# Reprocessing of the CROP M12A seismic line focused on shallow-depth geological structures in the northern Tyrrhenian Sea

A. Tognarelli[1], E.M. Stucchi[2], G. Musumeci[3], F. Mazzarini[4] and F. Sani[5]

[1] Consorzio di Geofisica, Università di Pisa, Italy
[2] Dipartimento Scienze della Terra, Università di Milano, Italy
[3] Dipartimento Scienze della Terra, Università di Pisa, Italy
[4] Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy
[5] Dipartimento Scienze della Terra, Università di Firenze, Italy

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***ABSTRACT*** This work deals with the reprocessing of the M12A CROP marine seismic profile, that crosses the northern Tyrrhenian Sea, south of Elba Island. The reprocessing was carried out to improve the visibility and resolution of the structures corresponding to the lower crust (two-way traveltimes lower than 4 s) that are located at depth. In this time window, we apply recently developed methodologies to enhance the signal-to-noise ratio, paying particular attention to the suppression of the short and long period reverberations and to the velocity model building for depth migration. The velocity field used for the depth conversion is iteratively updated by means of the migration velocity analysis on common image gathers. The final products of this work are time and post-stack, depth-migrated sections that can contribute to the understanding of the structural complexity of the investigated area.

## 1. Introduction

The northern Tyrrhenian-northern Apennines system represents a key area where the relevant part of the Cenozoic geological history of the central Mediterranean region is recorded. However, recent tectonics (<10-12 Ma) and the context in which this sector has evolved are open to debate and a shared geological model has not been developed as yet (Jolivet *et al.*, 1998; Boccaletti *et al.*, 1999; Bonini *et al.*, 1999; Sani *et al.*, 2001). To investigate the most important geological and structural aspects of this area, geophysical data and, in particular, seismic reflection are of primary significance, while the islands of the Tuscan archipelago may provide some geological constraints. The published seismic data of the northern Tyrrhenian Sea (commercial and research exploration profiles) puts in evidence a wide range of interpretations concerning the geometries of the subsurface reflectors, but these analyses leave some geological inconsistencies and therefore cannot be considered conclusive (Bartole, 1995; Mauffret and Contrucci, 1999; Pascucci, 2005). Moreover, the vertical scale of the interpreted sections is a two-way traveltime which can lead to mispositioning of the subsurface structures in geologically complex areas when vertically converted to depth. To overcome some of these issues and to get a clearer insight on the tectonic evolution of the area, we reprocessed the CROP M12A seismic line located in the northern Tyrrhenian Sea south of Elba Island (Fig. 1) from the raw field data up to the post-stack,


Fig. 1 - Location map of the M12A CROP profile. The location of four shots along the line are highlighted by red stars. The water depth is approximately 90 m for the most part of the line while it deepens to 800 m in the western part of the line (Corsica basin).

depth-migrated section. The final velocity field used for migration, which is the most critical factor in depth conversion, was built by means of migration velocity analysis (MVA) on common reflection point (also known as common image) gathers (CRP). This paper describes the applied reprocessing methodologies that lead to the new time and depth migrated seismic sections and reports on some geophysical and geological aspects put in evidence by the reprocessed seismic images. The published profiles of the M12A, used as comparison, are not reported here, but can be found in Scrocca *et al.* (2003), Finetti (2005) and Pascucci (2005).

## 2. Geophysical data

The CROP M12A seismic line was acquired in the framework of the Italian Deep Crust Project (CROP), aimed at investigating the structure of the deep crust in Italy and to delineate the depth of the Moho discontinuity (Scrocca *et al.*, 2003). These objectives focus the interest mainly on deep events of the recorded data, paying little attention to the shallow-depth reflectors. However, even if the acquisition parameters of the CROP surveys were designed for deep targets

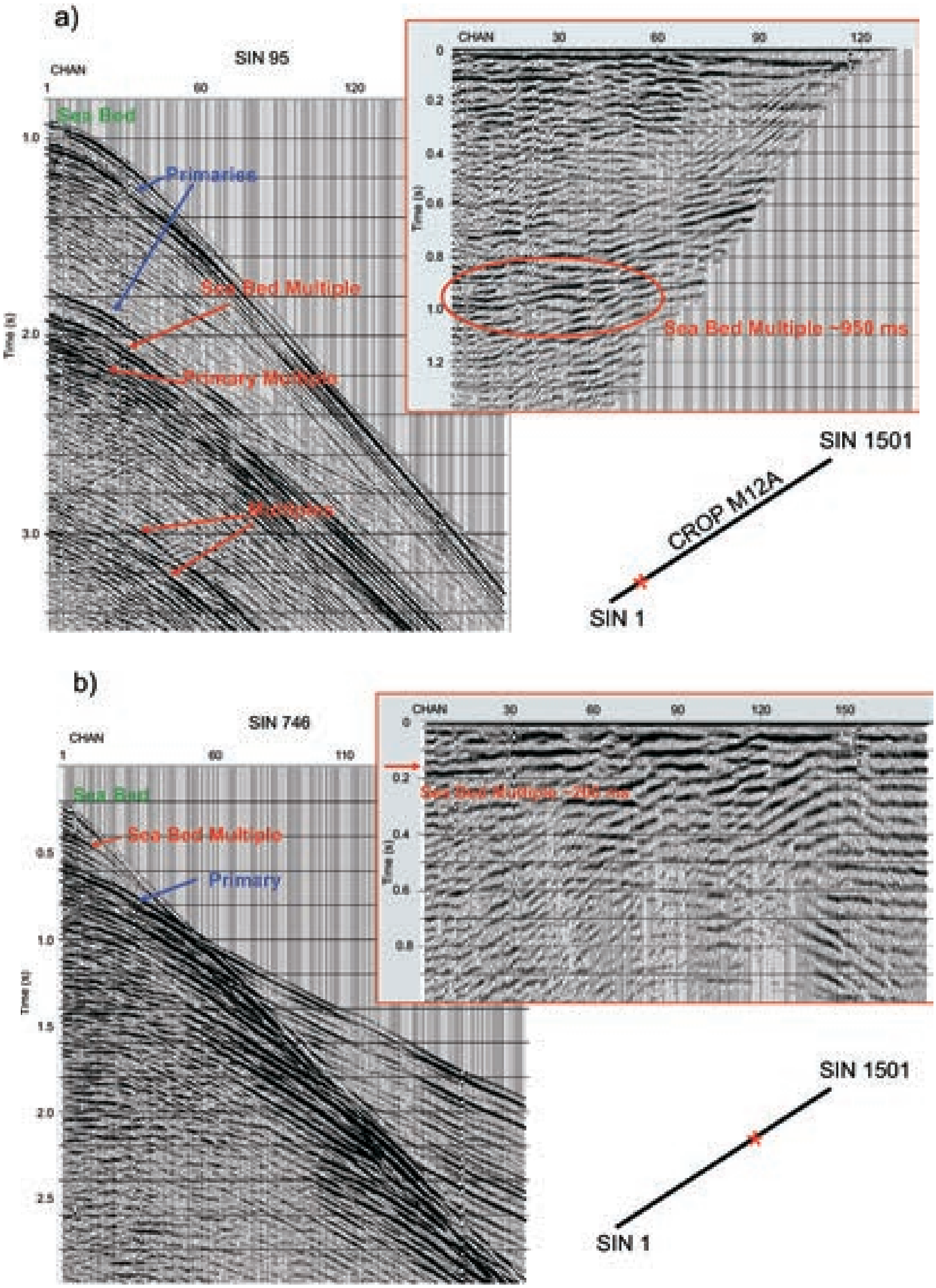


Fig. 2 - Common shot on the west side (a), and east side (b), of the M12A profile showing the long and short periodicity of the sea-bed multiples. The autocorrelation close-ups suggest a period of ≈ 950 ms (a), and ≈ 200 ms (b), respectively.

Table 1 - Acquisition parameters of seismic line M12A.

| | |
|---|---|
| Date: August 1991 | |
| Vessel | OGS-EXPLORA |
| System | Sercel SN-358-DMX |
| Record length | 17 s |
| Sample interval | 4 ms |
| Low cut filter | Out |
| High cut filter | 77 Hz at 70 db/octave |
| Energy source | Airgun |
| Source array | 4x8-Airgun linear strings |
| Volume | 80.40 l (4096 cu.in.) |
| Gun depth | 8 m |
| Shot interval | 50 m |
| Streamer | Prakla-seismos |
| Streamer length | 4500 m |
| Number of groups | 180 |
| Offset in line | 125 m |
| Group interval | 25 m |
| Streamer average depth | 14 m |
| Group length | 25 m (32 phones/group) |

(Table 1), the recorded data (Fig. 2) can give important information about the shallow-depth geological structures, if special care is taken during the processing phase. Relying on this assumption, the M12A CROP profile was reprocessed in order to enhance the visibility and the resolution of the structures located at shallow depth, that is down to 3 s - 4 s traveltime. We then exploit recently developed methodologies to improve the signal-to-noise ratio (S/N), paying particular attention to the suppression of the multiples that contaminate the data and to the velocity model building for depth migrating the seismic data set.

## 3. Stack section time reprocessing

Two different processing sequences have been developed: the first one tries to recover the true reflection amplitudes in the subsurface compensating for the geometrical spreading of the wavefront, while the second aims at putting in evidence the geometries of the bodies using an automatic gain, regardless of the contrasts in the acoustic impedances that are at the origin of the observed events. The final products of each sequence are a time section and a post-stack depth migrated section that, as a consequence of the different gains applied, have distinct characteristics. The deep reflections can be better delineated in the case of the processing flow employing an automatic gain but, because the resolution is more detailed in the upper layers for the outcome of the true amplitude sequence, the sections obtained with this more realistic procedure will be considered further on. The corresponding flow chart is illustrated in Fig 3, while the processing sequence used to obtain the final time section included in Scrocca *et al.* (2003) is reported in Table 2 for comparison. The main, noticeable feature in the processing sequence is the separation into two different processig flow after the Surface Consistent Amplitude Corrections (SCAC, see Fig. 3), a step which attempts to compensate in a statistical way for the different effectiveness of the shots and the receivers along the whole line. The reason for the flow splitting is related to the short and long period of the strong multiples that

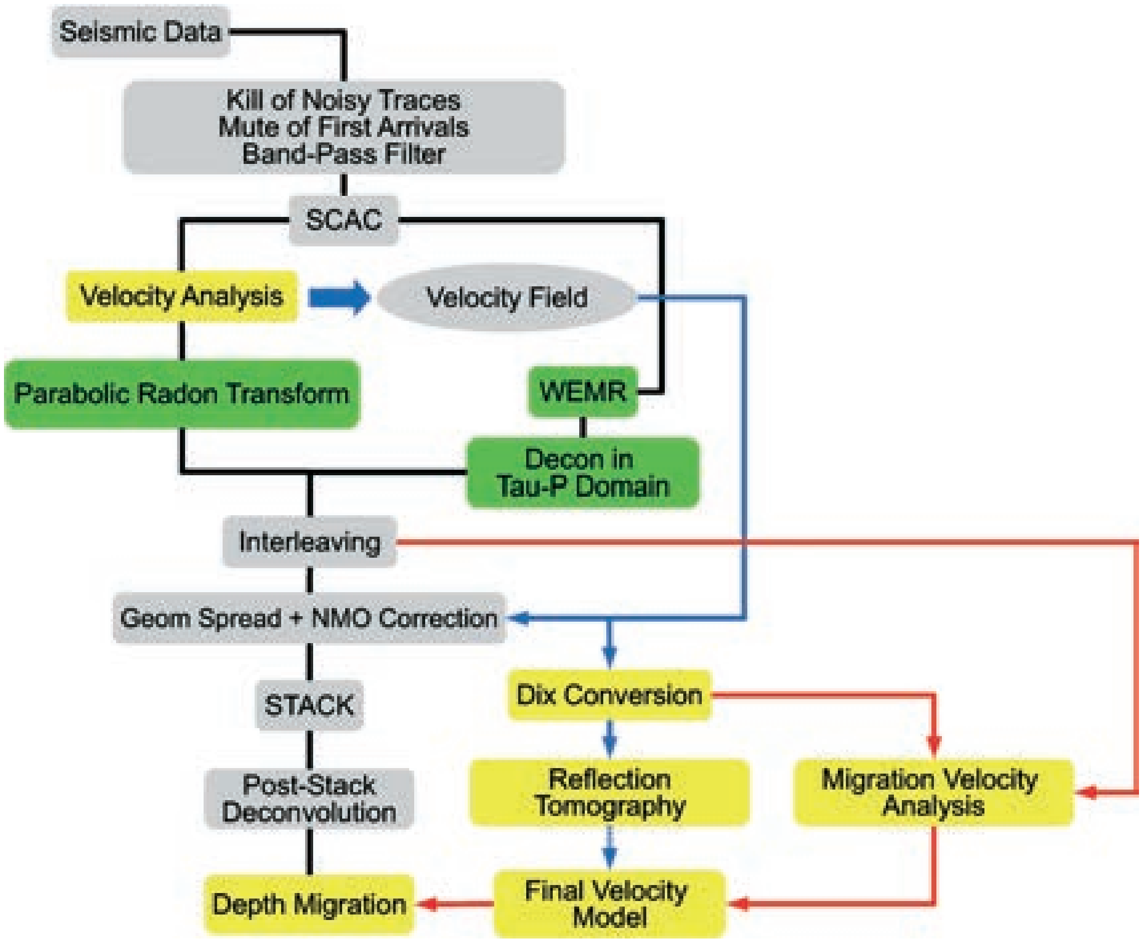


Fig. 3 - Reprocessing flow chart of the M12 profile. The multiple removal operations that require the splitting of the flow are pinpointed in green, while the steps employed for the velocity model building are highlighted in yellow.

Table 2 - CROP-Atlas processing sequence.

| | | |
|---|---|---|
| Time resampling to | 8 ms | |
| Prefilter | 0-17000 ms 3/24-out Hz/dB | |
| Trace balance | 7000-12000 ms | |
| Spherical divergence | | |
| FK filter shot domain | -6/10 ms/tr pass | |
| Predictive decon | 48-256 ms op | |
| Picking of water bottom multiple velocity function | | |
| NMO correction using the multiple velocity field | | |
| Karhunen-Loeve filtering on multiple | | |
| Inverse NMO correction | | |
| Velocity analysis on primaries | | |
| NMO correction | | |
| Stack | | |
| Time variant filter | | |
| above first WB multiple | | 1-2-25-35 |
| below first WB multiple | | 1-2-15-25 |

characterize this marine data set. Their removal without harming the primary reflections is one of the most important steps in the reprocessing. The different sea floor bathymetry along the profile suggests dealing with the multiple problem with two separate strategies. Where the sea floor is deepening and reaches up to an 800 m depth (Corsica basin, western part of seismic line), the removal of the long period reverberations is undertaken by dedicated algorithms such as the FK filter or Radon transform (Hampson, 1986; Yilmaz, 2001); on the other hand, where the sea floor is flat at a 90 m depth (Tuscan shelf, central-eastern part of the seismic line) the use of more traditional tools such as the predictive deconvolution is considered. In the western segment of the profile the FK filter (see Del Ben *et al.*, 1996; Scrocca *et al.*, 2003) is employed mainly as a comparison with the result of the application of the linear and parabolic Radon filtering. For the Radon algorithm to be effective, a good velocity field for the primary reflections is needed. This velocity field is built making use of pre-stack data on which successive iterations of Radon filtering are applied, especially where the identification of primaries and multiples is hampered by their interference. The Radon filter enables a more accurate removal of the reverberations (Fig. 4) and gives a more reliable image of the subsurface than FK filtering, but introduces a high frequency noise recognizable on the stack section. A post-stack FX deconvolution is used to get rid of this noise. On the eastern part of the profile, we have to deal with short period multiples. Because of the ineffectiveness of the traditional predictive deconvolution, we successively applied two different algorithms: the Wave Equation Multiple Removal (WEMR; Wiggins, 1988) and the deconvolution in the tau-p domain. The first one, based on the wave equation propagation, estimates the sea floor reverberations in shot domain and subtracts them from the data. The efficacy of this method relies on the knowledge of the sea-bed reflection coefficient and on the precise picking of sea-bed arrivals. In our case, both factors can not be determined with the required accuracy, so the outcomes are not as good as expected. This leads us to the successive application of the deconvolution in tau-p domain which gives satisfactory results (Fig. 5). To increment the signal-to noise-ratio especially at shallow times where the coverage is reduced by the killing of noisy traces and by the mute operation, an interleaving procedure is applied by reducing the spatial sampling rate in the cdp domain to 25 m, but doubling the cdp fold to approximately 9000% (full coverage). Besides the classical processing steps to get the final image in time (such as bandpass and TVF filtering, NMO correction and so on), a pre-stack predictive deconvolution and a post-stack spiking deconvolution are applied on the whole line to enhance the resolution and to attenuate the residual multiples. Table 3 illustrates the parameters used by these algorithms. The final section resulting from the above described reprocessing of the seismic data is shown in Fig. 6. To illustrate the resolution achieved for the shallow reflectors, Fig. 7 displays a close-up of the Punta Ala basin, an area that is considered of crucial importance for the interpretation, while Fig. 5b depicts the Montecristo basin south of Elba Island.

## 4. Velocity model and depth migration

To depth migrate the time section, an accurate interval velocity field in depth is needed. The starting point is a careful velocity analysis on CMP gathers (the one accomplished for the Radon demultiple step), followed by a Dix conversion of the resulting RMS velocity field. The Dix conversion is applied after filtering with a smoothing operator to reduce the short wavelength

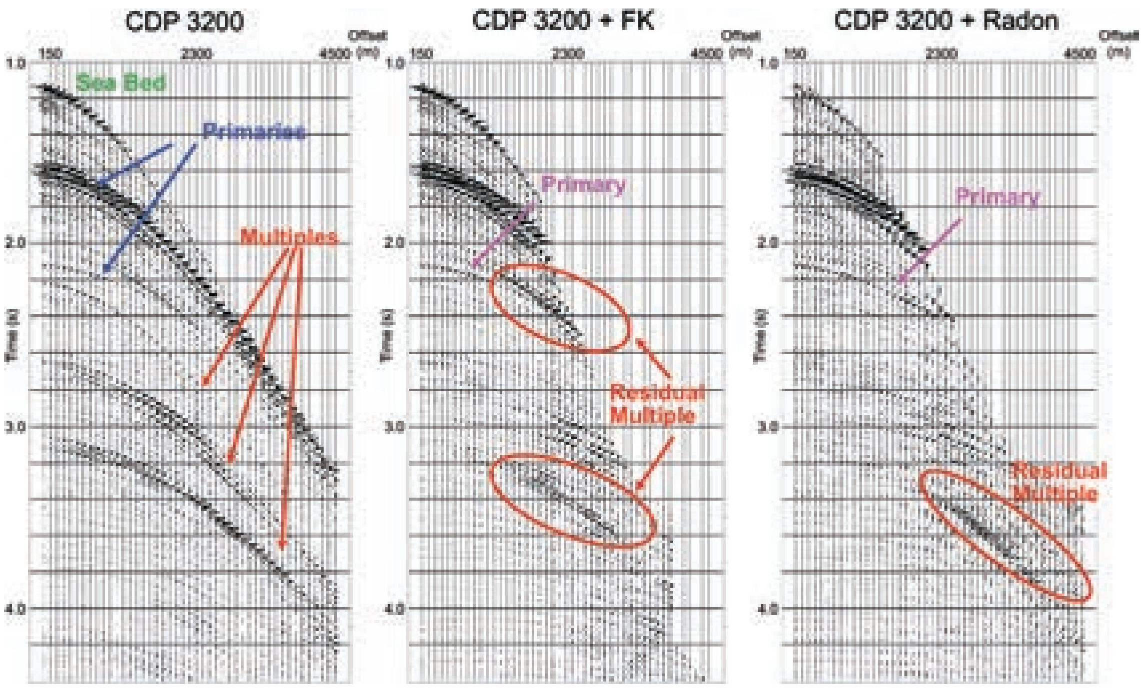


Fig. 4 - Comparison of the FK and Radon multiple removal algorithms applied to a CDP on the western side characterized by long period reverberations. The outcomes observed for the Radon filtering (right panel) show a more effective multiple attenuation and a better continuity of the primary reflections than the results obtained with FK filtering (see the magenta arrows).

velocity variations both in time and space. On the central-eastern part of the section, from CDP 4100 to CDP 6200, the computed Dix model is used as input in a reflection tomography approach carried out on shallow layers, for which the pre-stack picking of the reflected arrival times is

Table 3 - Parameters of the post stack processing steps.

| | | | |
|---|---|---|---|
| **Predictive Deconvolution** | | | |
| | Operator distance | 240 ms | |
| | Operator length | 180 ms | |
| | White noise level | 0.1 | |
| **Spiking Deconvolution** | | | |
| | Operator length | 220 ms | |
| | White noise level | 0.1 | |
| **FX Deconvolution** | | | |
| | Horizontal window length | 10 samples | |
| | Number of filter samples | 9 | |
| | Time window length | 80 ms | |
| **Time Variant Filter** | | | |
| | Time gates | 0-3000 ms | Frequency 5-8-35-45 Hz |
| | | 2500-6000 ms | Frequency 5-8-30-40 Hz |

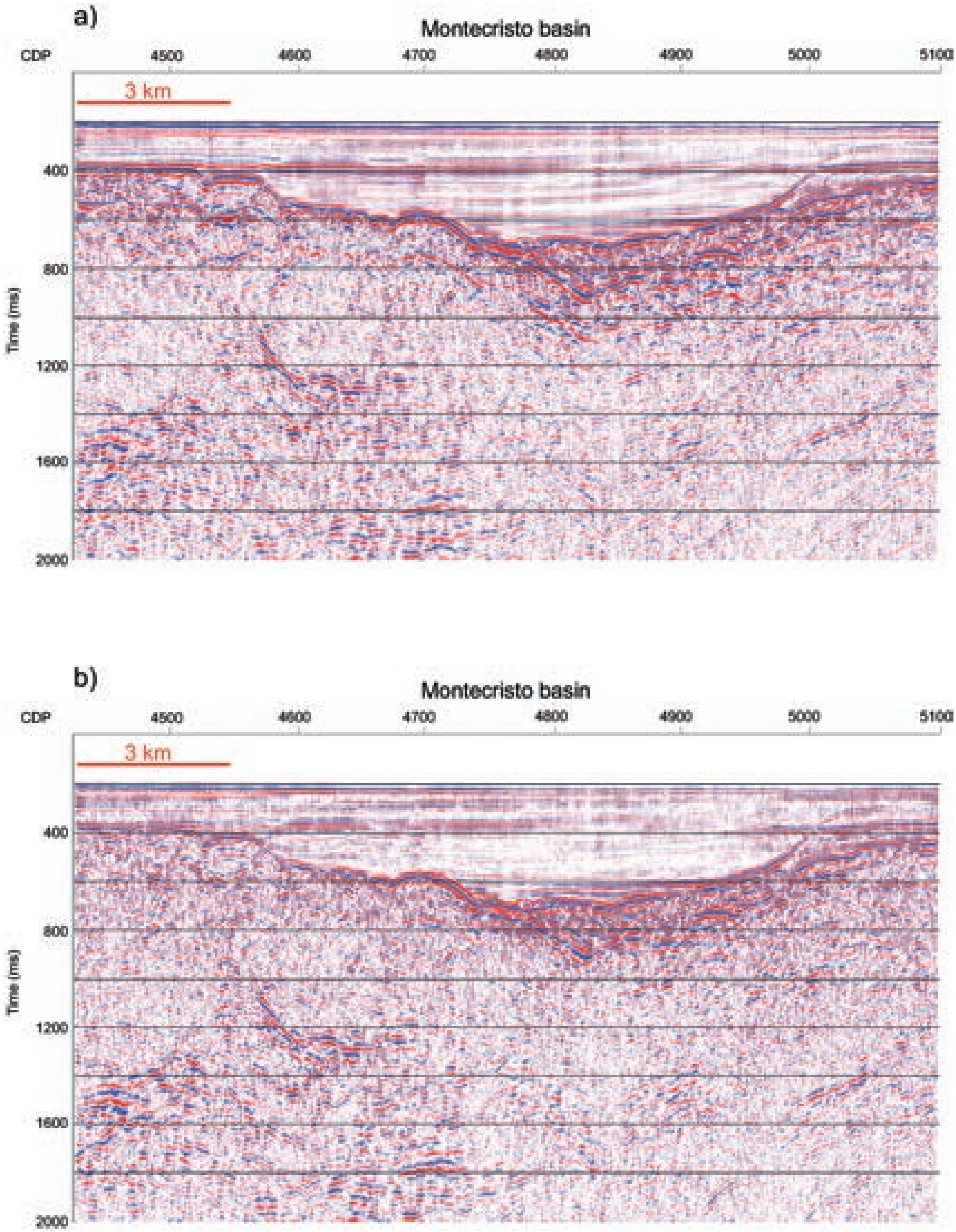


Fig. 5 - Close up of the stack section showing the (Montecristo) basin before (a) and after (b) the short period multiple attenuation. Sea bed and basement multiples are clearly reduced in b) after the application of the WEMR algorithm and the deconvolution in tau-p domain.

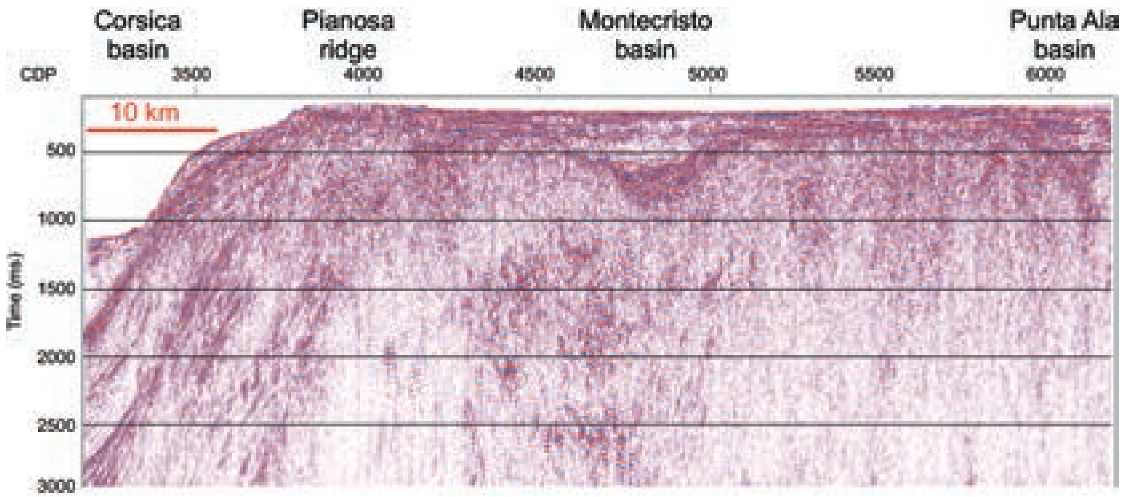


Fig. 6 - Final stack section in time of the M12A seismic line. Total profile length is more than 70 km, so the horizontal scale is quite compressed.

reliable (0.6 s maximum zero-offset TWT, Figs. 6 and 7). The tomography field obtained was merged with the smoothed Dix field of the whole line to build the velocity model used for a preliminary post-stack depth migration of the data. To ascertain whether the velocity model is

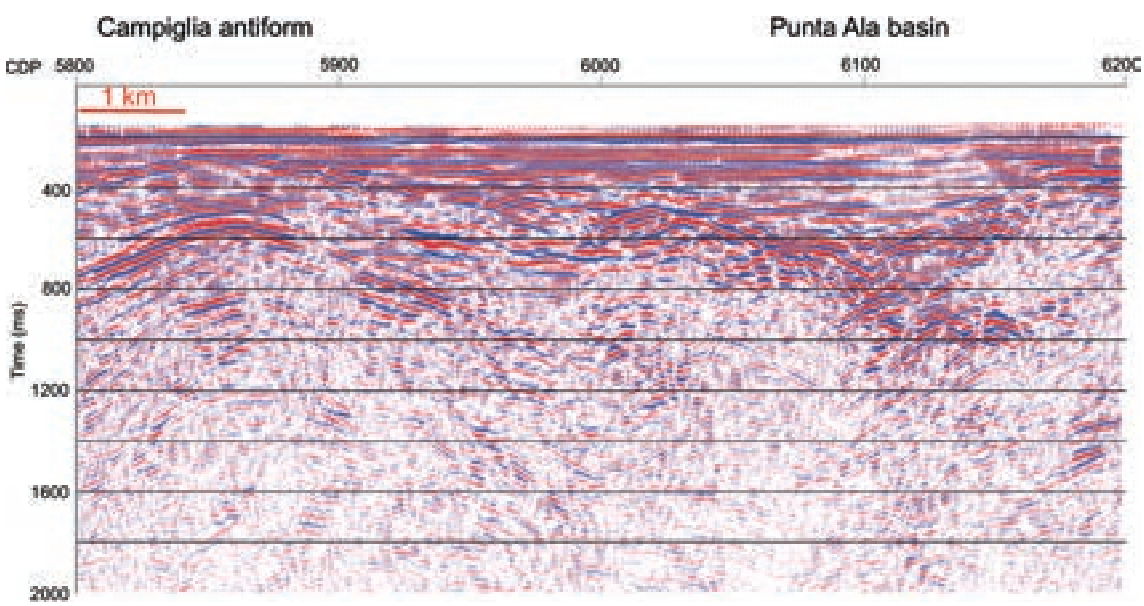


Fig. 7 - Particular of the Campiglia antiform and the Punta Ala basin, both located in the eastern part of the stack section. This region is widened; it is considered an important point for the interpretation.

optimal, a pre-stack analysis on common reflection point (CRP) gathers is needed: in fact, velocity models simply scaled by constants or increasing with depth coefficients, a procedure sometimes used for time migration velocity fields, can lead to depth migrated sections that are equally interpretable but with reflectors at incorrect depths. One of the most powerful tools for building an accurate velocity model is the migration velocity analysis (MVA). By pre-stack depth migrating the common offset ensembles (as required by the Kirchhoff algorithm we used) and then resorting the data into CRP gathers, it is possible to verify the reliability of the velocity model. If the reflections in the CRPs are horizontal, i.e., at constant depth as a function of the offset, then the proper velocity is used for migration and the model can be considered as correct; otherwise the model must be updated. Fig. 8a shows some CRPs located at interesting points along the profile after pre-stack depth migration with the Dix-tomographic velocity field. At the beginning of the line (CRP 3251 and 3451) it is evident that all the reflections, less the sea bed one, have an upward curvature as the offset increases. This is an indication that a low velocity is used for depth migrating the data (the contrary is true if the curvature is downwards) and that the velocity model must be updated. Instead, towards the east (CRP 3964 and 4652), where a tomographic approach has been used at least for the shallow layers, the horizontal alignment of the reflections is increased and only minor corrections are required. On the basis of this analysis performed on a dense sample of CRPs and following a top-down approach, as in a layer stripping case, the velocity field is updated for the whole profile starting from SW. The MVA procedure is heavily time consuming because the data need to be re-migrated after the velocity updating and then checked again. Nevertheless, it is reiterated until a satisfactory horizontal alignment of the reflections in the CRPs is obtained (Fig. 8b). Figs. 9a and 9b show the velocity field before and after the MVA. The main differences are observed from the beginning of the line to approximately CDP 4400. The alignment of the reflections on CRP gathers has required a considerable increase in the velocity values notwithstanding the efforts we put during the traditional velocity analysis phase. The depth migrated section and three close-ups illustrating the details of the shallow layers obtained are shown in Figs. 10, 11a, 11b, and 11c, respectively.

## 5. Discussion

Crustal data acquisition is designed to image deep reflectors associated with discontinuities at depth of the order of ten kilometres or more. The processing sequence is therefore generally focused to increase the signal-to-noise ratio for the deepest reflectors, paying lower attention to the shallower ones. In our study, the events with TWT $\leq$ 4 s have been considered, because their estimated depth corresponds to zones in the upper crust where an important part of the Cenozoic geological history is recorded, and the intrusive magmatic bodies that characterise the northern Tyrrhenian area are located. In this time window, we try different and recently developed techniques to enhance the resolution of the reflections and to attenuate the numerous multiples that affect this data set.

From the section in Fig. 2 of Pascucci (2005), sea-bed short and long period multiples can be clearly observed in the eastern and in the western part respectively, where the bathymetry of the sea floor and the dip of the subsurface layers complicate their moveout. Our reprocessing sequence, dealing with short and long period multiples with dedicated steps, leave us confident

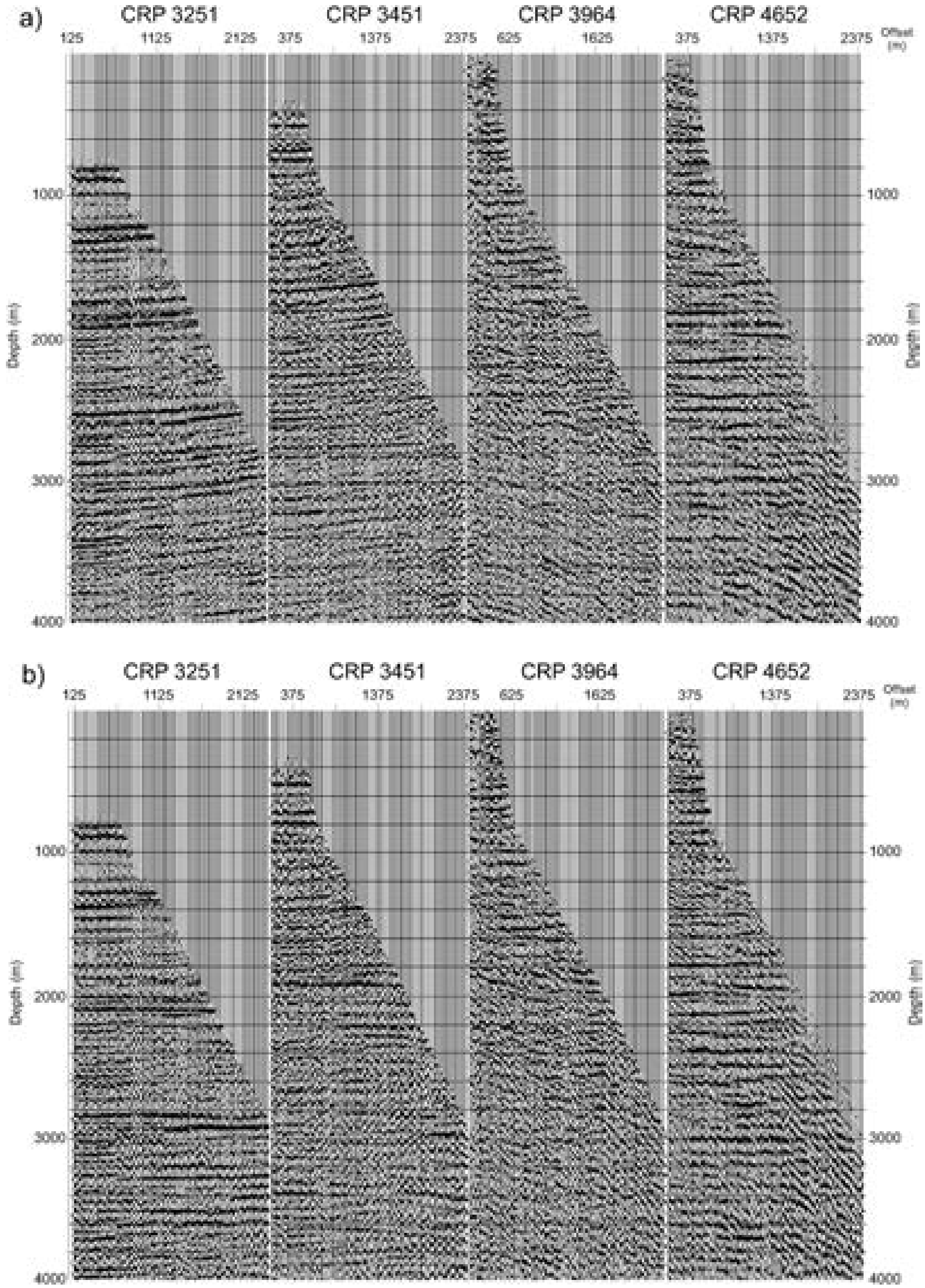


Fig. 8 - CRPs gathers at some interesting points before (a) and after (b) MVA analysis. The alignment of the reflections after the pre-stack depth migration with the updated velocity field allow us to build a more reliable and trustworthy velocity model.

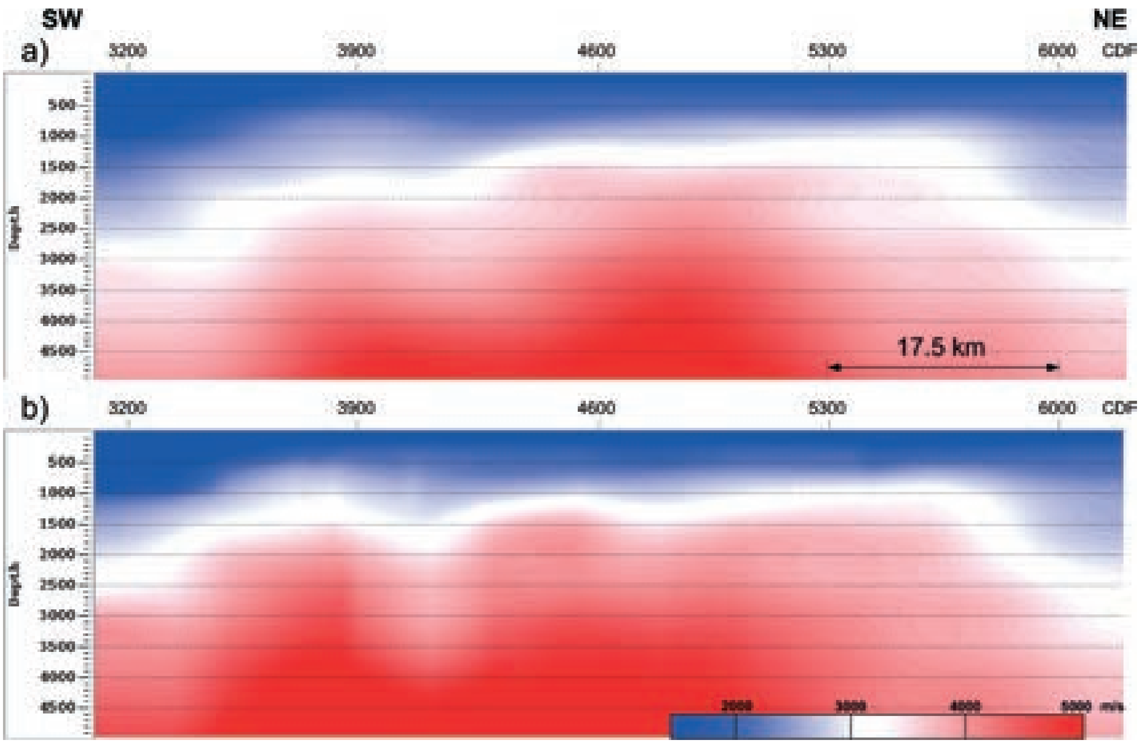


Fig. 9 - Preliminary velocity model (a) and final velocity model (b) updated through MVA analysis and used for post-stack depth migrating the data. The colour difference highlights the location where the main changes in the velocity occur.

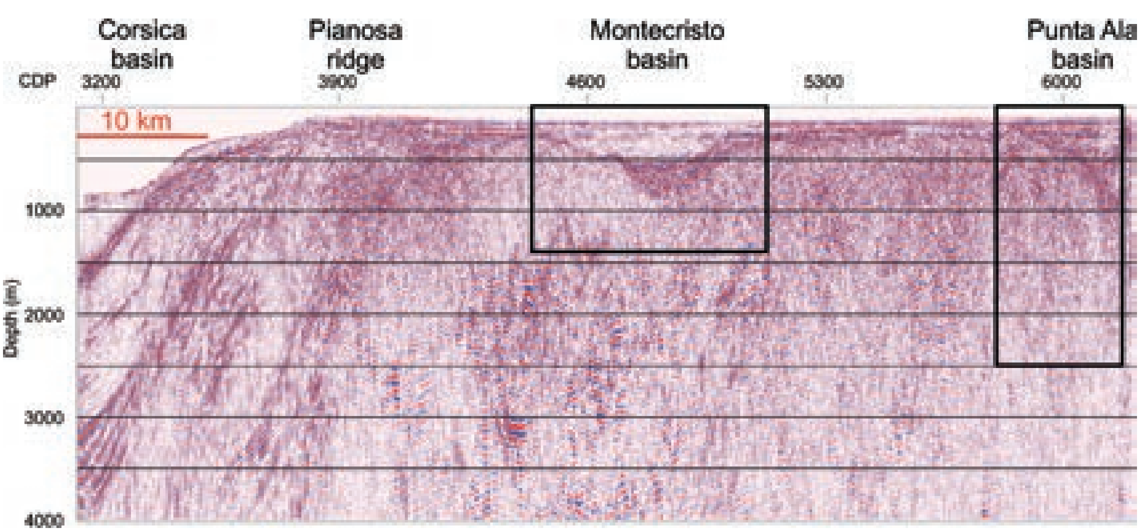


Fig. 10 - Final depth migrated stack section of the M12A seismic line. The boxes in the picture indicate the close-ups shown in Figs. 11a and 11b with a vertical-to-horizontal scale that allows to better appreciate the geometry of the subsurface structures.

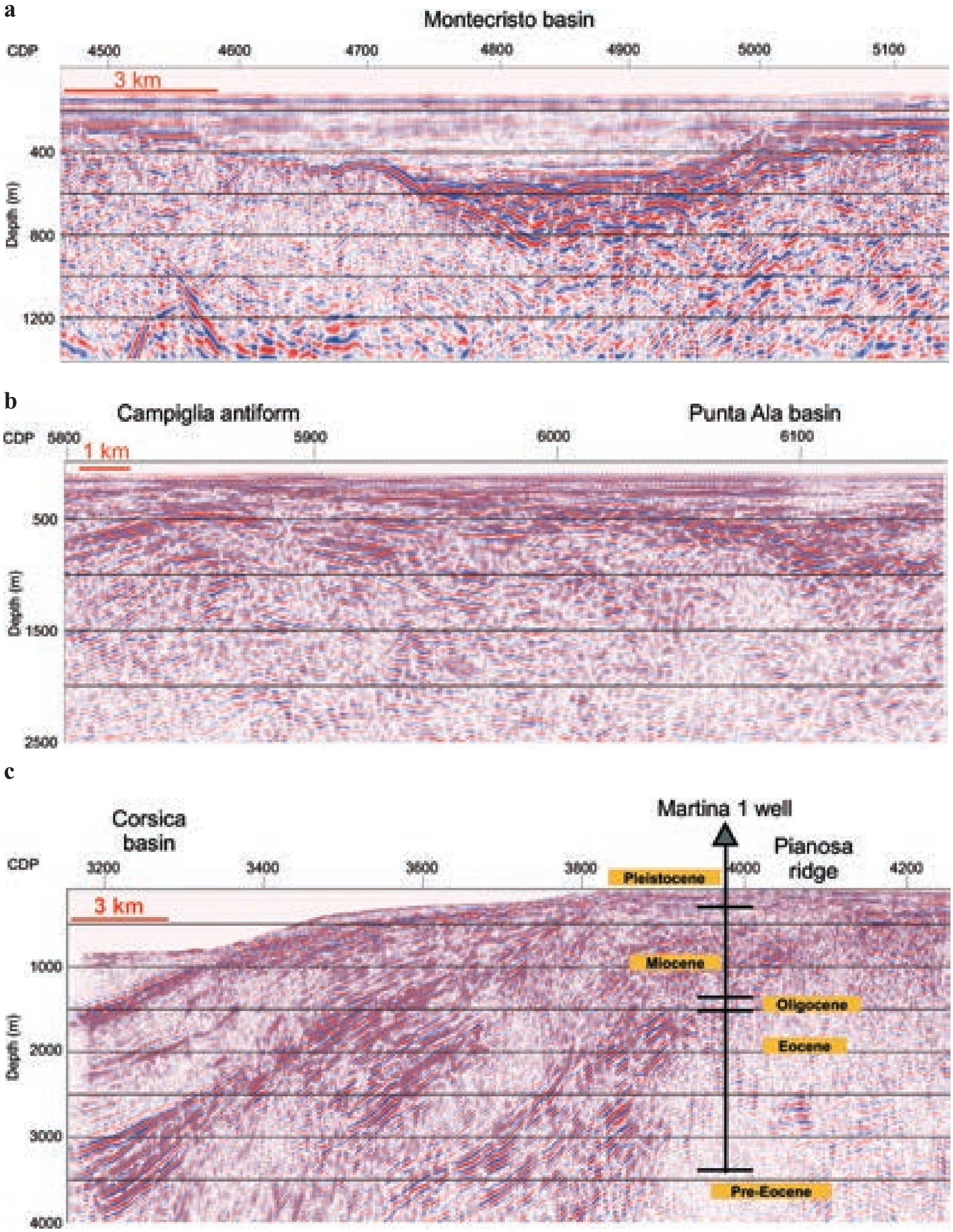


Fig. 11 - Close ups of the Montecristo basin, central part of the depth migrated section (a) and of the Campiglia antiform and Punta Ala basin, eastern part of the depth migrated section (b). Depth migrated section towards the Corsica basin (c). Superimposed are the major stratigraphic discontinuities reported on the Martina 1 log which is located 1 km to the north.

that a more effective multiple attenuation, as can be evinced by comparing Fig. 2 of Pascucci (2005) with Figs. 5b and 7 will be obtained. Moreover, the reprocessed section puts in evidence a greater continuity of the reflections and a better delineation of the shallow basins including the infilling and sub-horizontal shallow layers. The close-ups of the Montecristo and Punta Ala basins (Figs. 5b and 7) are good examples of the signal-to-noise ratio improvement achieved. An additional and fundamental aid to the interpretation is represented by the depth section. The horizontal alignment of the reflections in the CRP gathers is clear evidence of the reliability of the velocity field obtained after the MVA. This allows us to depth migrate the seismic section so that the geological structures are located in space with their correct position and shape. Consequently, an estimate of the layer thickness that can be trusted is obtained, in particular to the west where significant dips are present. In this area, two wells were also drilled in the 1970s by ENI-AGIP: the Martina 1 which is located approximately 1 km north of CDP 3970 on the Pianosa ridge, and the Mimosa 1 some 20 km to the south. In Fig. 11c the major stratigraphic discontinuities reported on the Martina 1 log are superimposed on the depth section. These allow the identification and dating of the main reflectors which deepen to the SW towards the Corsica Basin. Unfortunately, no synthetic seismogram can be built from these logs, because only spontaneous potential and resistivity measurements were acquired. The results obtained in this work give one the opportunity to better define the shape and geometries of shallow-depth geological bodies and structures, for which correspondences can be found on land and on the islands of the Tuscan archipelago. The geometries of the reflectors in both the stack section and the depth migrated section highlight the fact that the acoustic basement (tectonic units of the northern Apennines) and overlying late Neogene sedimentary deposits, define a sequence of open antiforms and synforms. These structures are discordantly covered by subhorizontal reflectors corresponding to the undeformed deposits of Middle Pliocene-Quaternary age. Besides, in both sections tectonic structures are imaged by west-dipping, parallel reflections cutting through more gently dipping reflectors. An example of these structures is recognised at CDP 4000-4200 on the eastern side of the Pianosa ridge. As a final remark both sections show regions that are transparent to the seismic signal. The relationship between these zones and the presence of intrusive magmatic bodies is a question open to debate and concerns the geological interpretation of the reprocessed profile; this is the topic of another paper, and is not considered further here.

## 6. Conclusions

In this study, we reprocessed the seismic data of the M12A CROP profile starting from the field records but limiting our analysis to traveltimes pertinent to the upper crust reflections (TWT $\leq$ 4 s). This choice is a consequence of the lack of a detailed image of the shallow structures which have recorded the recent (Neogene) geological history (<10-12 Ma) of the northern Apennines belt in the frame of central Mediterranean region. In fact, previous works focused mainly on deep reflections. In this time window, the final section obtained after the applied reprocessing sequence is characterised by an improved signal-to-noise ratio and a higher resolution compared with the previous images. In the proposed sequence, a great effort is devoted to the attenuation of the multiples. The changing periodicity of the water bottom reverberation makes this a complex task, and requires different approaches for the eastern and western part of the profile. Nevertheless, the result of the combined procedures can be considered successful so that the following steps in the sequence can be aimed at enhancing the resolution of the primary reflections. Another important result of this work is that it is not limited to the time domain. The depth migrated section obtained with a velocity field built by means of the migration velocity analysis, is an important aid for the geological interpretation of the profile. The horizontal alignment of the reflections on the CRP gathers leaves us confident of the correct positioning in depth of the reflectors on the migrated profile, so that the real geometry of the subsurface structures can be reconstructed. Moreover, the information coming from a nearby well and related to the major stratigraphic discontinuities gives the opportunity to identify and date the horizons accurately. In conclusion, the reprocessing of the M12A seismic line, focused at improving the quality and reliability of the upper part of the profile, represents the first step for a new and well-constrained interpretation of the geological structures in the northern Tyrrhenian Sea and gives also the possibility to delineate the position and shape of the intrusive bodies related to the late Miocene magmatism in the northern Tyrrhenian Sea.

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*Corresponding author:* Andrea Tognarelli
Consorzio Universitario per la Geofisica
Via Matteotti 61, 19032 Lerici (La Spezia), Italy
Phone: + 39 347 1235971; fax: +39 0187 969081; e-mail: tognarelli.consgeofisica@chd.it