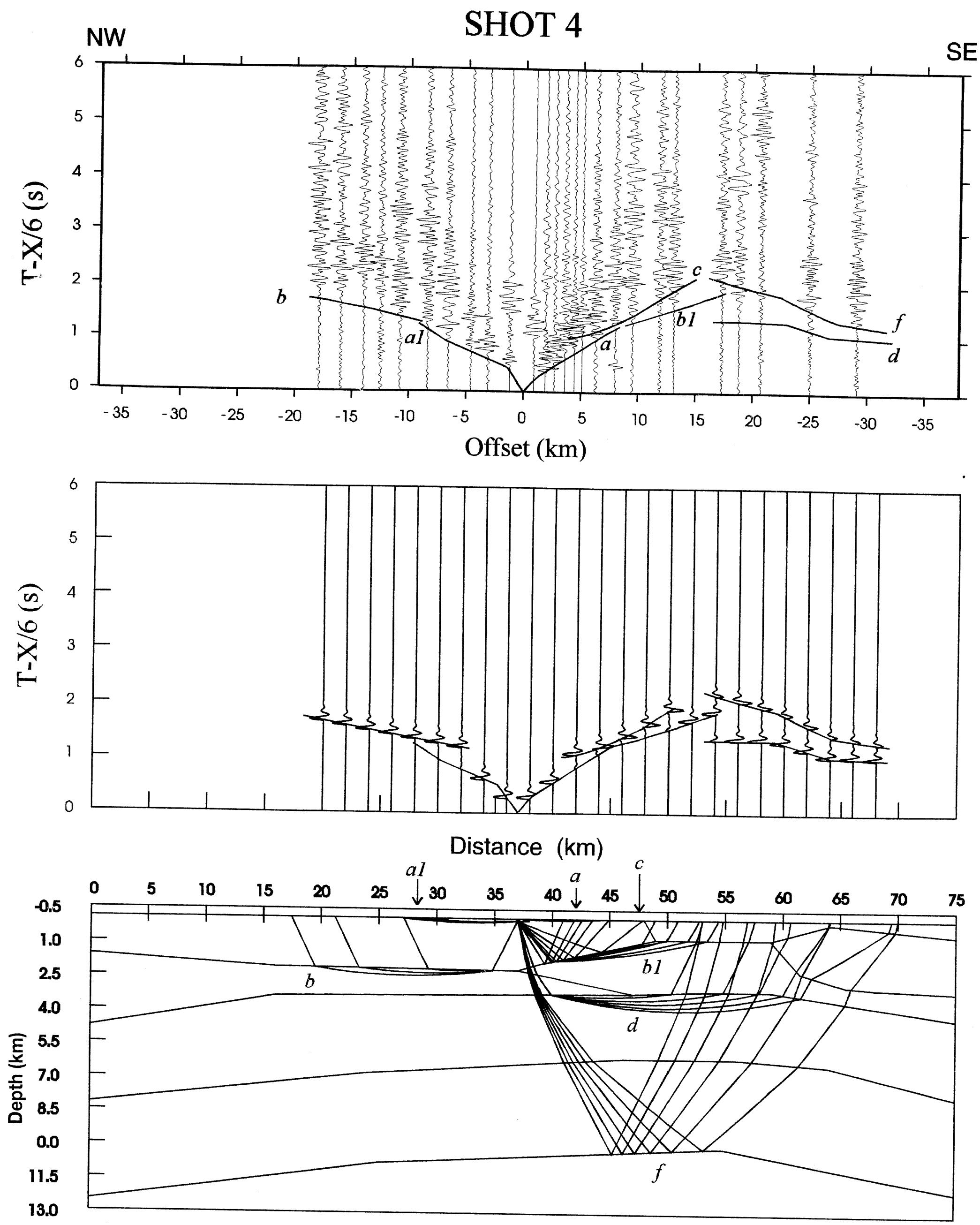

Fig. 2c. Data and interpretation of shot 4. See caption of fig. 2a.

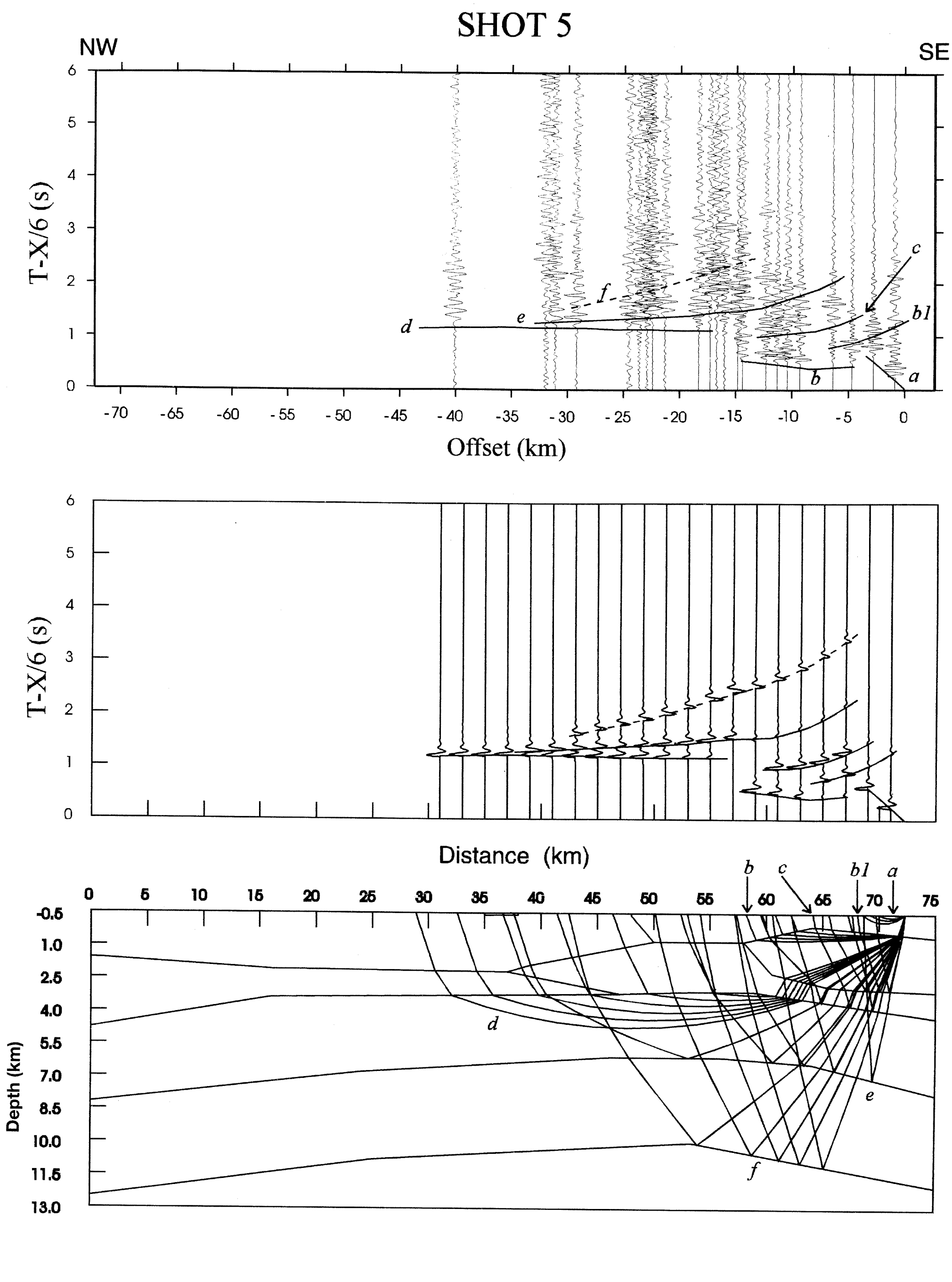

Fig. 2d. Data and interpretation of shot 5. See caption of fig. 2a.

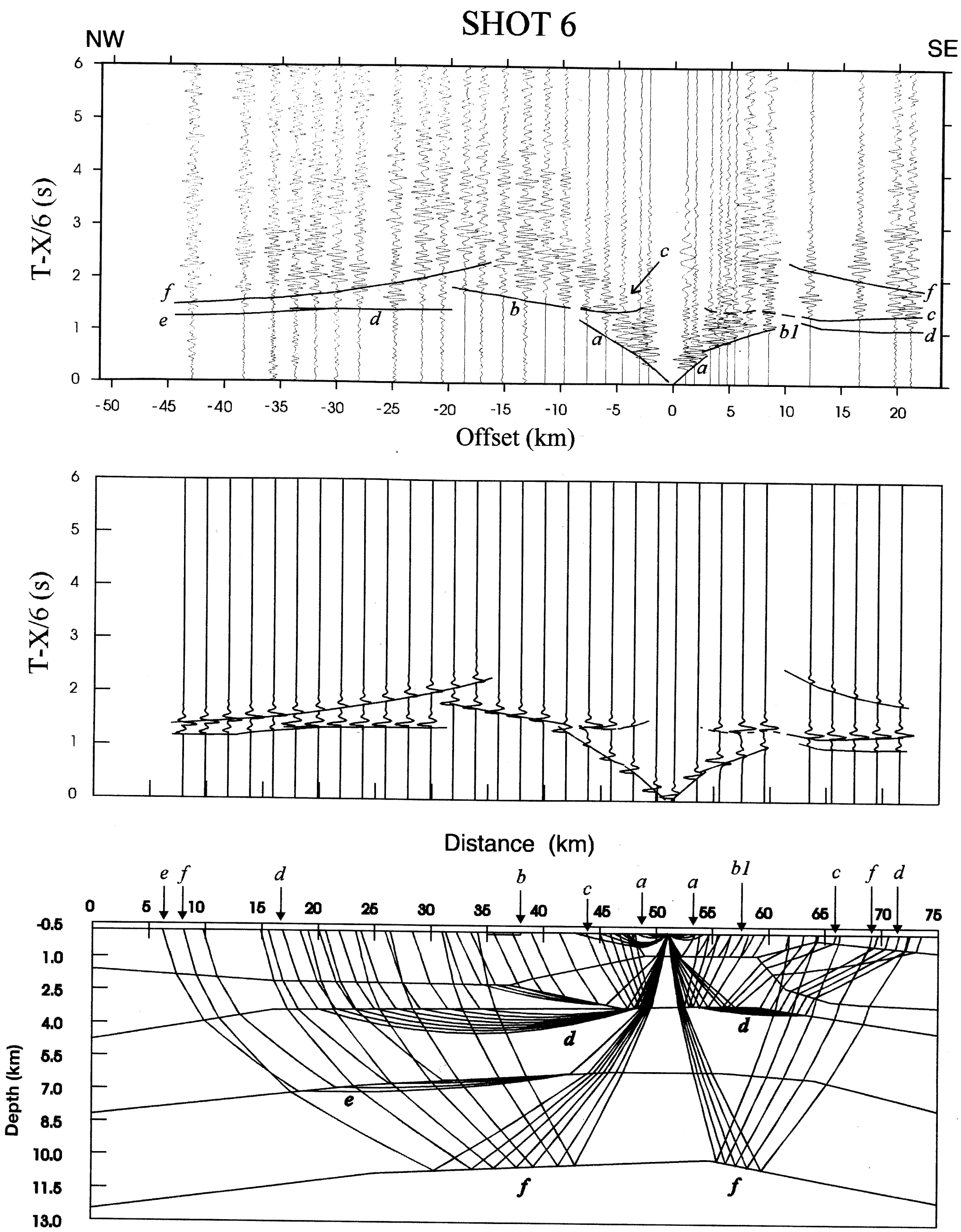

Fig. 2e. Data and interpretation of shot 6. See caption of fig. 2a.

(fig. 3) making it difficult to read the first arrival times. The maximum travel distance where we observe an acceptable signal level is about 40 km from each shot point. For this reason the seismograms recorded along the fan profile, with a mean distance of about 55 km, exhibit low signal/noise ratio with the result that they are quite uninterpretable. Consequently they are not considered in the present paper.

The arrival time picking of the first and second arrivals was performed from analysis of the raw data and bandpass filtered data. Record sections were plotted at various sizes and with various time zooms to help the arrival picking (fig. 4).

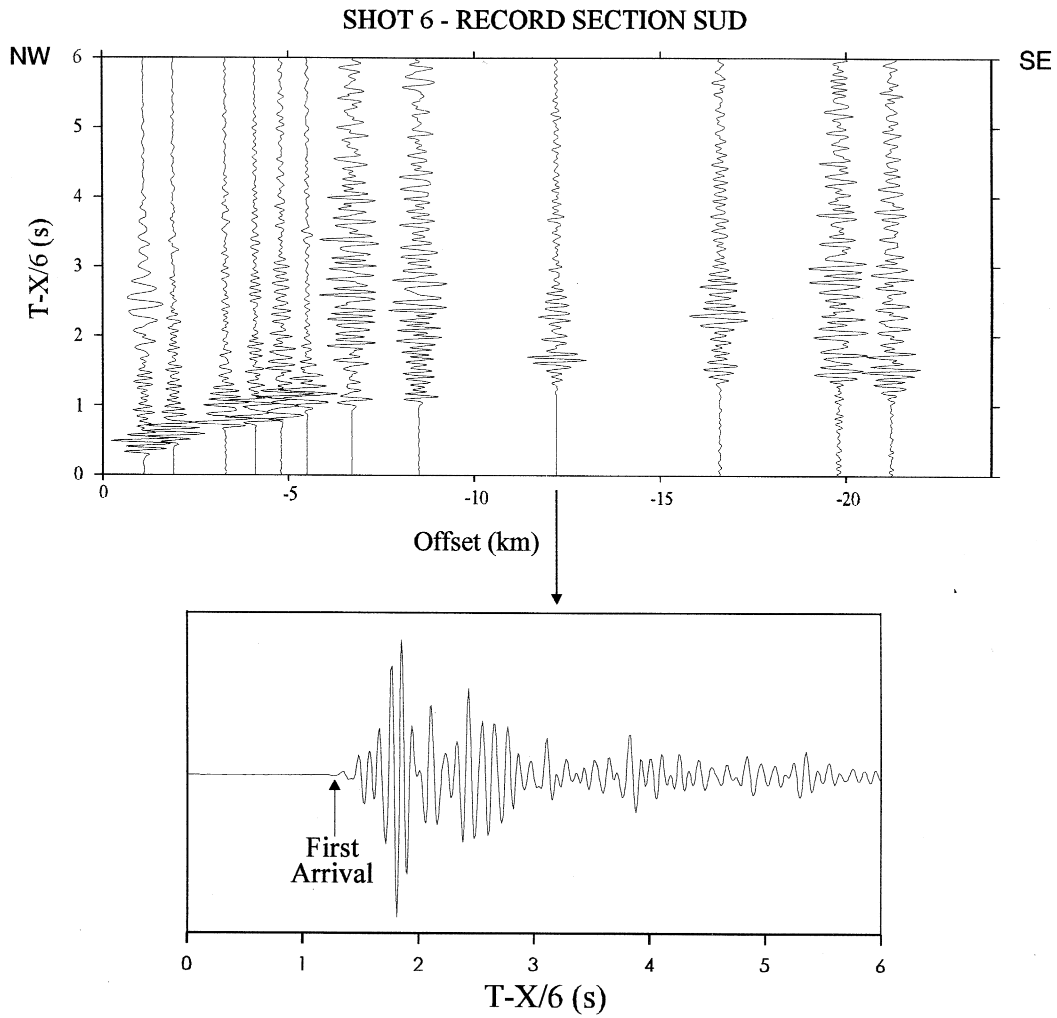

Fig. 3. Example of a seismogram with a weakly emergent first arrival; in this case, a high signal to noise ratio makes the uncertainty on first arrival time reading low. Data are plotted with normalized amplitude and reduced time scale, with a velocity reduction of 6 km/s.

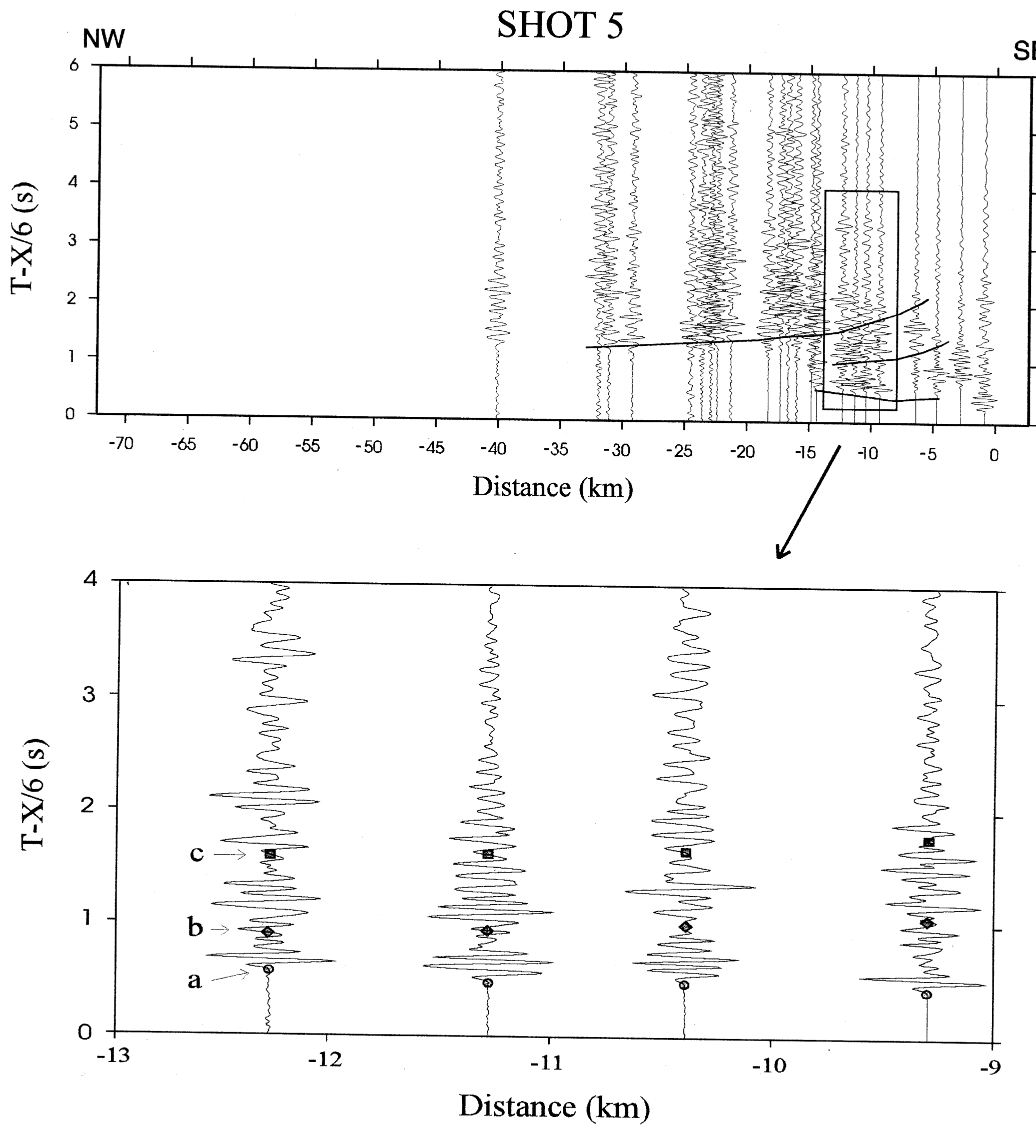

Fig. 4. Example of picking on seismograms: first arrival (*a*), reflected arrivals (*b*, *c*).

Arrival times of first and secondary phases identified on the seismograms were modelled by an interactive two-dimensional raytracing program based on asymptotic ray theory and implemented for PC computers by McGill University (1987). The trial and error procedure stopped when the difference between observed and computed time was less than the estimated uncertainty of arrival time readings.

Since the topography along the profile shows difference in height of about 450 m, we included it in the modelling by adding to each station a delay time computed using a mean subsurface velocity of 3 km/s. This value was obtained by averaging velocity estimates for stations close to the shots.

In performing our analysis we started interpreting the direct *P*-wave arrivals, critical refracted and near offset reflected phases to obtain a shallow velocity model (depth < 4 km). The deeper structure was constructed modelling refraction data and wide angle reflections.

The central and lower panels of figs. 2a-e represent synthetic seismograms and ray paths respectively (with a vertical exaggeration factor close to 2) computed for the final model, constrained by amplitudes and travel-times of identified phases. Synthetic seismograms are plotted using normalized amplitudes and 2 km spacing. The arrival branches superimposed on the data are determined by ray-tracing. They, together with the ray-diagram, show which part of the final *P*-wave seismic model is being highlighted (fig. 5).

The interpretation of the record sections S1, S2 and S4 indicates a surface *P*-wave velocity of 3.3 km/s in the central and northwestern segments of the profile. Delays in the arrival times within the first 5 km north of shot point S4 indicate the presence of a thin layer, about 0.2 km thick, with a *P* wave velocity of 2.2 km/s (phase a_1 in fig. 2c). The geometry of this low velocity body has recently been modelled in detail using data of shot S4 recorded by the 43 seismic stations deployed in the town of Benevento to study the local site effects (Improta, 1998). In the southern part of the profile the direct *P*-waves observed at offsets up to 4 km from shots S5 and S6 (phase *a* in fig. 2d and fig. 2e) define a surficial velocity of 3 km/s.

The second layer with a velocity of 4.8 km/s is at a depth of 1.6 km at the northern border and gently dips to a depth of 2.2 km near shot S4. The velocity and the dip of this layer are constrained by the first-arrival refracted branches observed in the range 10 to 25 km for shots S1, S2 and S4 and from near offset reflected arrivals from shots S1 and S2 (phases *b* in figs. 2a-c and phase *c* in figs. 2a,b, respectively). The relative amplitude between direct, refracted and reflected phases arising from the 4.8 km/s seismic discontinuity is really well matched in the synthetic seismograms of shots S1 and S2.

South of shots S4 and S6 (phases b_1 in fig. 2c and fig. 2e) first-arrival refracted branches with

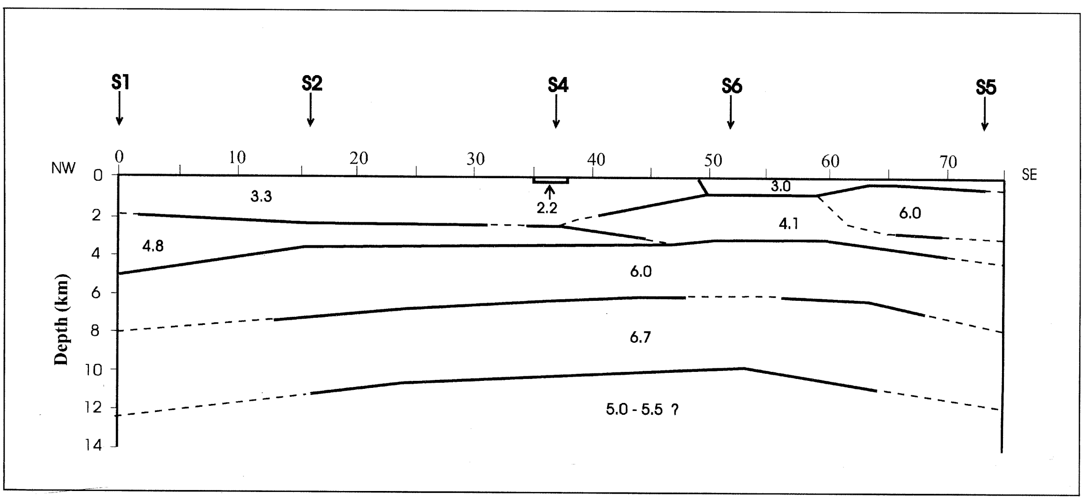

Fig. 5. Final 2D *P*-wave velocity model. Thick continuous lines correspond to the seismic interfaces investigated by seismic ray; numbers indicate *P*-wave velocity values (km/s). Shot points are also shown.

an apparent velocity in the range 4.1-4.3 km/s are observed. These phases define a seismic discontinuity with a velocity of 4.1 km/s at a depth varying from 0.8 to 2.3 km. Near-offset reflected arrivals south of shot S4 (phase *c* in fig. 2c) constrain its dip between 39 and 47 km along the profile.

A first-arrival refracted branch observed north of shot S6 (phase *b* in fig. 2e) with an apparent velocity of 5.2 km/s defines the southern termination of the 4.8 km/s body described above.

A prominent shallow feature of the model is a high velocity wedge, with a velocity of 6.0 km/s, overlying the 4.1 km/s body between 59 and 75 km. The velocity and horizontal dimension of the wedge is determined from the refracted first arrivals from shot S5 (phase *b* in fig. 2d). Its geometry is also constrained by the early refracted and reflected arrivals from shots S4 (phases *d* and *f* in fig. 2c) and S6 (phases *c*, *d* and *f* in fig. 2e) and by near offset reflected arrivals from shot S5 (phase b_1 in fig. 2d).

The 4.1 and 4.8 km/s bodies overlie a continuous layer, 3 to 3.5 km thick, with a velocity of 6.0 km/s. Velocity and depth (varying from 3.0 to 4.8 km) of the layer are determined primarily from the first arrival refracted branches, with apparent velocities in the 5.9-7.0 km/s range, observed south of shots S4, S6 and S1 and north of shots S6 and S5 (phases *d* in figs. 2a-e). In the southern part of the model, its top is really well constrained because refracted rays from shots S4, S6 and S5 turn in the same part of the model. Moreover, near offset reflected arrivals from shots S6 and S5 (phase *c* in figs. 2d,e) provide additional constraints. The relative amplitude between refracted and near offset reflected phases arising from the 6.0 km/s interface and other phases is quite well-matched in the S6 and S5 shots synthetic data.

In the northern part of the model, the depth of the 6.0 km/s discontinuity is determined from refracted first arrivals from shot S6. Corresponding arrivals from shots S1, S2 and S4 are not observed probably because the amplitude of the refracted phase is not wide enough to stand out against the noise level (especially on the shot S4) as shown by synthetic seismograms of the shot S1. The dip of the layer between 0 and 16 km is not determined by seismic refraction data (first-arrivals from shot S1 are not clear) but inferred from proprietary seismic reflection and well data for oil exploration.

A second layer, with a velocity of 6.7 km/s, occurs at depths of 6 km to 8 km. It is determined by critically refracted arrivals south of shots S1 and S2 and north of shot S6 with apparent velocities in the 6.4-7.0 km/s range (phase *e* in figs. 2a,b,e) and by middle angle reflections from shot S5 (phase *e* in fig. 2d).

The deepest detected seismic discontinuity occurs at depths of 10-12.5 km. Its morphology is determined by wide angle reflected arrivals for all shots (phase *f* in figs. 2a,b,c,e) but S5, where they are not clear (fig. 2d). The velocity below this interface is unconstrained. However, the large amplitudes of the reflected arrivals suggest a strong velocity contrast at the reflecting boundary. In order to model the relatively large amplitudes of the reflected waves, we performed several synthetic tests varying the velocity below this interface. In the case of a positive contrast the results provide high velocity values (V_p > 7.5 km/s) which are unrealistic for the explored depth in the Southern Apennines. Alternatively, large amplitude reflected phases can be modelled considering a negative contrast marked by a velocity lower than 5.5 km/s.

Our profile was conducted in a region with strong SW-NE structural variations. To estimate these effects on the proposed velocity model we estimated the errors in the depths of the layers as a consequence of their lateral inclination. According to the structural sections of the Southern Apennines proposed by Mostardini and Merlini (1986) we assume that the dip in the SW direction of the main units does not exceed 20°. The estimations indicate possible errors of about 6% in the corresponding values of the depth of each layer.

5. Geological interpretation

Geological interpretation of the velocity model is aided by surface geology (fig. 1) and wells (Mostardini and Merlini, 1986) and pro-

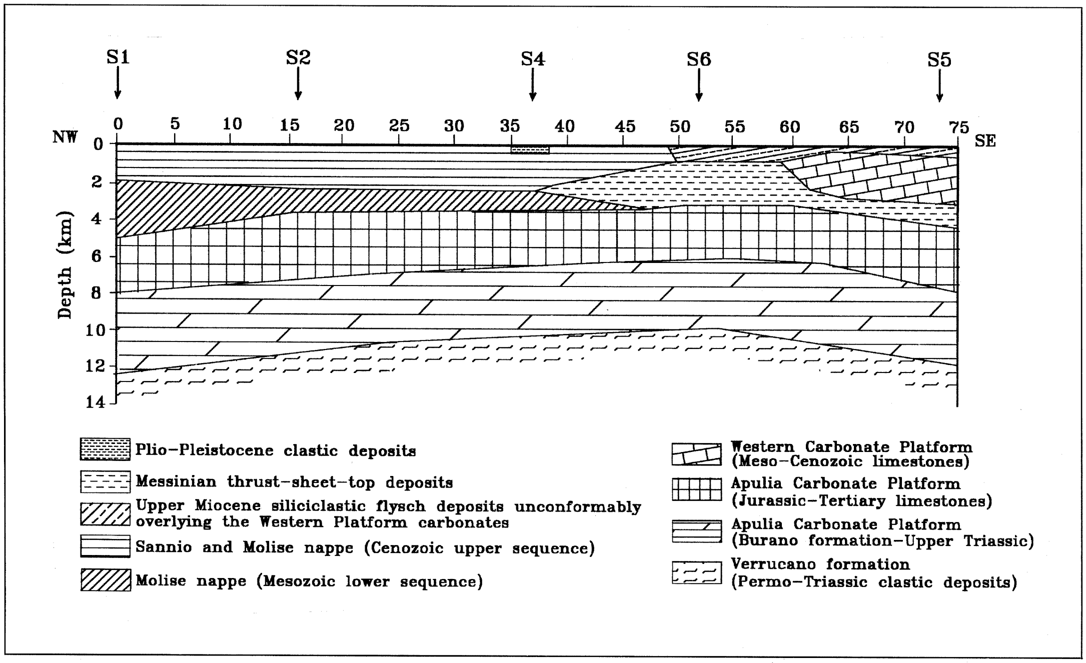

Fig. 6. Geological interpretation of the 2D *P*-wave velocity model. Shot points are also shown.

prietary seismic reflection profiles for oil exploration located in the study area. The resulting geological model is shown in fig. 6.

North of shot point S6, the first layer with a thickness ranging between 1.6 and 2.2 km and a velocity of 3.3 km/s corresponds to the Sannio nappe and the Tertiary portion of the Molise basin nappe (Patacca *et al.*, 1992). Evidence for this correlation comes from surface geology (fig. 1) and Circello 1 and S. Arcangelo Trimonte wells (Mostardini and Merlini, 1986). The layer below, characterized by a velocity of 4.8-5.0 km/s, may be related to the sedimentary rocks of the Mesozoic portion of the Molise basin nappe (Mostardini and Merlini, 1986; Patacca *et al.*, 1992). The lower surficial velocity (V_p = 2.2 km/s) observed north of shot point S4 corresponds to Middle Pliocene piggy-back basin deposits of the Ariano unit thickening in the SW direction.

South of shot point S6 the surface layer with velocities of about 3 km/s down to a depth of 0.8 km is mainly formed by Upper Miocene siliciclastic flysch deposits outcropping between shot points S5 and S6 (fig. 1). The high velocity (V_p = 6.0 km/s) wedge observed below this layer at the southern border of the model can be related to the Meso-Cenozoic limestone succession of the Western Carbonate Platform outcropping some kilometer west of shot point S5 and investigated by Nusco 2 well (Mostardini and Merlini, 1986). The carbonatic succession and the low velocity surficial layer form a major thrust sheet that tectonically overlaps a body with an average velocity of 4.1 km/s that has been interpreted as a Late Tortonian-Upper Messinian chaotic and/or deeply deformed sedimentary complex outcropping some kilometer east of the seismic profile.

The seismic discontinuity with a velocity of 6.0 km/s observed at a depth ranging from 3.0 km to 4.8 km along the whole profile corresponds to the top of the Apulia Carbonate

Platform, as inferred from well data (Mostardini and Merlini, 1986). A deeper interface (6 to 8 km deep) marked by a velocity of 6.7 km/s has been interpreted as a second-order discontinuity within the Apulia Carbonate Multilayer produced by a lithological transition between the Jurassic-Cretaceous carbonates and the Upper Triassic dolomites and evaporites of the Burano formation (Bally *et al.*, 1986).

Wide angle large amplitude reflected arrivals define the deepest discontinuity, located at 10-12.5 km of depth. The velocity below this interface is unconstrained. However synthetic tests performed to fit the observed amplitudes seem to indicate the existence of a strong inversion of velocity at the reflecting boundary. This hypothesis is supported by seismic reflection profiles for oil exploration performed in the Central Apennines and in the Bradano foredeep showing a strong deep reflector interpreted as the low velocity Middle Triassic-Upper Permian siliciclastic deposits of the Verrucano sequence drilled at the bottom of the Apulia Carbonate Platform (Bally *et al.*, 1986; Roure *et al.*, 1991).

6. Conclusions

The analysis of the NW-SE seismic refraction profile performed in 1992 in the Sannio region (Southern Apennines) allows to defines a *P*-wave velocity model of the upper crust in the Sannio region. The model shows a shallow structure (upper 4 km) with strong lateral variations in the southern part of the profile produced by the tectonic superposition of nappes derived from Meso-Cenozoic sedimentary domains, including basins and shelves. Deeper, the model becomes laterally homogeneous.

The main aspects of the velocity model described above are as follows:

a) Sedimentary rocks of basin and foredeep domains provide *P*-wave propagation velocities in the 3.0-4.1 km/s range for the Tertiary deposits and 4.8 km/s for the Mesozoic successions.

b) In the area of the Benevento basin (close to shot S4) the surficial layer with a *P*-wave velocity of 3.3 km/s, corresponding to Tertiary basin deposits, reaches its maximum thickness of about 2.5 km.

c) Meso-Cenozoic limestones of the Apulia and Western Carbonate Platforms show velocities of about 6.0 km/s.

d) Higher velocities, up to 6.7 km/s, characterize the lower part of the Apulia Platform formed by Upper Triassic dolomites and evaporites of the Burano formation.

e) A low velocity layer is hypothesized at a depth of 10-12.5 km. Due to the limited profile length we were unable to determine the vertical extent and seismic velocity of this layer that could correspond to the Permo-Triassic siciliclatic deposits of the Verrucano sequence.

Acknowledgements

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