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Re-processing of the CROP-04 seismic data

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ABSTRACT

We present the results of a re-processing of the CROP-04 NVR profile. This re-processing was carried out to improve the interpretability of the data that, due to a number of causes, was deemed as insufficient after the first processing. A complete discussion on the causes responsible for the low data quality can be found in another note in this volume (MAZZOTTI A., STUCCHI E., FRADELIZIO G.L. & ZANZI L., *Analysis of the Crop-04 seismic data*). In the new processing sequence, we have paid attention from the very start of the operations at the removal of the large incoherent noise component and at the solution of some additional problems related to the structural complexity of the area, to the crooked line acquisition and to the rough topography.

The re-processing sequence consists of the following principal steps: semi-automatic killing of the data that are below a given S/N threshold, static corrections computed with two different refraction methods, common offset sorting and FX deconvolution, predictive deconvolution (in two time windows), CMP crooked line sorting (optimized by exploring three different criteria), velocity analyses by means of CVS and of velocity spectra, surface-consistent residual static corrections, reiteration of the velocity analyses, weighted stack based on S/N estimation (by means of Singular Value Decomposition). Part of the re-processing strategy was also driven by some a priori knowledge of the regional tectonic setting of the area and by models. Moreover, some steps required internally developed codes to overcome particular problems. The final result shows an increment of the signal quality up to 4-5 s, and, at least in some segments, the presence of deep events up to 7 s in the west and up to 9-10 s, in the eastern part of the line.

KEY WORDS: *Crop-04 seismic line, reprocessing, Southern Apennines, Italy.*

RIASSUNTO

Rielaborazione del profilo sismico CROP-04.

Vengono presentati i risultati della rielaborazione della linea sismica NVR CROP-04. Questa rielaborazione si è resa necessaria per rendere maggiormente interpretabile il profilo sismico che, al termine della prima fase di elaborazione, si era rivelato di qualità insufficiente. La discussione completa sulle cause della bassa qualità dei dati sismici può essere trovata in un'altra nota in questo volume (MAZZOTTI A., STUCCHI E., FRADELIZIO G.L. & ZANZI L., *Analysis of the Crop-04 seismic data*). Nella nuova sequenza di elaborazione si è puntato fino dalle prime fasi alla rimozione delle estese parti di rumore incoerente e alla soluzione di problemi aggiuntivi quali la complessità strutturale dell'area, la tortuosità della linea e gli elevati dislivelli. La sequenza di elaborazione consiste nei seguenti passi principali: eliminazione semiautomatica dei dati che sono inferiori ad una data soglia di S/N; correzioni statiche calcolate con due diversi metodi a rifrazione; raggruppamento in common offset e deconvoluzione FX, deconvoluzione predittiva (su due finestre tempi), raggruppamento in CMP tramite crooked line sorting (ottimizzato esplorando tre criteri diversi), analisi di velocità tramite CVS e spettri di velocità, calcolo ed applicazione delle statiche residuali surface consistent, reiterazione delle analisi di velocità, stack pesato tramite stime del S/N (mediante decomposizione ai valori singolari). Alcune fasi del processing sono state guidate anche dalle conoscenze geologiche disponibili e da modelli. Inoltre, alcuni passi di elaborazione sono stati realizzati usando codici software sviluppati internamente. Il risultato finale mostra un incremento della qualità dei segnali fino ai 4-5 s e, almeno in alcuni tratti, la presenza di eventi fino a 7-8 secondi nel segmento occidentale della linea e fino a 9-10 secondi nel tratto orientale.

TERMINI CHIAVE: *linea sismica Crop-04, rielaborazione, Appennino meridionale, Italia.*

INTRODUCTION

Following an extensive data analysis (see MAZZOTTI A., STUCCHI E., FRADELIZIO G.L. & ZANZI L., *Analysis of the Crop-04 seismic data*) it was decided to make an attempt to re-process the whole CROP-04 profile. The reprocessing was carried out in two phases: first we processed the western part of the line, from Agropoli to Fiumara di Venosa, and then we completed the re-processing of the remaining portion that ends at Barletta on the Adriatic Coast. The results relative to the first part of the reprocessing may be found in MAZZOTTI *et alii* (2000).

Due to the rather discouraging quality of the field data, we were given the task of reprocessing the first 4 seconds of the recorded data, but we decided to take into account an additional «buffer» window of 6 seconds. Thus we ended up processing the first 10 seconds of field data. The reprocessing is focused on vibroseis data. The few dynamite recordings are used as a guide and as reference, e.g. in the refraction static computation. In addition to the field data tapes and documentation we had available a detailed geological map (1:25.000) along the line and several other information such as borehole profiles and published geological interpretations.

MAIN CHARACTERISTICS OF THE RE-PROCESSING

The re-processing is principally aimed at solving the problems that were detected in the previous phase of data evaluation. In particular, many operations are devoted to the attenuation of the large noise components present in the field data. The processing sequence that was applied during the first attempt is shown in fig. 1. It is a standard processing sequence, although some steps such as the refraction static corrections are particularly time con-

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AGC (windows: 256 ms - 2048 ms)

Refraction Statics (single refractor, constant replacement velocity, flat datum, 400 m a.s.l.)

Array Simulation (five traces, Chebyshev weights: .164 .584 1 .584 .164)

Predictive Deconvolution
windows: 1- from 0.0 to 3.0 seconds
2- from 3.0 to 10.0 seconds
prediction distance 56 ms
operator length 300 ms
white light 1%

Sorting to CMP Gathers (minimum curvature criterion)

Velocity Analysis
velocity increment 100 m/s

NMO

CMP Consistent Residual Statics
traces 3
windows: 1- from 0.0 to 6.0 seconds
2- from 6.0 to 12.0 seconds
maximum shift 24 ms

Stack

Radial Predictive Filter (19 traces)

Time Variant Filter

time (s)	L.C. (Hz, DB/OCT)	H.C.
1.0	9 / 24	45 / 48
3.0	8 / 24	40 / 48
6.0	7 / 24	35 / 48
25.0	6 / 24	30 / 48

Fig. 1 - Main operations of the standard processing sequence that was first applied to the CROP-04 seismic data.
– *Principali operazioni della sequenza standard di rielaborazione applicata ai dati sismici del profilo CROP-04.*

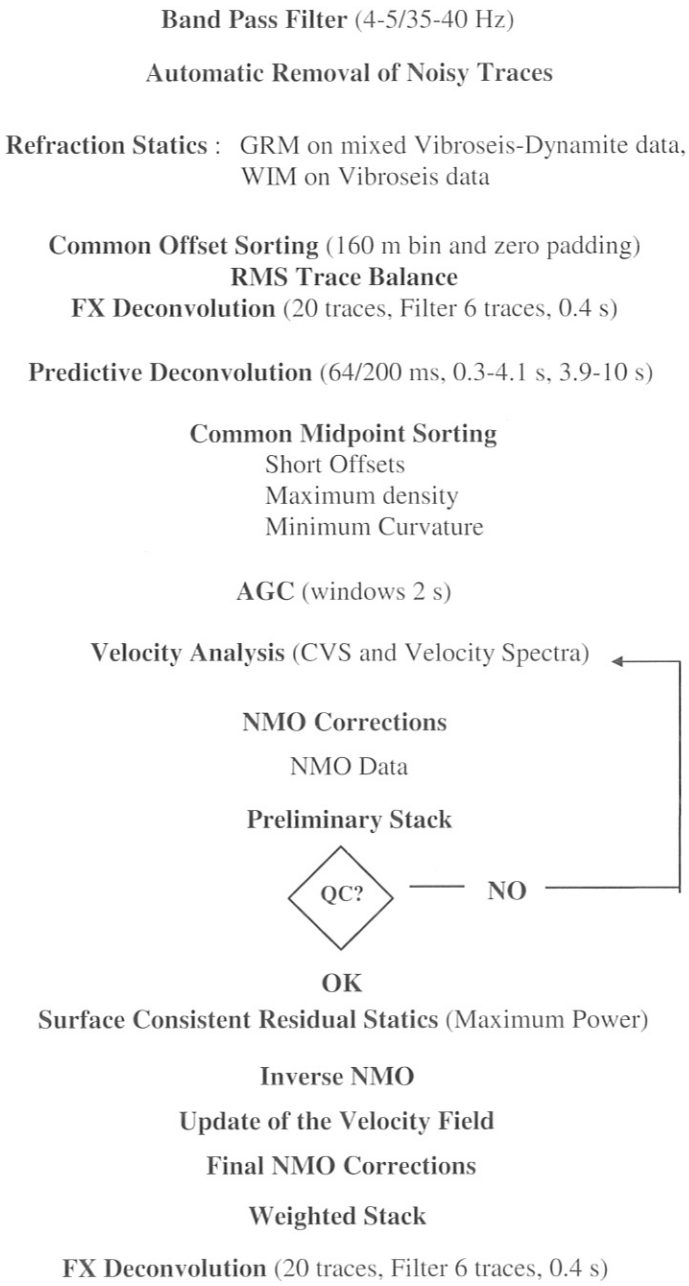

Fig. 2 - Main operations of the new processing sequence applied to the CROP-04 seismic data. Note the relevant differences with the previously applied processing illustrated in fig. 1. See text for explanations.
– *Principali operazioni della nuova sequenza di rielaborazione applicata ai dati sismici del profilo CROP-04. Si notino le differenze tra questa sequenza e quella precedentemente applicata (fig. 1). Le spiegazioni sono contenute nel testo.*

suming and thus are not exactly «standard», that is effective in most land seismic surveys. The new processing sequence we applied to the data is illustrated in fig. 2. It differs from the previous one in many aspects, in particular in the early attempts to remove the contaminating noise and in an extensive testing of alternative solutions. In addition, a strong interaction with the geologists in charge of the profile interpretation and some a priori knowledge about the possible geological setting characterise the new processing approach. In some cases, such as static computation, noisy trace detection, S/N estimation and weighted stacking, we apply specific software codes we wrote to achieve an optimal solution.

After a band-pass filter of the field data, we proceed to the removal of the noisy traces that were previously detected by means of appropriate indicators (amplitude and frequency variations versus time, see the other note in the present volume). This leads to remove an average of 40% of the total field traces with peaks as high as 70% in areas characterised by strong noise that may be related either to structural complexity (in the Apennine chain) or to human activities (in the Apulia basin). Fig. 3 shows a particular shot gather, located at station 620 (Apennine chain), before and after the operation of trace killing. Note the relevant portion of data traces that have been removed.

The operation of static corrections is quite important in the processing of the CROP-04 line where we have strong lateral velocity variations in the shallow layers, very rough topography and several segments with a high tortuosity of the acquisition profile. To optimise the computation of the static corrections we make use of software we developed in house. In fact, in some instances, such as in

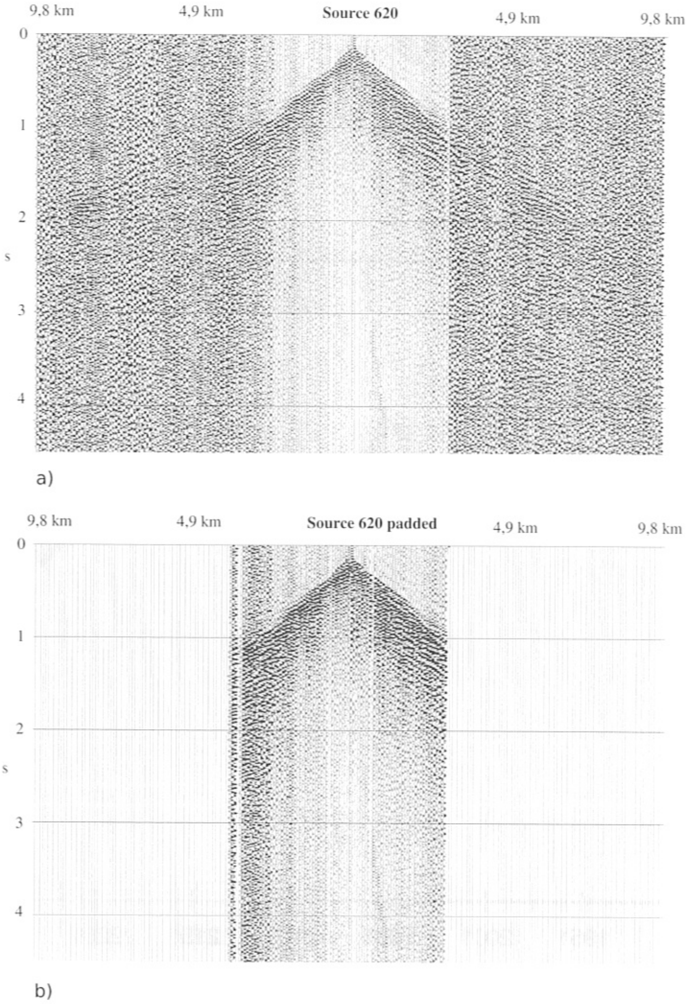

Fig. 3 - Example of bad trace removal: *a*) original vibroseis field gather, *b*) same gather after bad trace rejection.
– *Esempio di rimozione di tracce rumorose:* a) *dati originali vibroseis,* b) *stessi dati dopo l'eliminazione delle tracce rumorose.*

the case of particularly crooked acquisition, the codes of the industrial package were not able to produce acceptable results. We compute the refraction statics by means of GRM (PALMER, 1980) and of WIM (ZANZI, 1996) on the basis of a set of first break traveltimes picked on both dynamite and vibroseis data. The dynamite data, which yield neater first breaks are taken as a reference and are integrated by vibroseis first breaks where necessary. In fact, it is known that the picking of vibroseis first breaks may be rather difficult due to the presence of precursors generated by the vibro-correlation. The computation is carried out in two phases: first we compute the corrections needed to shift the traces to a floating datum, that is the smoothed topographic profile; second, we compute the residual time shifts needed to position the traces to a final (flat) datum that is set at 400 m above the sea level. To verify the reliability of the results we monitored the effects of the static correction application to the data (fig. 4) and we checked the consistency of the estimated refractor velocities with the outcropping lithologies (fig. 5). These procedures, and in particular the picking and the interpretation of the first breaks, are rather time consuming but lead to discernible improvements on the data quality.

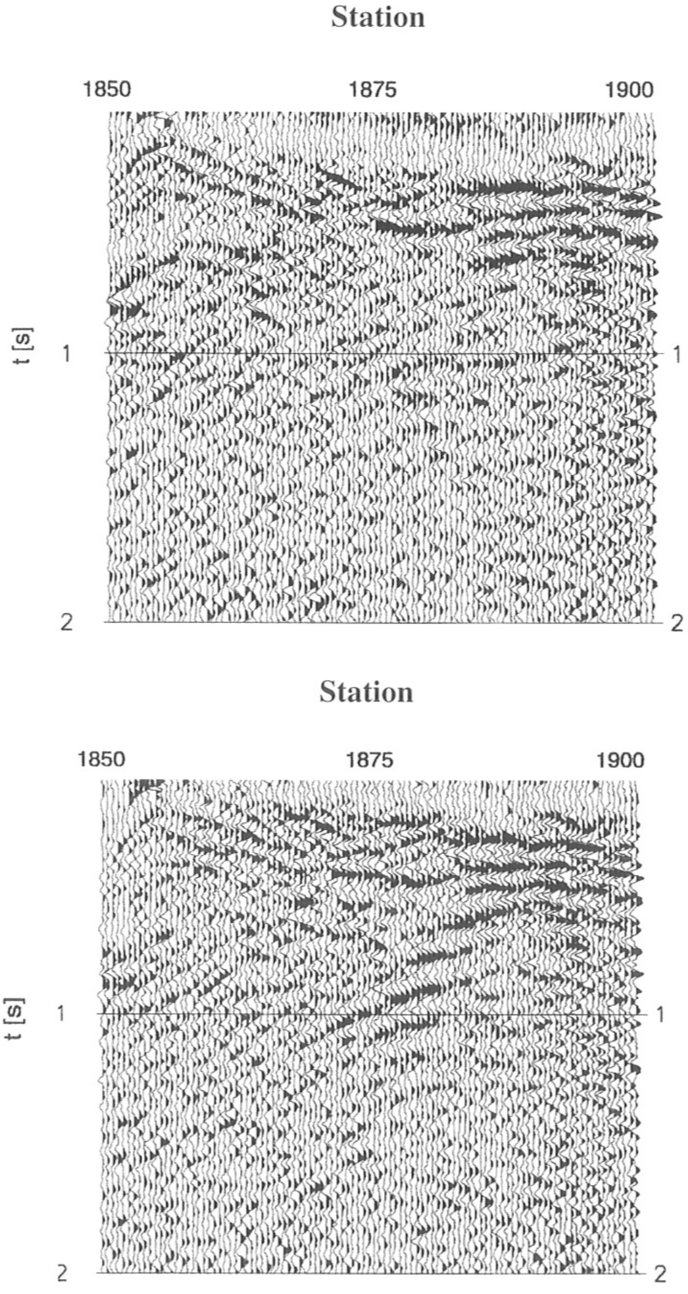

Fig. 4 - Effects of statics correction application on the seismic data. The upper frame represents a close-up of a Constant Velocity Stack (4500m/s) located in the eastern part of the CROP-04 profile, without the corrections. The lower frame represents the same portion of data but after the statics correction application. Note the improvement of the signal continuity around 1 s travel time.
– *Effetti dell'applicazione delle correzioni statiche ai dati sismici nella parte orientale del profilo CROP-04. In alto, esempio di stack a velocità costante (4500m/s), senza correzioni statiche. In basso, stessa porzione del profilo dopo l'applicazione delle correzioni statiche. Si noti il miglioramento nella continuità del segnale intorno ad 1 secondo.*

The next set of operations, common offset sorting, RMS trace balancing and FX deconvolution, with relevant parameters indicated in fig. 2, is aimed at establishing a consistent amplitude level in all the field traces and in further attenuating the incoherent noise. For this purpose FX deconvolution (GULUNAY, 1986) is applied, although with a very careful choice of the parameters to

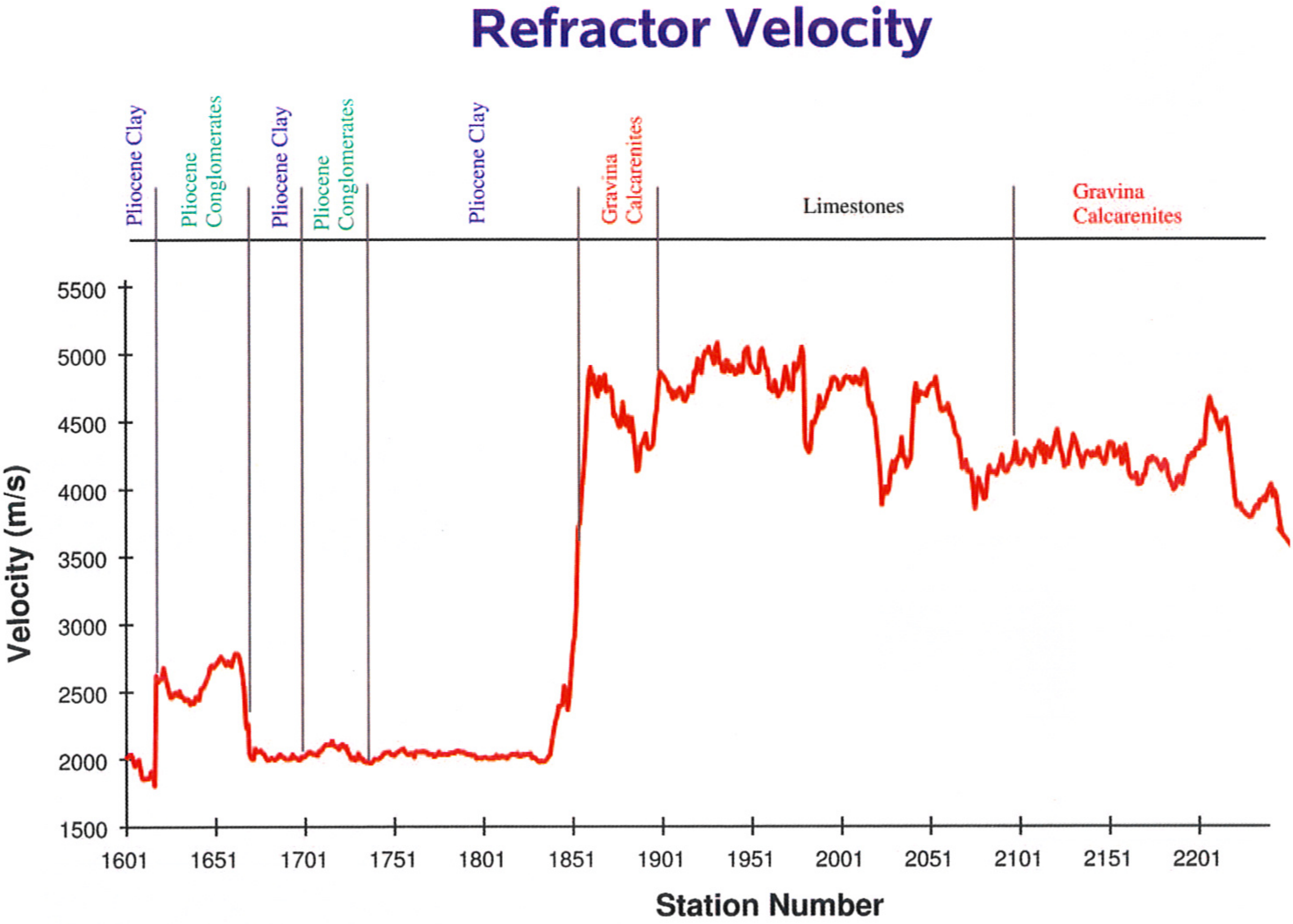

Fig. 5 - Velocity of the refractor as estimated by the GRM code we developed. Note the jumps in the velocity values and their correspondence with lithological transitions.
– Valori di velocità del rifrattore stimati attraverso il codice GRM sviluppato internamente. Si osservino i salti di velocità in corrispondenza dei limiti tra le diverse litologie.

avoid the introduction of artefacts. Briefly, the FX deconvolution is a multi-channel operation which may be driven to attenuate, frequency by frequency, what finds as unrepetitive in the X (distance) direction; this portion of data is often associated to incoherent noise, while the repetitive part is related to coherent reflections.

After several tests, the operation of predictive deconvolution is applied in two time windows (0.3-4.1 s and 3.9-10 s) with a rather large prediction lag (64 ms). In fact, due to the noise still present in the data and to the uncertain phase characteristic of the vibroseis signal, shorter, spiking like prediction distances are inadequate. However, the application of this predictive deconvolution, while not really increasing the bandwidth of our data, it is effective in removing ground roll noise.

Due to the tortuosity of the field acquisition layout, especially for the vibroseis data, the Common Mid Point sorting is not trivial and influences the quality of the stack section especially at shallow times (about up to 2 s). Also in this case, the new processing differentiates from the previous one in that three different approaches have been tested. The «minimum curvature» approach, that was used in the previous processing, gathers the traces in such a way to minimise the curvature of the resulting CMP distribution and hence of the stack profile. The «maximum density» criterion yields a profile that follows the most densely spaced CMPs. The «short offsets» approach follows a path that results from gathering the traces up to a given source to receiver offset, that in this case was set to +/- 2.5 km. With the exception of two segments of the profile (between CMPs 1271-1390 and 1470-1490) where the «maximum density» approach is the most effective, the best results along the whole profile are obtained with the application of the «short offsets» method.

The following operations of velocity analysis, NMO correction and stack constitute an iterative and interactive procedure that brings to the construction of the preliminary stack image. This phase requires a constant interaction among geophysicists and geologists to test and to verify different stacking velocity fields, their effects on the stack section and their consistency with plausible geological models. In fact, although at this stage the data are considerably of better quality than before, uncertainties in the interpretation of the optimal stacking velocity still occur. Thus, we first proceed by means of constant

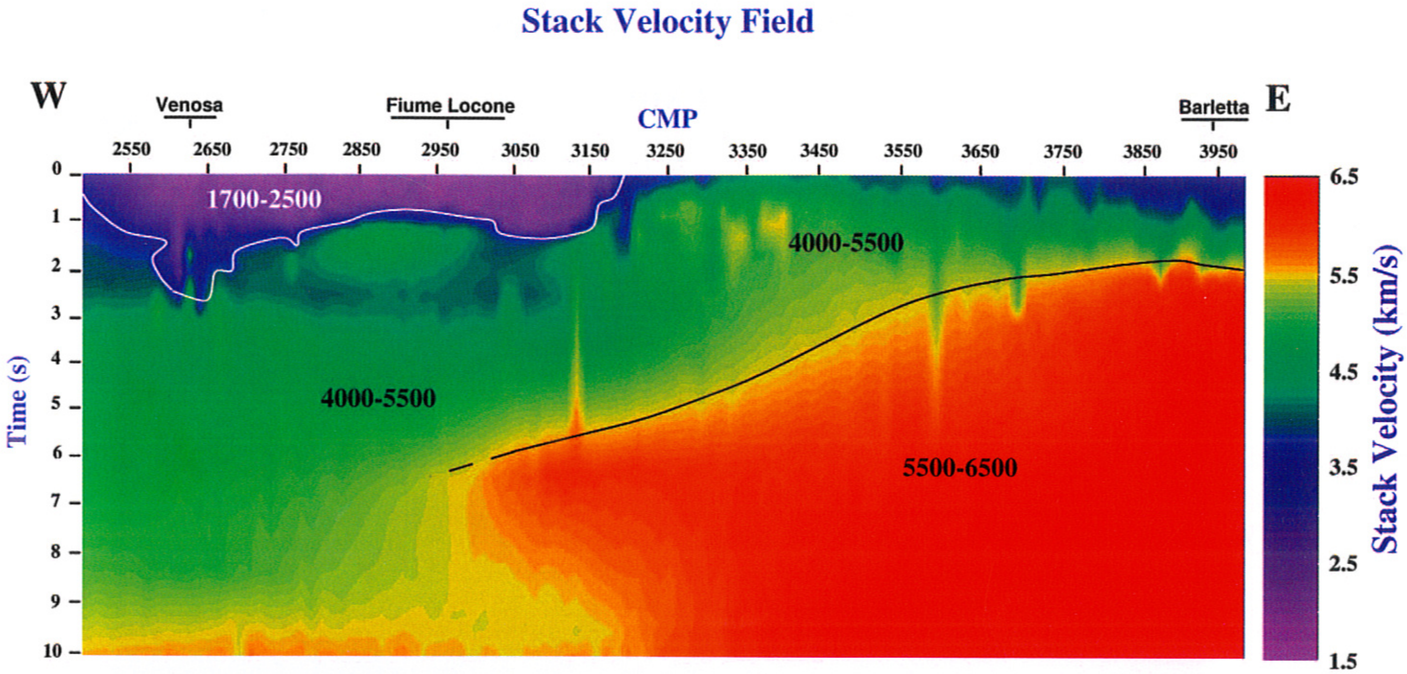

Fig. 6 - Stacking velocity field relative to the eastern segment of the CROP-04 profile (Fiumara di Venosa-Barletta) with outlined the zones of homogeneous velocity.
– *Velocità di stack nella parte orientale del profilo (Fiumara di Venosa-Barletta), con evidenziate le zone a velocità omogenea.*

velocity stack panels, from 2000 m/s to 6500 m/s in 500 m/s steps, and then by refining the velocity field by means of detailed analysis on velocity spectra, although at few specific locations and for limited depths of investigation, the determination of the optimal velocity field benefits from the knowledge of velocities derived from bore-hole logs. This procedure is iterated until a satisfactory result is obtained. Then, the NMO corrected CMP gathers are the input to the surface consistent residual static correction (RONEN & CLAERBOUT, 1985; TANER *et alii*, 1974) that, by means of cross-correlation among the traces, establishes the residual time shifts to apply to the traces in order to maximise the horizontal alignment of the reflections and thus the power of the stack. The computation of the residual statics is carried out on the data included in time gates of about 1 s that are shaped along the major seismic horizons. To better constrain the solution, we use at least three time windows for each CMP gather and we allow for a maximum shift of 30 ms at each station. A further update of the stacking velocity field is carried out after the application of the residual statics. Fig. 6 shows in colour codes the final stacking velocities relative to the eastern segment of the CROP-04, from Fiumara di Venosa (located close to CMP 2600) to Barletta (close to CMP 3950). We have outlined the zones with homogeneous velocities to point out that their trends, not their actual values due to the lack of physical significance of stacking velocities, are indeed correlated with major geological elements. The purple and blue area (1700 m/s-2500 m/s), roughly from CMP 2550 to CMP 3150 and up to 2500 ms traveltime, corresponds to the terrigenous units of the Fossa Bradanica. Moving eastward, we find a zone of higher stacking velocities (4000 m/s-5500 m/s, in green and yellow) that corresponds to the carbonatic units of the Apula Platform. Also, note the trend of this «green and yellow» area that dips westward, underneath the low velocities of the Fossa Bradanica. Finally, from the easternmost CMP 3950 to CMP 3200 and respectively from about 2000 ms to 5500 ms traveltime, it is evident the transition between the green-yellow area and the red, higher velocity (5500 m/s-6500 m/s) area which may be related to deeper units.

The two final operations are again aimed at attenuating the noise that still contaminates the data. The weighted stack reduces the noise because it weights each sample of the NMO corrected gather by a scalar that is proportional to the local signal/noise ratio. The S/N estimation is carried out by means of cross-correlation or by singular value decomposition of adjacent traces. Details on the methodology for the computation of the stacking weights may be found in GRION & MAZZOTTI (1998). Briefly, higher weights are assigned to samples showing a higher S/N while lower weights are applied to noisy samples. Thus, signals showing some lateral coherence are enhanced while noise is penalised. A final FX deconvolution helps to further reduce the noise.

Further operations of gaining and time variant filtering may be carried out mainly for plotting purposes.

RESULTS

This section is dedicated to the assessment of the reprocessing results along the whole CROP-04 profile. We show seven segments of the final stack section up to 8 s traveltime, each composed of about 290 CMPs, and we compare them with the same portions of data at the end of the previous processing. Fig. 7 shows the westernmost segment of the stack section, from Agropoli to Monte Soprano. In the upper frame, the results from our repro-

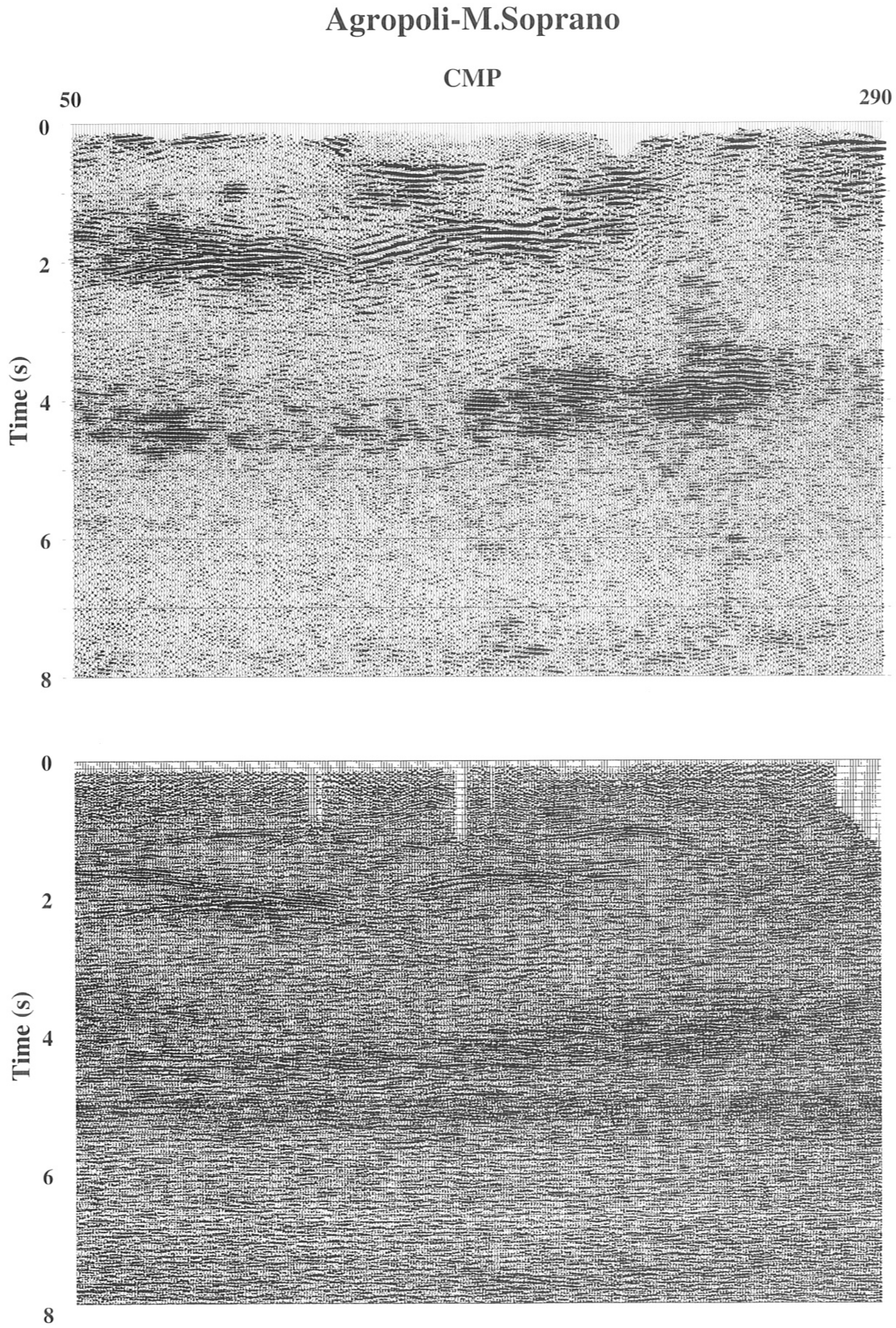

Fig. 7 - Segment of the stack section from Agropoli to Monte Soprano. Upper frame: results after our reprocessing; lower frame: previous results. – *Segmento Agropoli-Monte Soprano della sezione stack. In alto, risultato della rielaborazione; in basso, risultato precedente ottenuto attraverso una sequenza di operazioni standard.*

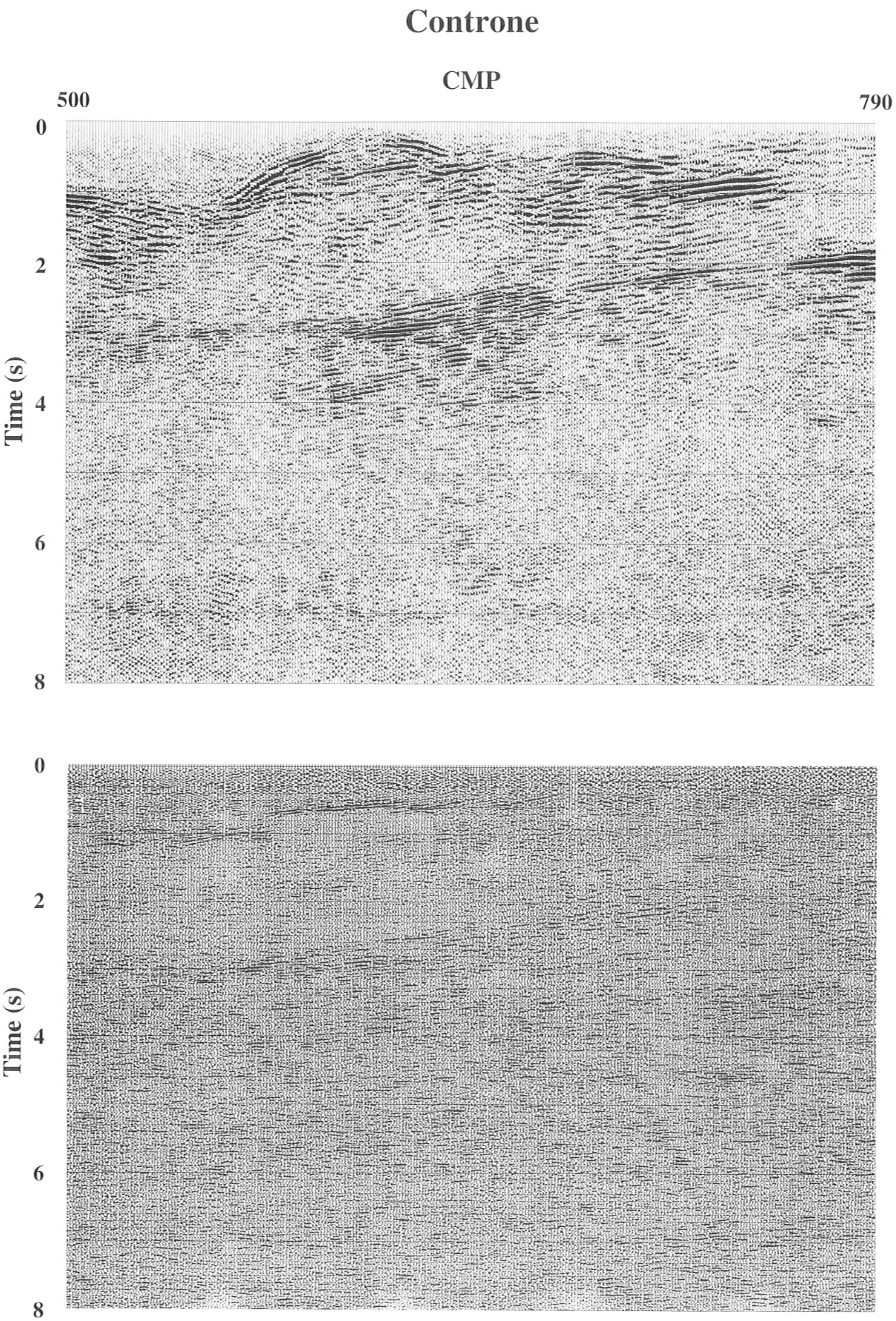

Fig. 8 - Portion of the stack section near Controne area. Upper frame: results after our reprocessing; lower frame: previous results. – *Segmento della sezione stack nell'area di Controne. In alto, risultato della rielaborazione; in basso, risultato precedente.*

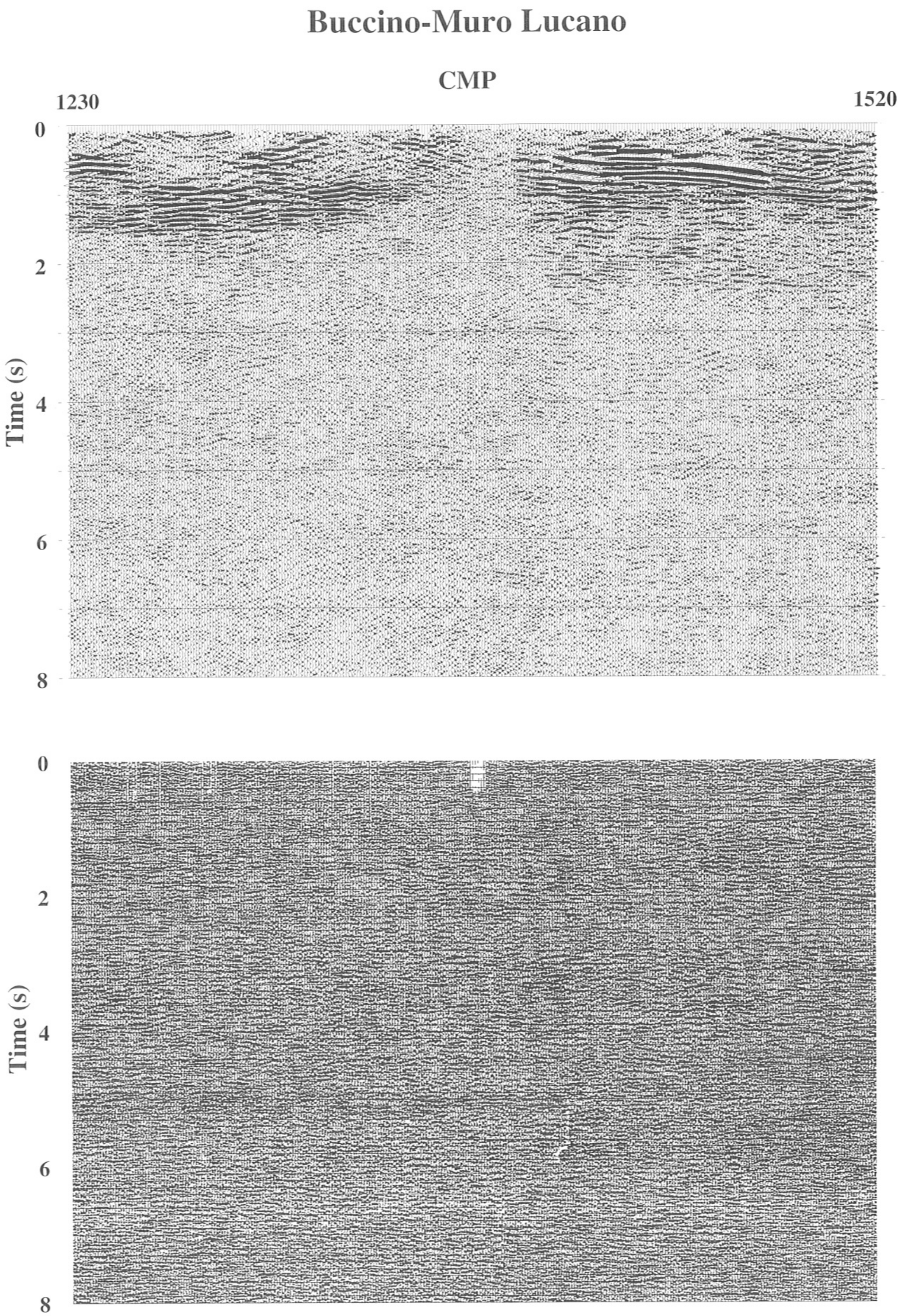

Fig. 9 - Segment of the stack section from Buccino to Muro Lucano. Upper frame: results after our reprocessing; lower frame: previous results.
– *Segmento della sezione stack tra Buccino e Muro Lucano. In alto, risultato della rielaborazione; in basso, risultato precedente.*

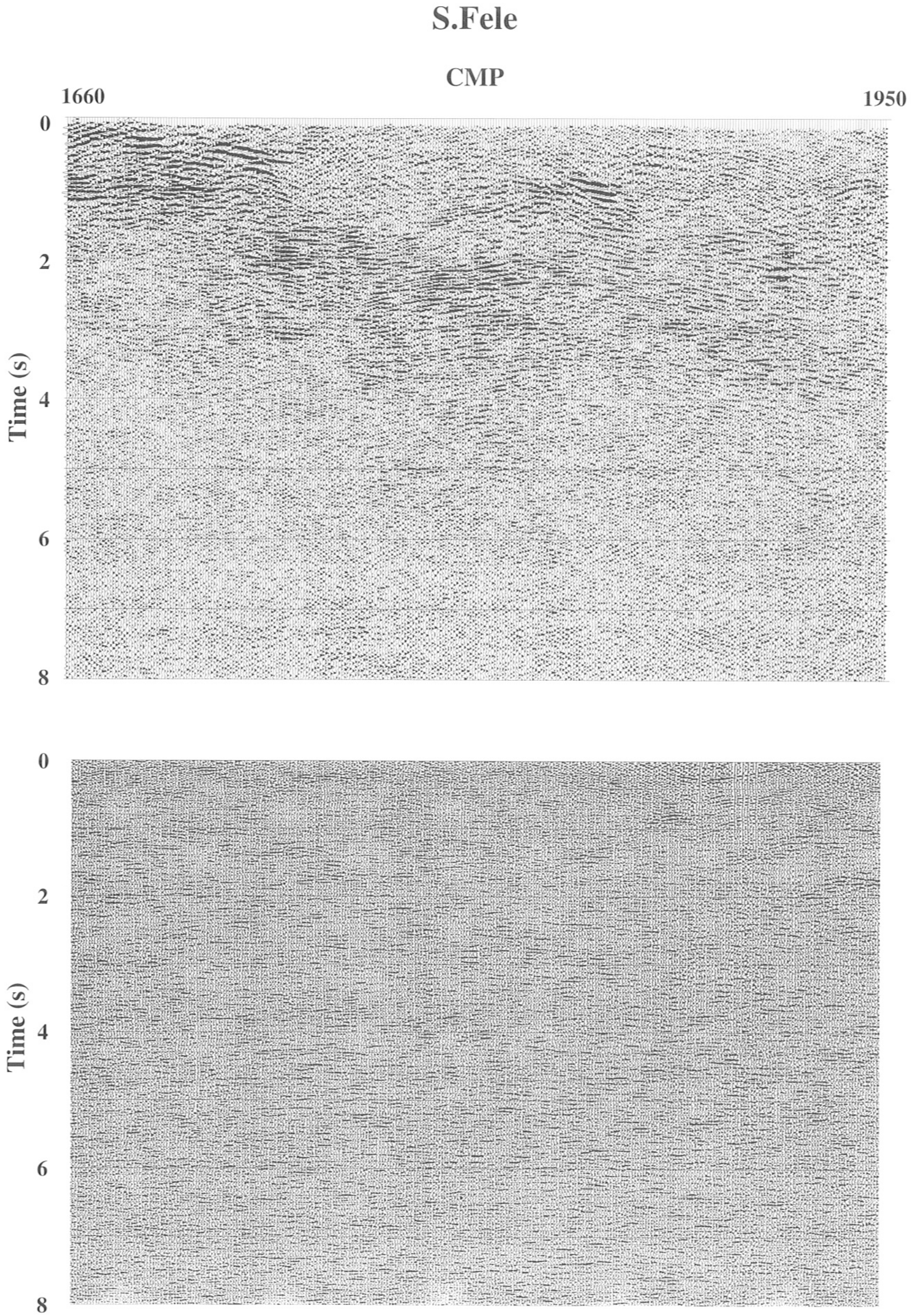

Fig. 10 - Portion of the stack section near S. Fele area. Upper frame: results after our reprocessing; lower frame: previous results.
– *Segmento della sezione stack nell'area di San Fele. In alto, risultato della rielaborazione; in basso, risultato precedente.*

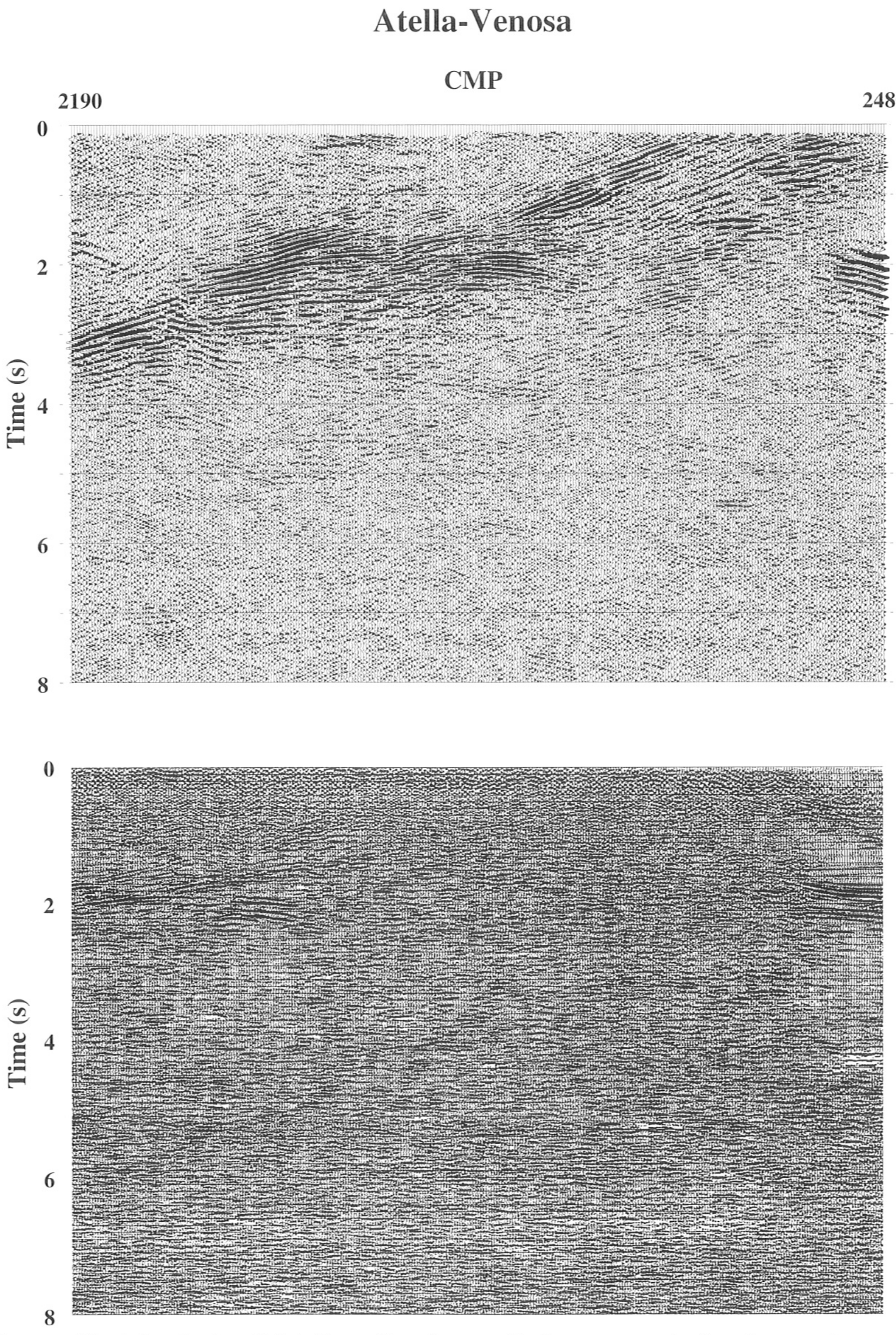

Fig. 11 - Segment of the stack section from Atella to Venosa. Upper frame: results after our reprocessing; lower frame: previous results. – *Segmento della sezione stack tra Atella e Venosa. In alto, risultato della rielaborazione; in basso, risultato precedente.*

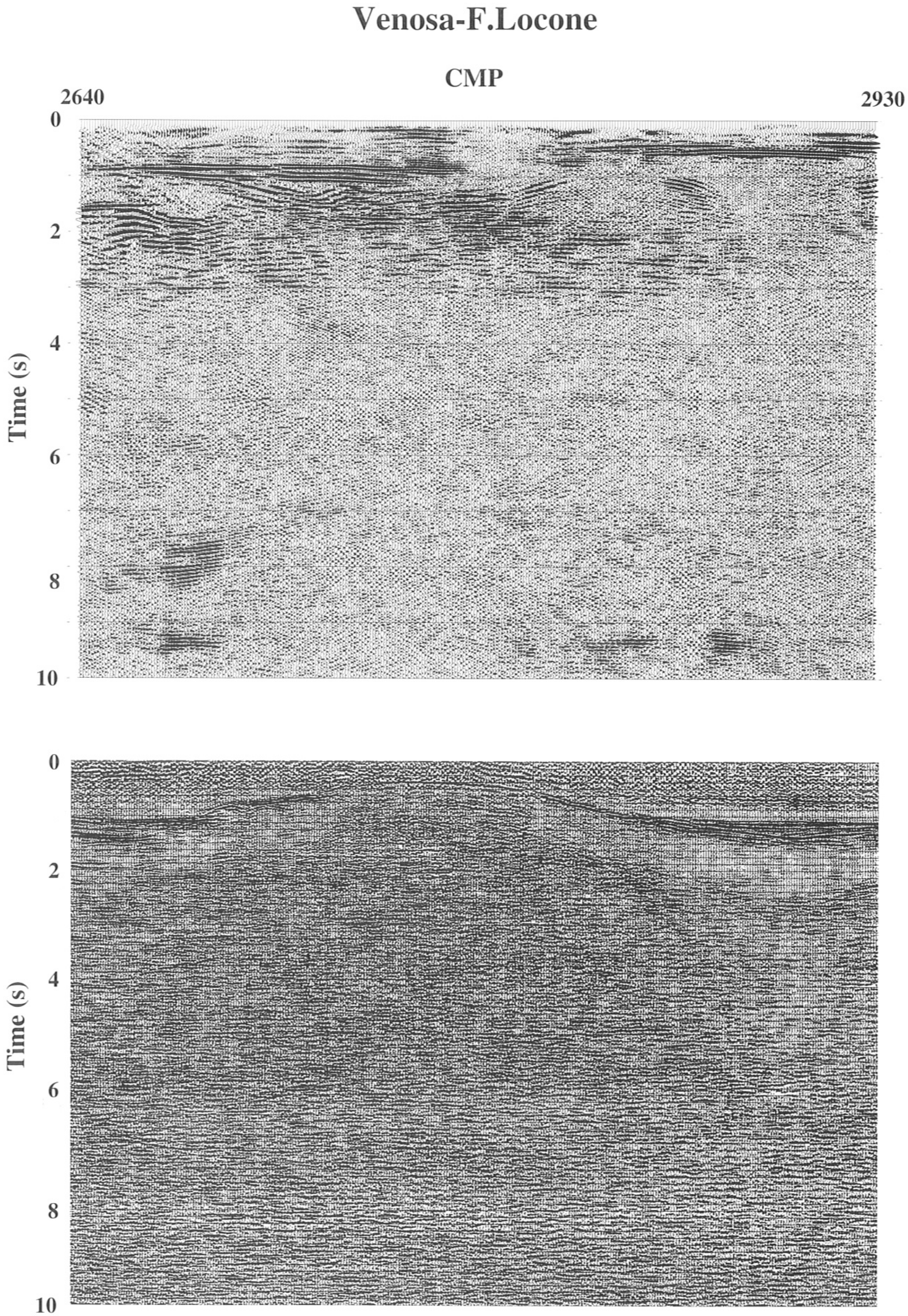

Fig. 12 - Segment of the stack section from Venosa to Fiume Locone. Upper frame: results after our reprocessing; lower frame: previous results.
– *Segmento della sezione stack tra Venosa e Fiume Locone. In alto, risultato della rielaborazione; in basso, risultato precedente.*

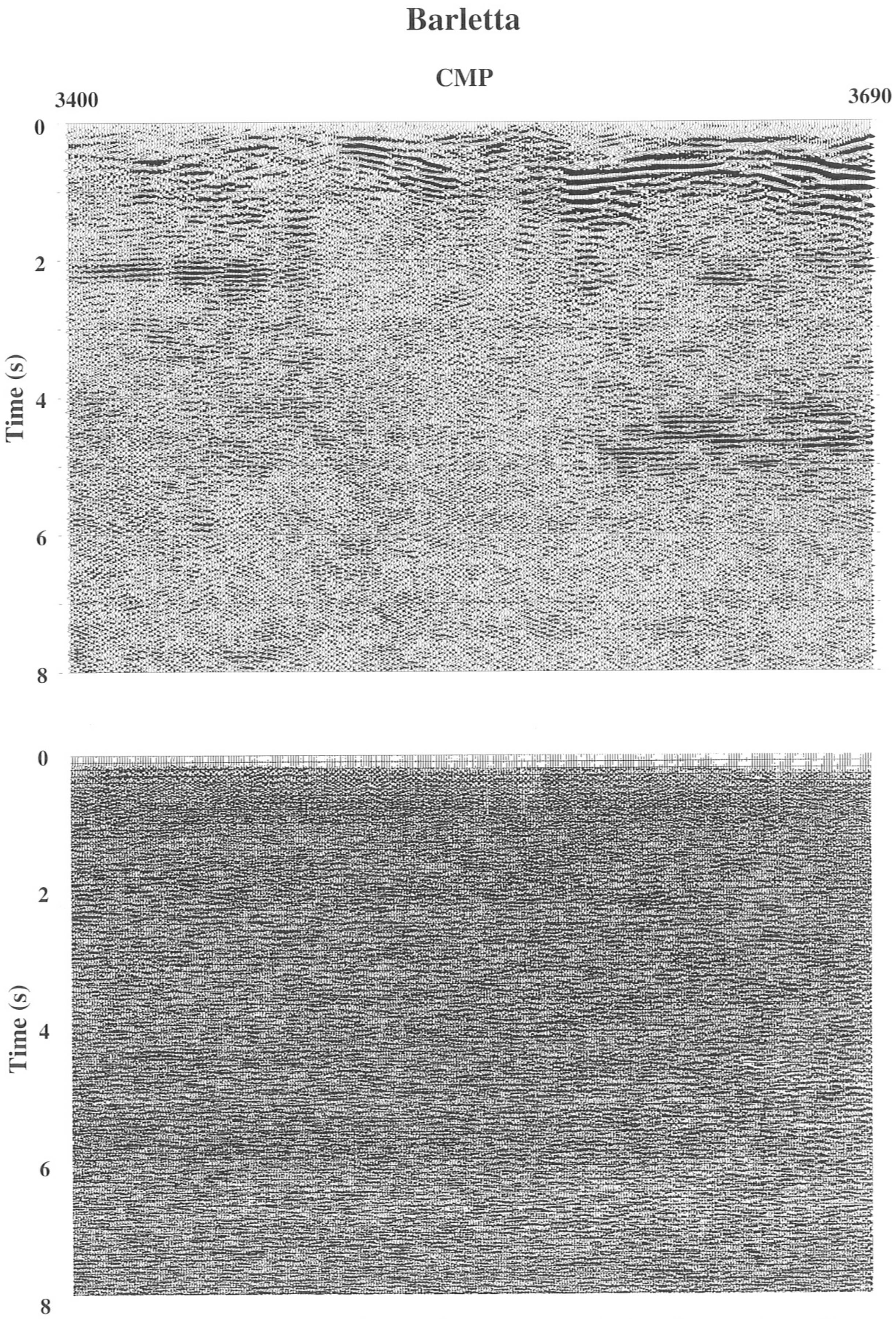

Fig. 13 - Portion of the stack section near Barletta. Upper frame: results after our reprocessing; lower frame: previous results. – *Segmento della sezione stack presso Barletta. In alto, risultato della rielaborazione; in basso, risultato precedente.*

cessing, in the lower frame the previous results. Seismic horizons are also present in the old section but the increase in data quality due to the reprocessing is quite evident. Moving eastward, we examine the next segment in the Controne area (fig. 8). Again we observe a better quality of the data after the reprocessing and in particular we are able to detect deep reflectors, located around 7 s that in the previous results were totally obscured by the noise. Fig. 9 refers to the Buccino-Muro Lucano segment, which is located at the heart of the Apennine chain. This is one of the most difficult parts of the entire section but the improvement resulting from the reprocessing clearly stands out. Fig. 10 illustrates the results in the S. Fele area, where an antiformal stack of Lagonegro imbricates, evidenced by previous industrial surveys and drilled by the San Fele 1 well, is visible in the reprocessed stack section while is difficult to detect in the previous section. Similar considerations may be made for the remaining segments of fig. 11 (Atella-Venosa), fig. 12 (Venosa-Fiume Locone) and fig. 13 (Barletta). In these easternmost segments, deep reflectors (around 9-10 seconds) are clearly distinguishable.

CONCLUSIONS

The reprocessing of the CROP-04 seismic data has produced a significant improvement in the quality of the final stack section, which is now comparable with the best commercial lines in the area that however are limited to 4-5 s of recording time. Thus the CROP-04 brings additional and valuable information on deeper events. The success of the reprocessing is not due to a single operation: the improvement of the final data quality is the consequence of a number of processing steps carefully planned and executed, each of bringing a small improvement. The previous study on the data was of primary importance since it indicated the problems that had to be tackled by the processing and allowed us to focus on those problems. The final results may be considered fairly good for a structural interpretation of the main horizons. On the contrary, considerations on the reflection amplitudes and their relations with petrophysical or lithological factors are not reliable because the processing is dedicated at enhancing the coherent reflection but not at restoring their correct amplitudes. Due to the low quality of the field data, we doubt that this will be ever possible with a high degree of confidence and without strong constraints from a priori information such as well logs and core data. For what concerns structural interpretation, further works may be carried out. These concern the depth migration of the time data. Again, due to the low data quality, especially at high traveltimes, it is doubtful that wave equation migration algorithm, either prestack or poststack, will give satisfactory results even with an optimal migration velocity field. It seems more appropriate to proceed with ray tracing depth migration of interpreted time horizons, iteratively updating the velocity field and checking the geological plausibility of the depth conversion results. These may finally constitute the input to section balancing algorithms.

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