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CROP ATLAS

SEISMIC REFLECTION PROFILES OF THE ITALIAN CRUST

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Line CROP 04: Southern Apennines

La linea CROP 04: Appennino Meridionale

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ABSTRACT - The CROP 04 line extends from the Tyrrhenian coast (Agropoli) to the Adriatic one (Barletta) cutting across the entire thrust belt-foredeep-foreland system. The total length approximates 160 kilometres. In the thrust belt, the line crosses most of the tectonic units that form the roof of the Apennine duplex system in Campania and Basilicata.

Answers to the following questions were considered major aims of the experiment:
- What is the depth of the sole thrust beneath the Apenninic chain and where is the backstop of the orogenic system?
- Is it possible to recognise the lower crust of Apulia? If a lower crust is recognisable in Apulia, how far does it extend westwards beneath the thrust belt?
- Was the crystalline basement of Apulia involved in the post-Tortonian compressional deformation?

The acquisition of the CROP 04 seismic line lasted from December, 1989 to April, 1990. Vibroseis and dynamite were both used as source types. The processing of the whole line was completed in March, 1991.

Due to the poor quality of the field data, the processing was not successful in providing an interpretable seismic profile. After a pause in which frustration and discouragement prevailed, an additional effort was planned, aimed at determining the causes of the very low signal/noise ratio of the field data. In addition, a new processing was required, aimed at exploiting as much as possible the signal content also making use of some a priori geological knowledge of the area.

The analysis of the field data has revealed the occurrence of three negative factors:
- Excessive spread length (about 20 km) in situations where lateral variations in the P- wave velocity exceed 1000 m/sec near the surface and lateral variations in the ground elevation reach several hundred metres within a single spread length;
- Crooked acquisition of the seismic data due to the rough topography that made difficult the accessibility for the vibroseis trucks. The high tortuosity in many parts of the line caused problems in CMP sorting and degraded the seismic image;
- Large occurrence of incoherent noise both in the dynamite and vibroseis data. At large offset (> 4000 m) the signal was often completely hidden by the noise. The reasons for this incoherent noise consist of recording inadequacies and wrong choices of the seismic-profile course in areas affected by severe tectonic deformation.

As concerns the new processing, a quality threshold defined by amplitude and frequency indicators was preliminary established and the traces whose quality fell below that threshold (30-40% on average) were removed from the dataset. After having removed the "bad" traces, the following processing steps were applied:
- Computation of the static corrections by means of inversion of refracted arrivals from a single refractor. First break picking was carried out manually on both vibroiseis and dynamite data;
- Optimisation of the CMP sorting in order to limit as much as possible the deleterious effects of the line tortuosity;
- Careful stack velocity analysis.

Presently, the line has been entirely reprocessed in the interval 0-10 seconds TWT. The reprocessed section is comparable to the best commercial lines in the region. Nevertheless, records suitable for geological interpretation usually do not exceed 5-6 seconds in commercial lines whilst in the new stack continuous and well-structured events are recognisable up to 8-9 seconds.

A key point for any geological interpretation is represented by the existence of a west-dipping package of faint, but well-organized reflectors evident between 6 and 8 seconds in correspondence to the Alburni Mountains. These reflectors fix an important constrain for the sole thrust of the Apenninic tectonic wedge that in this region reaches a depth of 20-25 kilometers. This depth coincides with the depth of the so-called "Tyrrhenian Moho" revealed by seismic refraction experiments already in the seventies.

KEY-WORDS: Southern Apennines, reflection seismic, deep crust.

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RIASSUNTO - Il profilo CROP 04 si estende per una lunghezza di circa 160 chilometri dalla costa tirrenica (Agropoli) alla costa adriatica (Barletta) della penisola, attraversando interamente il sistema catena-avanfossa-avampaese. Nell'area di catena il profilo interseca la gran parte delle unità tettoniche che compongono il tetto dell'edificio appenninico nel suo segmento campano-lucano, dai massicci carbonatici dell'Alburno-Cervati alle coltri lagonegresi e alle scaglie frontali delle unità Serra Palazzo e Daunia.

I principali punti di domanda ai quali si sperava di dar risposta attraverso il profilo CROP 04, quando questo fu progettato, erano i seguenti:
- qual'è la reale geometria del thrust basale sotto la catena appenninica e dove è ubicato il backstop del sistema ?
- dove si trova il trailing edge del duplex apulo sepolto ?
- è possibile individuare nell'avampaese apulo il limite tra crosta superiore e crosta inferiore ? E in caso affermativo fin dove si spinge al di sotto della catena la crosta inferiore apula?
- il basamento cristallino apulo è implicato nella deformazione compressiva post-tortoniana ?

Il profilo CROP 04 Appennino Meridionale fu acquisito tra il 1989 e il 1990 e processato nel 1990. I risultati di queste operazioni, tuttavia, delusero completamente le aspettative dal momento che il profilo ottenuto appariva di qualità così bassa da non permettere alcuna interpretazione geologica. Fu deciso, allora, di effettuare una attenta revisione dei dati sismici con il duplice obiettivo di chiarire le cause dell'insuccesso e di procedere ad un riprocessamento della linea nel caso in cui fosse stato possibile migliorare il rapporto segnale/disturbo.

I risultati delle analisi sulla qualità dei dati hanno messo in evidenza la concomitanza di tre fattori negativi:
- dimensioni eccessive dello spread (circa 20 chilometri) in situazioni dove all'interno di una lunghezza di spread si possono avere differenze di quota di diverse centinaia di metri e variazioni di velocità in prossimità della superficie maggiori di 1000 m/s;
- tortuosità della linea legata a problemi di accessibilità ai vibratori, con ovvi problemi di CMP sorting e degrado dell'immagine sismica;
- forte contaminazione in rumore incoerente sia nei dati a dinamite sia nei dati vibroseis, in questi ultimi soprattutto a grandi offset sorgente-ricevitore (4000 m). Le ragioni dell'alto contenuto in rumore appaiono molteplici ed includono sia inadeguatezze di registrazione sia scelte sbagliate di tracciato in aree tettonicamente disturbate.

Una volta eliminate le tracce giudicate al di sotto di una soglia minima di qualità e rimosso per quanto possibile il rumore incoerente, i passi operati nel riprocessamento sono stati i seguenti:
- calcolo delle correzioni statiche attraverso picking manuale del first break nei dati vibroseis e dinamite;
- ottimizzazione del CMP sorting al fine di ridurre gli effetti negativi della tortuosità della linea;
- determinazione del campo di velocità di stacking.

Le operazioni di riprocessamento hanno dato risultati insperati. Malgrado fosse stato rimosso mediamente circa il 40% delle tracce (con punte estreme fino al 70%), la sezione riprocessata appare comparabile, dal punto di vista della qualità, con le migliori linee commerciali esistenti nell'area. L'elemento di novità è rappresentato dal fatto che la linea CROP contiene segnali coerenti sino ad oltre 9 secondi, ben al di sotto degli orizzonti più profondi identificati in precedenza da linee sismiche commerciali. Un punto chiave è rappresentato, in corrispondenza dei Monti Alburni tra 6 e 8 secondi, dalla presenza di un pacco di riflettori ben organizzati, immergenti verso SW, che vincola il thrust basale del cuneo orogenico a profondità non inferiori a 20-25 chilometri. L'immagine sismica, inoltre, mostra chiaramente che il duplex apulo sepolto è ancora presente in corrispondenza della costa tirrenica, come del resto suggerito dal pozzo Acerno 1. Questo implica che il trailing edge del sistema duplex deve trovarsi ancora più ad ovest, in aree esplorate dal CROP MARE.

PAROLE CHIAVE: Appennino meridionale, sismica a riflessione, crosta profonda.

1. - INTRODUCTION

The overall structural architecture of the Southern Apennines may be approximately described as a huge duplex system of Mesozoic-Tertiary shallow-water carbonates overlain by a complex pile of platform- and basin-derived rootless nappes (MOSTARDINI & MERLINI, 1986; CELLO *et alii*, 1987; CASERO *et alii*, 1988; PATACCA & SCANDONE, 1989; CASERO *et alii*, 1991; ROURE *et alii*, 1991; PATACCA *et alii*, 1992; ROURE & SASSI, 1995; LENTINI *et alii*, 1996; MONACO *et alii*, 1998; CELLO & MAZZOLI, 1999).

The buried duplex system is made up of carbonate imbricates detached from the Apulia platform during Pliocene and Pleistocene times. In the mountain chain, the top of the duplex lies at depths ranging from 1500 to 6000 metres b.s.l. except in the Monte Alpi tectonic window where the deformed Apulia carbonates reach the surface. The autochthonous portion of the Apulia platform crops out in the Gargano, Murge and Salento regions that belong to the present foreland of the Southern Apennines.

Between the Gargano-Murge region and the leading edge of the buried duplex system, the autochthonous Apulia carbonates form a sort of homocline gently dipping towards the thrust belt. This structural depression, called in the geological literature Bradano Trough, represents the youngest foredeep basin of the Southern Apennines, active in Pliocene and Pleistocene times.

The allochthonous sheets forming the roof of the carbonate duplex system are constituted of Mesozoic-Tertiary sedimentary sequences (fig. 1) referable to platform and basin depositional domains (Sicilide and North-Calabrian basinal realms, Alburno-Cervati platform, Lagonegro basin, Matese-Simbruini platform and Molise basin). Nappe stacking took place through Miocene times.

In the early Pliocene, the entire pile of nappes overthrust the Apulia platform before the latter began to be involved in the compressional deformation. The severe telescopic shortening of the Apulia carbonates during Pliocene and Pleistocene times caused a further forward (north-eastward) transport of the rootless nappes; in addition, duplex-breaching processes irregularly alternating with the forward nappes transport caused important re-imbrication of the allochthonous sheets and generation of important antiformal stacks in the roof units of the Apennine system (PATACCA & SCANDONE, 2001).

In the foreland area, the Apulia platform was entirely penetrated by the Puglia 1 well (total depth:

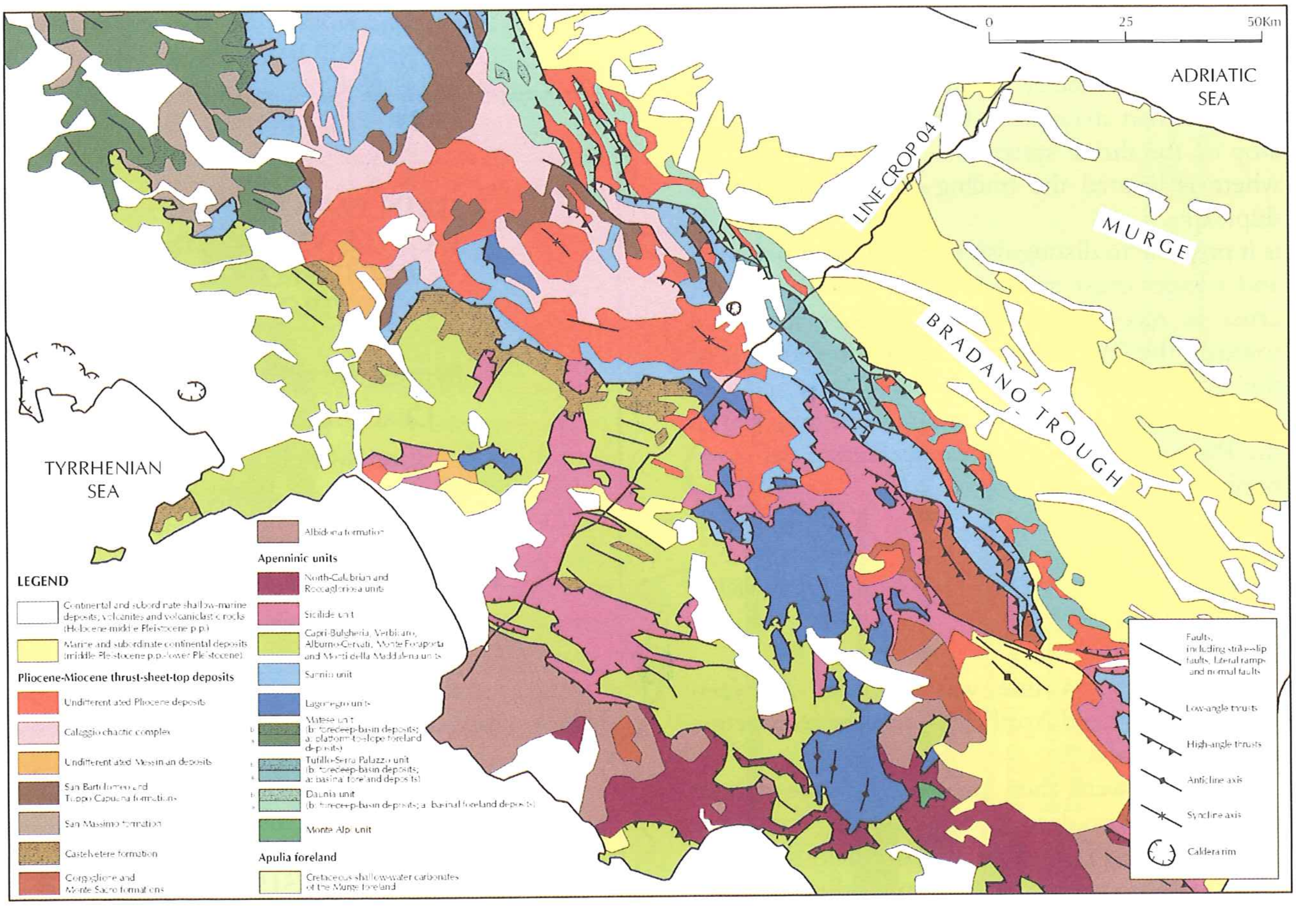

Fig. 1. – Simplified geological map of the area crossed by the CROP 04 seismic line.
– *Carta geologica semplificata dell'area attraversata dalla linea sismica CROP 04.*

7070 m) that encountered at 6112 m Permian-lower Triassic siliciclastic deposits stratigraphically underlying upper Triassic dolomites and evaporites. The contact between the shallow-water carbonates (plus anhydrites) and the siliciclastic deposits corresponds to a sudden decrease in the P-wave velocity. In several commercial lines, the contact is marked by a package of well-organized reflectors conformably underlying the reflection-free carbonate platform. We do not know whether the Apulia platform carbonates and the underlying siliciclastic deposits unconformably overlie a Hercynian crystalline basement or they represent the Alpine sedimentary cover of an older continental crust.

In the whole of the Southern Apennines, the Mesozoic-Tertiary Apulia carbonates forming the buried duplex system represent the main target of petroleum research. As a consequence of the extensive oil exploration in the region, considerable information on the subsurface structures is available. At the time in which the line CROP 04 was planned, the knowledge of the subsurface features, together with the stratigraphical and structural information derived from the regional geology, made possible the construction of realistic geological profiles across the thrust belt-foredeep-foreland system down to a depth of 8-10 kilometres. At greater depths, the interpretation of the tectonic structures was mostly based on the analysis of the gravimetric and magnetic anomalies, as well as on a number of constraints derived from the results of scattered experiments of deep seismic sounding.

The CROP 04 profile was aimed to fill the large gap that existed between the well-defined shallow structures recognized on commercial seismic lines and tested by exploratory wells and deeper crustal structures inferred from different geophysical investigations. The profile is about 160 Km long and explores the whole thrust belt-foredeep-foreland system from the Tyrrhenian coast (Agropoli) to the Adriatic one (Barletta). The line cuts across most of the thrust sheets forming the roof of the Apulia-carbonate duplex system and intersects at high angles the major structural features in the region (see fig. 1).

Answers to the following questions were considered major goals of the experiment:

- what is the geometry of the sole thrust beneath the mountain chain and where is located the backstop of the thrust system ?
- where is located the trailing edge of the buried duplex ?
- is it possible to distinguish between an upper crust and a lower crust in the foreland area? If a lower crust is recognizable, how far does it extend towards the Tyrrhenian basin in the footwall of the mountain chain ?
- was the Apulian crystalline basement involved in the Pliocene-Pleistocene compressional deformation?

2. - SEISMIC ACQUISITION AND EARLY PROCESSING

The CROP 04 line was recorded between November 1989 and April 1990 with the parameters illustrated in Table 1.

The data were then processed following the standard sequence described in Table 2.

Due to the poor quality of the field data, this processing was not successful in providing an interpretable seismic section. Thus, an additional effort was required to determine the causes responsible for the very low S/N ratio of the field data and to apply a new processing sequence aimed at exploiting the signal content, also making use of some a priori geological knowledge of the area. The complete description of the steps we followed in this project can be found in MAZZOTTI *et alii* (2000).

3. - ANALYSIS OF THE FIELD DATA

In order to effectively define an appropriate processing strategy, we first performed a detailed analysis of the data to single out the real couses of the noise.

As shown in figure 2, the roughness of the topography and the abrupt succession, within one spread length, of "soft" and "hard" surface lithologies, characterize the course of the seismic line.

These factors affect processing steps such as static computation and velocity analysis. Moreover, in such a context, conventional muting schemes of initial breaks are not applicable. Below the geological cross section of figure 2 we have also plotted the estimated refractor velocities as computed for static corrections. The subweathering velocity is compared with the geology at the surface: the final data show a good correspondence between lithology and velocity that results in an optimal correlation when faults are present. Note that within one spread

Table 1.- *Main parameters of the vibroseis acquisition of the CROP 04 line.*
- *Principali parametri di acquisizione con vibroseis della linea CROP 04.*

MAIN PARAMETERS OF THE VIBROSEIS ACQUISITION FOR THE CROP 04 LINE
Symmetric split spread
Channels: 120+120
Short offset: 360m
Maximum offset: 9880m
Group interval: 80m
Vibration Point Interval: 80m
Nominal coverage: 120

Table 2. - *Flow chart of the previous processing sequence.*
- Schema della sequenza di processing adottata in precedenza.

STANDARD PROCESSING SEQUENCE OF THE CROP 04 LINE
AGC
Static Corrections by means of refraction method (flat datum, constant replacement velocity)
Array Simulation (five traces, Chebyshev weights: .164 .584 1 .584).164)
Predictive Deconvolution (56/300 ms, 0.0-3.0s, 3.0-10s)
Common Midpoint Sorting. (Crooked Line, minimum curvature criterion)
Velocity Analysis and NMO correction
CMP Consistent Residual Statics
Stack
Radial Predictive Filter (19 traces)
Time Variant Filter
Display

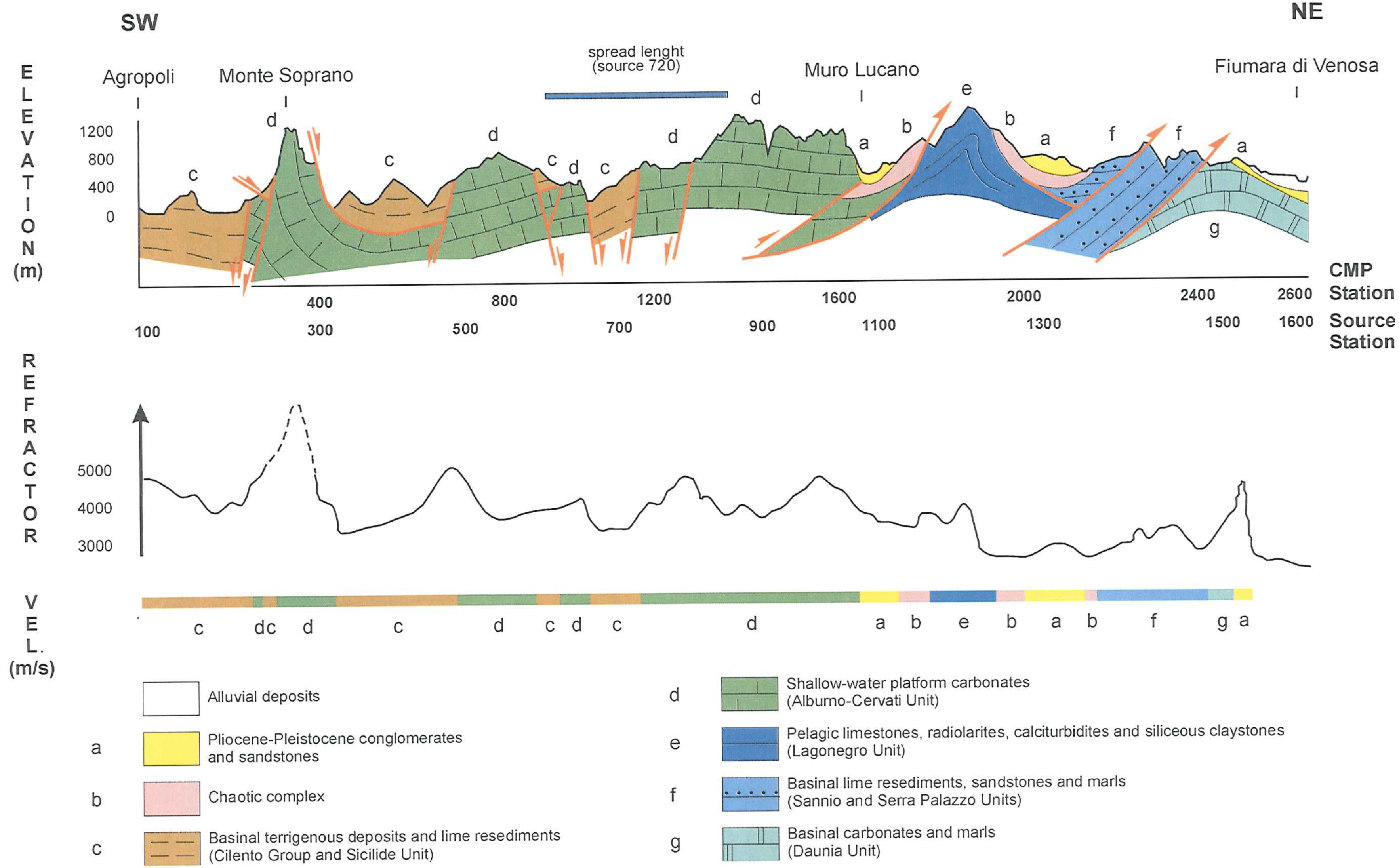

Fig. 2. – Cross-section of the shallow geological structures along the first 80 km of the seismic profile (from Agropoli to Fiumara di Venosa). The graph below the section shows the refractor velocity estimated for the computation of the static corrections. Note the correlation between lithology and velocity changes. (Re-drawn from MAZZOTTI *et alii*, 2000 with slight modifications).

– *La sezione evidenzia le strutture geologiche superficiali lungo i primi 80 km del profilo sismico (da Agropoli alla Fiumara di Venosa). Il grafico sotto mostra la velocità del rifrattore stimata con il calcolo delle correzioni statiche. Da notare la correlazione tra litologia e cambiamenti di velocità. (Da MAZZOTTI et alii, 2000, con lievi modifiche).*

length we may have several hundred meters of difference in the elevation and more than 1000 m/s of near-surface velocity variation.

Another consequence of the rough topography and of the difficulties in the accessibility for the vibroseis trucks, is the distorted acquisition of the seismic data. Such high tortuosity in many parts of the line causes conspicuous problems in CMP sorting and degrades the seismic image particularly at shallow times.

Many vibroseis gathers show patterns of incoherent noise, which appear suddenly at large offset (> 4000 m) and completely hide the signal. In some cases, the occurrence in the spread of this particular noise coincides with the transition to hard surface rocks.

We also found that the noise content in the vibroseis data, as well as in the explosive data, increases significantly in the areas of intense tectonic deformation, which may be the cause of a diffused wavefield scattering. Data of better quality were recorded in areas of lower structural complexity.

To define automatically the quality of each data trace, we used two indicators that are the average amplitude variation with time and the frequency variation with time. A "good" trace should exhibit both amplitude decay and frequency decay with time. Instead, a "bad" trace is the one which manifests a constant status of the amplitude and frequency content with time. After a few tests all the field traces were inspected and, depending on the resulting "good" or "bad" nature of each trace, an appropriate code was inserted into a location of its header. Figure 3 shows the percentage of "bad" traces with respect to the total number of traces in each common source gather. The higher occurrence of "bad" traces between the sources 500 and 750 is related to the fact that in this segment the trace of the profile almost coincides with the surface projection of an important fault that borders westwards the Alburno mountains (see fig. 1).

The percentage of "bad" traces remains constantly high (an average of about 40%) along the whole Apennine chain, and starts to decrease near the less perturbed areas of the foredeep basin. A high percentage of bad traces has been also found in the final part of the line.

In conclusion, it turns out that a combination of causes, such as the remarkable extension of the spread (about 20 Km), which unfavourably matches with the rapid variations of the near surface geology and with the tectonic complexity, the crooked line acquisition and the rough topography associated with outcropping rocks with variable velocities, was responsible for the very low quality of the seismic data.

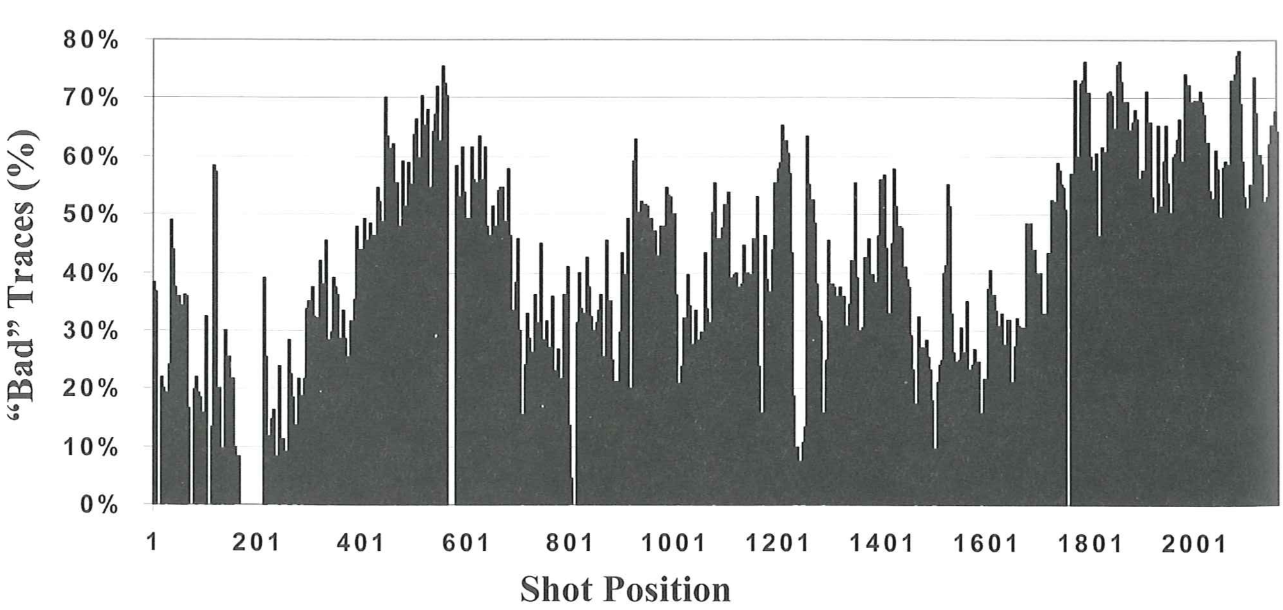

Fig. 3 - Classification of the trace quality along the profile based on the amplitude and on the frequency versus time indicators (see text for explanation). The largest quantity of "bad" traces is between station 500 and station 750 and from station 1800 to the end of the line. In the first segment the profile runs parallel to an important fault that borders westwards the Alburno carbonate massif. Stations with null percentage of "bad" traces do not indicate good data quality but absence of vibroseis data.

- Classificazione delle qualità delle tracce lungo il profilo basata su indicatori di ampiezza e frequenza contro il tempo (v. spiegazione in testo). La gran parte delle tracce "cattive" si trova tra la stazione 500 e la stazione 750 e tra la stazione 1800 e la fine della linea. Nel primo segmento il profilo corre parallelo ad un'importante faglia che borda ad occidente il massiccio carbonatico dell'Alburno. Stazioni con percentuale 0 di tracce "cattive" non indicano buone qualità dei dati, bensì assenza di dati vibroseis.

The results of this analysis were finally stored in a database, which can be later used for further studies regarding possible cause-effect relations between data quality and seismic parameters (e.g. tortuosity of the line, type of energy source, source-receiver offset, etc.) or between data quality and geological parameters (e.g. surface lithology at the source and/or at the receiver, local tectonic setting, etc.). The outcome of this specific study will be useful for the planning of seismic acquisition in nearby areas or in zones with similar characteristics.

4. - NEW PROCESSING SEQUENCE

The re-processing of the CROP04 line was carried out by means of the PROMAX software from Landmark Graphics Corporation. The codes for static corrections, weighted stacking and trace quality analysis were developed internally and included in the processing flow. The processing sequence we applied to the data is depicted in Table 3, where the relevant set-up parameters are also shown.

The processing steps on which we focus our discussion are the following: a) noise attenuation operations, b) removal of static time shifts, c) optimization of the CMP sorting and d) model-driven velocity analysis.

Noise attenuation operations were applied early in the processing sequence. On the basis of the trace classification carried out in the data analysis phase, the traces whose quality (as defined by the amplitude and frequency indicators) falls below a given threshold were immediately removed from the dataset. This led to the rejection of about 40% of the field traces.

F-X deconvolution was applied on common offset sections. The parameters (20 traces correlation, in time gates of 0.4 s., 6 traces filter length) were carefully set so as not to introduce artificial coherency into the data. The same parameters were adopted to carry out another step of F-X deconvolution, at the end of the proposed sequence, on the data of the weighted stack section.

Another operation that was effective in reducing the noise is the weighted stack where the weights are the local estimates of the S/N. The computation of the local, i.e. sample by sample and trace by trace, S/N ratio of the data is carried out by means of SVD or, alternatively, by correlation of adjacent traces (Grion & Mazzotti, 1998).

Static corrections were computed by means of inversion of refracted arrivals from a single refractor. First break picking was carried out manually on both vibroseis and dynamite data. The velocity for the first layer of the model was reconstructed by interpolating the information derived from up-hole times. As a consequence of the near-surface complexity and of the crooked line acquisition, the near-surface model is estimated by means of in-house developed codes based on the WIM (Zanzi, 1996) and the GRM (Palmer, 1980) methods. Statics were estimated to a floating datum designed by smoothing the topography. A variable replacement velocity was used to take into account the rapid lateral variations of the near surface lithology. The final (flat) datum was set at an elevation of 400 m a.s.l., which is the average elevation of the profile.

The correspondence between the variations of the refractor velocity and the changes in the shallow

Table 3 - *Flow chart of the new processing sequence.*
- Schema della nuova sequenza di processing.

NEW PROCESSING SEQUENCE OF THE CROP 04 LINE
Band Pass Filter (4-5/35-40 Hz)
Automatic Killing of Noisy Traces through Energy and Frequency Analysis
Static Corrections by means of refraction methods (floating datum, variable replacement velocity)
Common Offset Sorting (160 m bin and zero padding)
Trace RMS Balance
FX Deconvolution (20 traces, Filter 6 traces, 0.4 s)
Predictive Deconvolution (64/200 ms, 0.3-4.1s, 3.9-10s)
Common Midpoint Sorting. (Crooked Line, short offsets criterion)
AGC
Iterative Velocity Analyses and NMO corrections
Surface Consistent Residual Statics
Weighted Stack
FX Deconvolution (20 traces, Filter 6 traces, 0.4 s)
Display

lithology is remarkable (see fig. 2). Also, note that the repetition of lithological units along the line nicely matches with the refractor velocity values (see e.g. the segments indicated by the letter "c", the terrigenous deposits and by "d", the Alburno-Cervati carbonates). In the Monte Soprano area, where the coverage is very low due to missing shots, the refractor velocities directly estimated from the first break are not reliable and are not comparable with the ones obtained for the same lithology in other parts of the line (4000-4500 m/s). Thus, for this specific section static corrections were determined by means of trial and error and by visual inspection of the results. Each test was carried out using for the static computation different refractor velocities, including those pertaining to the same lithology along the line.

Residual time shifts were further corrected by means of surface consistent residual statics computed on NMO corrected CMP gathers. The maximum allowed time shift at each station was 30 ms.

The high tortuosity of the line contributes significantly to degrading the data quality, especially for the shallow reflections. To limit as much as possible this deleterious effect we tested different criteria for CMP sorting and we finally applied the "Short offsets" criterion. This is the one that yields a CMP line that honours the zones that are more densely populated by traces with source-receiver offset up to a given value. In other limited segments of the profile we made use of the "Maximum density" criterion, that produces a line that follows the zones of the profile where the CMPs are more densely spaced.

Although the quality of the data at this phase was considerably improved with respect to the original one, there were still areas where the selecting of velocities was difficult. The lateral surface velocity variation and the low S/N ratio induced us to proceed first with a global preliminary analysis of the velocity field. Constant Velocity Stacks (CVS) for the whole line with velocity intervals of 250-500 m/s were produced and carefully studied to determine the initial velocity field. This was then refined on CMP velocity spectra for a more detailed definition. The resulting stack was compared with the CVS and the procedure was iterated until the result was satisfactory. Any small evidence of lateral coherence appearing or disappearing during these iterations was also discussed with interpreters and compared with the available geological data of the area. In some part of the line the geological data (outcrops, borehole data) made it possible to define plausible models of the subsurface that were used as soft constraints to guide the velocity analysis. A further revision of the velocity field was also performed after the residual statics application.

5. - RESULTS

The CROP 04 line has been entirely re-processed from the Tyrrhenian coast to the Adriatic one in the interval 0-10 seconds TWT. The re-processed seismic section is comparable with the best commercial lines in the region. However, records suitable for geological interpretation usually do not exceed 5-6 seconds in commercial lines, whilst continuous and well-structured events are recognizable in the new stack section down to 8-9 seconds.

The previous standard processing sequence differs from the adopted re-processing sequence in many respects, including the following:

- There was no substantial removal of low quality traces;
- The refraction statics were computed directly to the flat datum and with a constant replacement velocity; picking of first breaks was performed on vibroseis data only;
- As previously mentioned, the CMP sorting was carried out adopting a less effective "minimum curvature" method;
- Attempts to enhance the coherency of the data were carried out by means of CMP consistent residual statics and by post-stack dip enhancement techniques.

Thus, apart from the array simulation filter, there was no early attempt to remove the large amount of noise affecting the data and both statics and CMP sorting were performed differently. Instead, attempts to recover some coherence in the data were carried out "in extremis" by means of post-stack coherency enhancement techniques.

We carry out the comparison between the final results of the two processing sequences in two segments of the whole profile. The first segment is located at the beginning of the line, between CMP 500 and 790, close to the Controne area. The new stack section presents continuous and structured events at time of up 8 seconds (fig. 4a), not clearly discernible in the previous version (fig. 4b). The second segment, close to the San Fele area (CMP 1720-1960), cuts across a thick (more than 5500 m) antiformal stack of Lagonegro imbricates developed in the roof units of the duplex system (San Fele antiform). This is the most difficult segment of the profile and, as shown in figure 5a, was previously affected by a very low seismic response. It has been clearly improved and now presents many events, at least in the upper part of the section, of up to 4 seconds (fig. 5b).

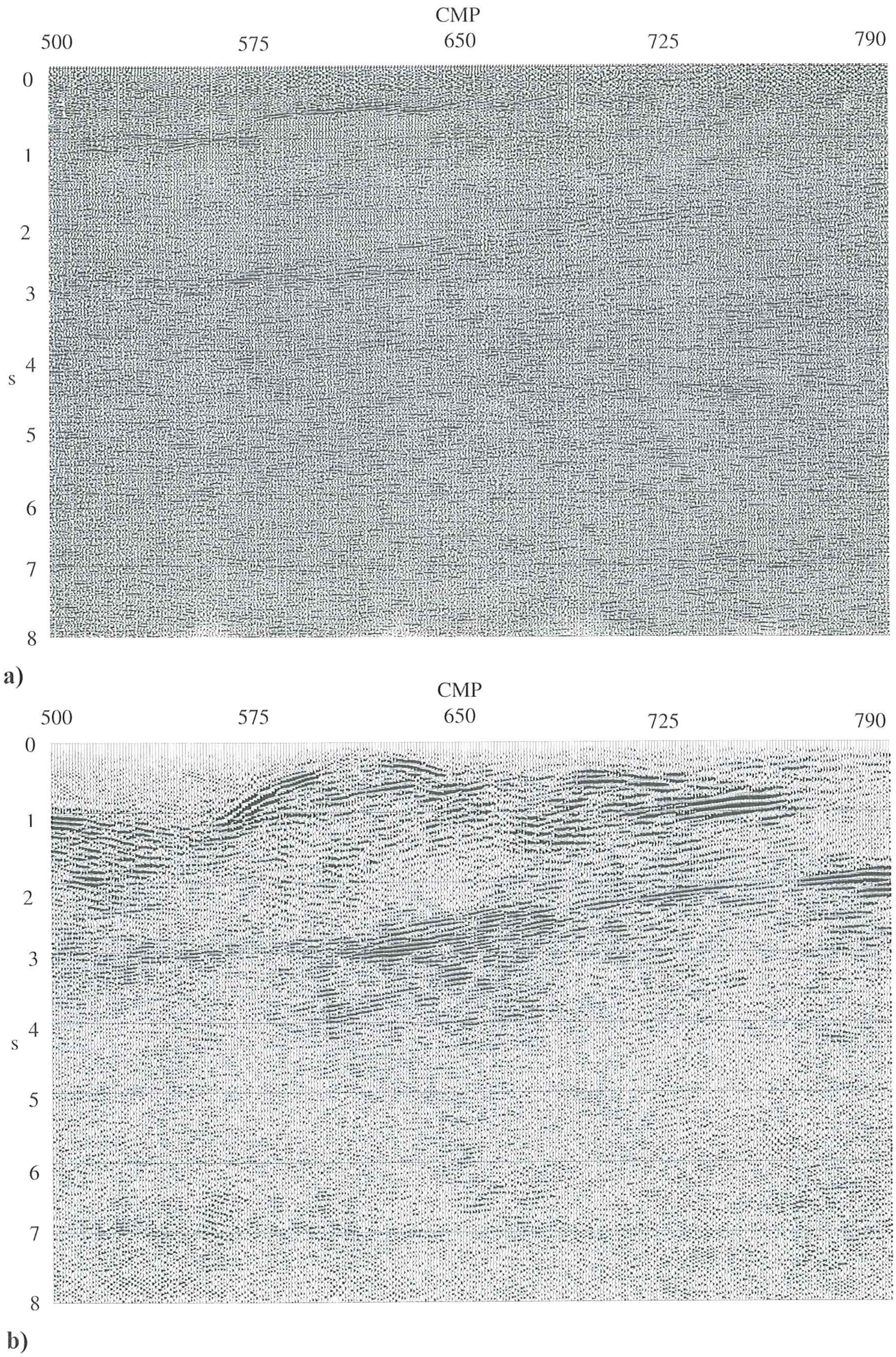

Fig. 4. - Comparison of the final results in the Controne area: a) final stack section from the previous processing sequence; b) final stack section produced with the new processing sequence.

- Confronto dei risultati finali nell'area di Controne: a) stack finale prodotto con la precedente sequenza di processing; b) stack finale prodotto con la nuova sequenza di processing.

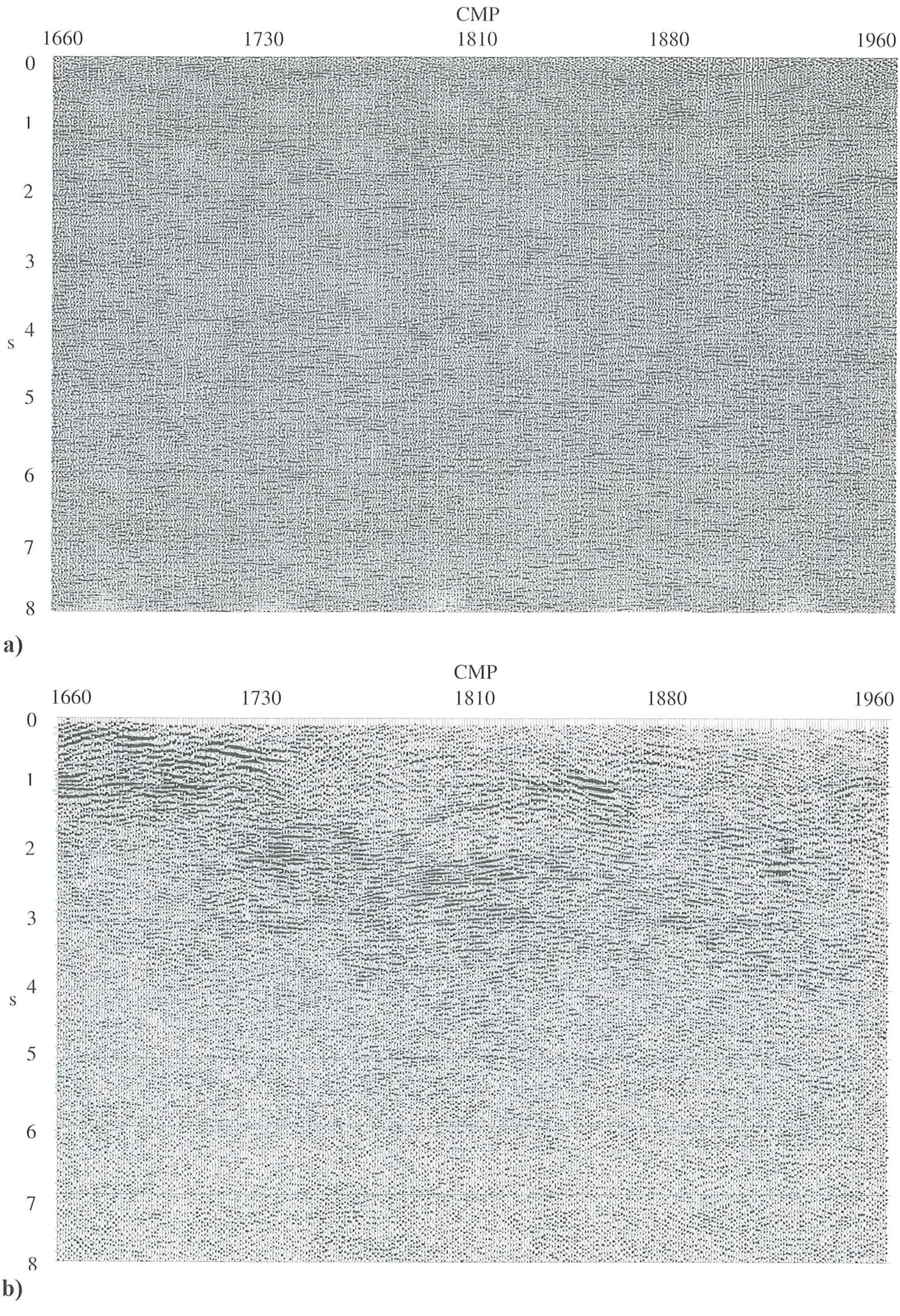

Fig. 5. - Comparison of the final results in the S. Fele area: a) final stack section from the previous processing sequence; b) final stack section produced with the new processing sequence.

- *Confronto dei risultati finali nell'area di S. Fele: a) stack finale prodotto con la precedente sequenza di processing; b) stack finale prodotto con la nuova sequenza di processing.*

The most remarkable feature recognized on the re-processed seismic line is represented by the well-structured package of low-amplitude reflectors between CMP 565 and 1265. The package deepens towards SW from 4-5 seconds to 7-8 seconds, following the regional architecture of the thrust system. These reflectors had never been recognized on commercial lines. Whatever their interpretation may be, they mark a geological horizon which has been involved in the compressional deformation and as been incorporated in the thrust belt. Consequently, they establish the minimum depth (around 8 seconds, that is at least 25 km) at which the sole thrust of the Apennine mountain chain lies near to the Tyrrhenian coast.

In addition, the dip of this horizon, almost parallel to the well-defined package of reflectors that at shallower depths underlies the Alburno-Cervati carbonates, makes it very probable that the trailing edge of the Apulia duplex system is located somewhere in the offshore, beyond the southwestern termination of the CROP 04 line.

REFERENCES

CASERO P., ROURE F., MORETTI I., MULLER C., SAGE L. & VIALLY R. (1988) - *Evoluzione geodinamica neogenica dell'Appennino Meridionale.* Mem. Soc. Geol. Ital., **41**: 109-120.

CASERO P., ROURE F. & VIALLY R. (1991) - *Tectonic framework and petroleum potential of the southern Apennines.* In: SPENCER A.M. (Ed.), *"Generation, accumulation, and production of Europe's hydrocarbons"*, Spec. Publ. European Assoc. Petroleum Geosci., **1**: 381-387.

CELLO G. & MAZZOLI S. (1999) - *Apennine tectonics in southern Italy: a review.* Geodynamics, **27**: 191-211.

CELLO G., PALTRINIERI W. & TORTORICI L. (1987) - *Caratterizzazione strutturale delle zone esterne dell'Appennino molisano.* Mem. Soc. Geol. Ital., **38**: 155-161.

GRION S. & MAZZOTTI A. (1998) - *Stacking weights determination by means of SVD and cross-correlation.* 68th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstract: 1135-1138.

LENTINI F., CATALANO S. & CARBONE S. (1996) - *The external thrust system in Southern Italy: a target for petroleum exploration.* Petroleum Geosci., **2**: 333-342.

MAZZOTTI A., STUCCHI E., FRADELIZIO G.L., ZANZI L. & SCANDONE P. (2000) - *Seismic exploration in complex terrains: a processing experience in the Southern Apennines.* Geophysics, **65** (5): 1402-1417.

MONACO C., TORTORICI L. & PALTRINIERI W. (1998) - *Structural evolution of the Lucanian Apennines, southern Italy.* J. Struct. Geol., **20** (5): 617-638.

MOSTARDINI F. & MERLINI S. (1986) - *Appennino centro-meridionale. Sezioni geologiche e proposta di modello strutturale.* Mem. Soc. Geol. It., **35**: 177-202.

PALMER D. (1980) - *The generalized reciprocal method of seismic refraction interpretation.* Society of Exploration Geophysicists, Ed: KENNETH B.S. BURKE.

PATACCA E. & SCANDONE P. (1989) - *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab.* In: BORIANI A., BONAFEDE M., PICCARDO G.B. & VAI G.B. (Eds.): *"The Lithosphere in Italy. Advances in Earth Science Research".* Atti Convegni Lincei, **80**: 157-176.

PATACCA E. & SCANDONE P. (2001) – *Late thrust propagation and sedimentary response in the thrust-belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene).* In: VAI G.B.& MARTINI I.P. (Eds.): *"Anatomy of an Orogen: the Apennines and the adjacent Mediterranean Basins".* Kluwer Academic Publishers: 401-440, Dordrecht, The Netherlands.

PATACCA E., SCANDONE P., BELLATALLA M., PERILLI N. & SANTINI U. (1992) - *La zona di giunzione tra l'arco appenninico settentrionale e l'arco appenninico meridionale nell'Abruzzo e nel Molise.* In: TOZZI M., CAVINATO G.P. & PAROTTO M. (Eds.): *"Studi preliminari all'acquisizione dati del profilo CROP 11 Civitavecchia-Vasto".* AGIP-CNR-ENEL, Stud. Geol. Camerti, Vol. spec. 1991/**2**: 417-441.

ROURE F., CASERO P. & VIALLY R. (1991) - *Growth processes and melange formation in the southern Apennines accretionary wedge.* Earth Planet. Sci. Letters, **102**: 395-412.

ROURE F. & SASSI W. (1995) - *Kinematics of deformation and petroleum system appraisal in Neogene foreland fold-and-thrust belts.* Petroleum Geosci., **1**: 253-269.

ZANZI L. (1996) - *The WIM method for refraction statics.* Geophysics, **61**: 1859-1870.