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New information from "old" seismic lines: an updated geological interpretation from the re-processing of the CROP line M-2A/I (Bonifacio Straits) at shallow depths

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Abstract

The shallowest part (about 3 sec two-way traveltime) of the CROP line M-2A/I, acquired during 1991 in the Bonifacio Strait (between Corsica and Sardinia), has been reprocessed to improve its geological interpretation. The original target of the M-2A/I profile was the entire crust and therefore the shallowest part was only partially interpreted. In this context, the re-processing procedure was carried out to improve the signal-to-noise ratio and the resolution of the M-2A/I seismic profile at shallow depth. The geological interpretation of the reprocessed data aimed at the reconstruction of the sedimentary succession and the contact with the underlying Hercynian basement.

The M-2A/I seismic profile has been interpreted identifying diverse seismic facies, interpreted considering the geological units outcropping to the north (in Corsica) and to the south (in Sardinia) of the seismic profile. The study supports the existence of a thick Mesozoic succession, onlapping the Hercynian basement, preserved below the Cenozoic succession in the Asinara Gulf, suggesting that the Nurra succession continues northward below the sea. The Mesozoic succession is bordered by a major, east-dipping normal fault, east the Asinara Island ridge. The faults recognized in the seismic profile indicate a prevailing strike slip/transtensional tectonics, questioning the role of compressional tectonics suggested in a previous interpretation. The obtained results also indicate the potential of re-processing of existing seismic profiles, whose interpretation can be significantly updated thanks to the development of new processing procedures and to the continuous upgrade of the regional geological knowledge.

Key Words: seismic processing, seismic interpretation, CROP, Central Mediterranean

1) Introduction

Seismic processing capabilities and regional geological knowledge gradually increase with the development of new geophysical techniques and the continuous collection of new geological data. For this reason, elaboration and geological interpretation of seismic profiles strongly reflect the moment in which they have been acquired, processed and interpreted. It follows that the availability of new processing tools and new geological data provides favourable conditions for updated interpretations of existing seismic lines acquired in the past years, with the opportunity to obtain new information from "old" data. Actually, major scientific projects of the past provided rich geophysical databases that were studied in the years following the acquisition and then partly abandoned. One example is the Italian deep crust geophysical exploration project (CROP Project) that acquired and gathered a huge amount of geophysical data (seismic, gravimetric and magnetic), proving a deeper understanding of the geological and geodynamical processes that involve the Earth crust. These research efforts produced a large number of scientific papers of which the atlases of SCROCCA *et alii* (2003) and of FINETTI (2005) summarize the main results. Notwithstanding this commendable work, an enhancement of our knowledge of the upper Earth crust in the Mediterranean region can still be possible starting from the existing CROP seismic dataset, as new geophysical processing procedures have been developed and geological knowledge has improved. In this context, one possibility that can be pursued is the use of reflection seismics to investigate in greater detail the shallower part of the Earth crust. Indeed, due to the deep targets of the CROP Project, the seismic data could have not been exploited in their full potential for shallow depths. The investigation of the shallowest seconds of this dataset can benefit from the application of a new dedicated processing sequence (for two-way traveltime, TWT, up to about 3 sec), coupled with a discussion and integration of the updated geological knowledge. Examples of this approach have been given by TOGNARELLI *et alii* (2011), who use the seismic data of the CROP M12A profile to better delineate the shallow structures in the Northern Tyrrhenian Sea, south of Elba Island, and by BONINI *et alii* (2014), that use the CROP 03/c seismic data to investigate the structural setting of some of the Late Miocene-Pliocene hinterland basins in the inner sector of the Northern Apennines (western Tuscany and Tyrrhenian basin). In the work of BONINI *et alii* (2014) the stack section is used as the basis for the interpretation, whereas the work of TOGNARELLI *et alii* (2011) mainly focuses on the processing sequence up to the depth migrated image, which requires a considerable man power effort to perform the Migration Velocity Analysis for an accurate estimation of the velocity model in depth.

In this study we focus our attention on part (about 100 km) of the M-2A/I profile, a segment of the M-2A line, acquired in the Bonifacio Strait, between the Corsica and Sardinia islands. Differently from TOGNARELLI *et alii* (2011), we limit our reprocessing to the pre-stack time migrated image because we considered the resolution and the accuracy of the reflector positioning attained by this methodology adequate for the goal of our study.

The applied re-processing improved the signal-to-noise ratio and allowed for the identification of several facies (geologically interpreted after a comparison with the geological units outcropping in Sardinia and Corsica) providing new insight on the architecture of the upper crust along the considered seismic line.

2) Geophysical dataset

2.1) The seismic data of the CROP M-2A/I marine line

The CROP Project is a multidisciplinary research project to study the Italian lithosphere, in which seismic data play a major role. The seismic data set amounts to 9941 km of seismic sections, of which 8687 km are offshore. The marine data set was acquired using a seismic source consisting of an airgun array of 4906 cu and a 4500 m long, 180 channel streamer, with a 150 m minimum offset. The recorded trace length varies generally between 17-20 s and the sample rate is 4 ms (FINETTI, 2005). The whole data set is characterised by 25 m group interval and 50 m shot interval, with a nominal coverage equal to 45 (Table 1).

The acquisition of the M-2A/I line was carried out by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) in the summer 1991. The East-West profile crosses the Bocche di Bonifacio Strait (between Corsica and Sardinia Islands) (Fig. 1). As can be observed in Fig. 1, the profile was not acquired along a straight line and unfortunately the receiver coordinates are not available. For this reason, different approaches to bin the data using the crooked-line technique were pursued but were unsatisfactory, due to variations of fold coverage from adjacent CMPs and unrealistic lateral dimension of the bins. Therefore we had to resort to a nominal 2D profile (as if it was a straight line) and then using the source coordinates for repositioning the final section on the map.

2.2) Processing

The processing sequence has been designed in order to improve in terms of signal-to-noise ratio and resolution the shallowest part of the M-2A/I seismic profile, using the data until 3.5 s TWT and focusing the attention down to 1.5 s. This section would only give a glimpse of the processing applied and is intentionally kept at an informative level. For a deeper analysis one can refers to the papers of MAZZOTTI *et alii* (2000), STUCCHI & MAZZOTTI (2009), TOGNARELLI *et alii* (2011) and to the YILMAZ (2001) book.

Fig. 2a,b displays two raw shot gathers where the sea-bed and some deeper reflections, some refractions at far offset and the direct arrivals are clearly visible; Fig. 2c,d shows the raw data of a noise contaminated near channel (channel 4, FFID 4460-4550) and the corresponding de-noised version respectively (see below for the de-noising procedure applied). Frequency analysis has shown a bandwidth between 5-65 Hz at -25 dB, as can be observed in the insets in Fig. 2a,b. On these gathers are also visible some bursts of noise that manifest on many shots at the arrival time corresponding to the sea-bed reflection.

The flow chart in Fig. 3 shows the sequence that has proved to be the most effective for our objectives. The first steps in the sequence have been performed, after setting up the database of the nominal acquisition geometry, in order to attenuate the bursts of noise observed in Fig. 2a,b,c. . An ad-hoc procedure based on the cross-correlation technique was used to process the data of the near channels where the noise bursts interfere with the reflections, while a simple mute was applied at far offset (Fig 2a,b). Due to the shape similarity between these noise bursts, we selected a family of representative noise pulses recorded before the first arrivals and cross-correlate them with the short offset traces on a channel basis. In fact, these noise bursts were quite consistent in each channel (Fig. 2c). From the cross-correlation the time of arrival and the amplitude of the most representative noise burst can be estimated, the noise modelled and then subtracted from the channel traces (Fig. 2d).

We also had to deal with a similar problem at shallow water (about 80 m depth), where the secondary lobes of the source wavelet interfere with the sea-bottom reflection as a consequence of the shallow bathymetry (Fig 2b,c). These interference effects modify the wavelet of the sea-bottom reflection and lower the efficacy of the wave equation multiple rejection (WEMR) and predictive deconvolution techniques for the multiple attenuation. One noisy channel (channel number 36) has been eliminated in the whole data set, and a conservative band-pass filter characterized by [0-5-80-100] Hz, whose design is based on the spectral analysis of the raw shot gathers (see insets in Fig. 2), was applied.

For the gain recovery two main approaches were followed that also had impact on the procedures used to tackle the multiple problem: the first one corrects for the amplitude decay due to the geometrical spreading of the seismic waves and the second one makes use of a numerical gain, the automatic gain control (AGC). The AGC used a window of 500 ms and the computed gain values were stores sample by sample so that they can be successively removed. Both the inverse geometrical spreading and the AGC gain were applied after the wave equation multiple rejection step (WEMR). The WEMR procedure simulates the wave propagation in shot domain, estimates the sea floor reverberations and then subtracts them from the data. The efficacy of this method is based on the accurate picking of the sea-bed arrivals. In our case, this picking cannot be determined with the required accuracy because of the interference effects previously discussed, so the outcome is not as good as expected.

Several attempts with different combination of predictive deconvolution, spiking deconvolution and Radon filtering techniques were carried out in each of the two gain recovery approaches before defining the procedure shown in Fig.3, that also includes a velocity analysis before the Radon filter application. The sequence that makes use of the AGC proved more efficient against the multiples and also better highlights the geometry of the geological bodies we are interested in. To limit the impact that this choice can determine on the amplitudes of the seismic events on the final section, we removed the AGC before the pre-stack time migration which took care of the amplitude recovery.

The Radon (parabolic) filtering technique requires a good velocity field to be effective, because it is based on the residual moveout to discriminate between the multiples and the primaries. Therefore, an accurate velocity analysis step was carried out whose output velocity model was then refined on the same CDP supergathers after the application of the Radon filter (Velocity Analysis 2). Indeed, the coherency values of the multiples were strongly attenuated on the high-resolution coherency functionals (TOGNARELLI *et alii*, 2013) used to check the velocity analysis on some points along the line. The application of the proposed sequence has given satisfactory results in terms of multiple attenuation, as can be observed comparing Fig. 4a, the stack of the raw data (only band-pass filtered), with Figure 4b, the stack of the data processed up to the Radon filter, where many reverberations and in particular the sea-bed multiple at 0.5 s have been attenuated. Other techniques such as the f-k transform, were less effective due to the actual low coverage of the shot or CDP gathers at short offset and shallow times, or because they also attenuate the signal (Karhunen-Loeve transform). Figure 4c shows the same portion of the final section after the pre-stack Kirchhoff time migration and the post-stack processing steps described later.

The pre-stack Kirchhoff time migration allows to increase the spatial resolution by collapsing diffractions, moving dipping events to their correct subsurface locations and improving the definition of the contact between horizons in the subsurface (Fig. 4c) (YILMAZ, 2001). Before stacking the migrated data, a mute on CDP gathers was helpful to eliminate some noise, especially at far offset, introduced by the migration algorithm. Figure 5 a) and b) shows, as an example, the CDP gather number 5291 before and after the pre-stack time migration, respectively. As can be observed, the reflection events are nearly flat after migration, suggesting that the velocity used was sufficiently accurate for time migration.

To achieve the final image (Fig. 4c) a post-stack predictive deconvolution has been applied to reduce some residual reverberations and increase the resolution in time. This deconvolution was followed by a Time-Space Variant Filter with a frequency band narrowing as the time increases and an FX deconvolution designed with conservative parameters to improve the signal-to-noise ratio in the entire section.

Summarizing, the main difficulties we faced during the reprocessing were the attenuation of the multiple reflections, in particular the sea-bottom multiple, and the low actual coverage of the shallow data due to the acquisition parameters for deep exploration employed. For this reason, the WEMR and the Radon filter were not applied where the Basement is very shallow, relying only on the pre-stack spicking deconvolution for the multiple attenuation. Another issue is that the profile was not acquired along an actual straight line and only the source coordinates are available. The lack of receiver coordinates forced us to use a nominal 2D profile.

3) Geological setting

Corsica and Sardinia are divided by an E-W oriented narrow strait (Bonifacio Strait) that rapidly deepens to the east (toward the Tyrrhenian Sea) and, less rapidly, to the west (Balearic Sea; Fig. 1). The narrowest part of the strait is characterized by the presence of a granitic ridge that continues from southern Corsica to the Gallura region in northern Sardinia (CARMIGNANI *et alii*, 2000; Fig. 1). Whereas southern Corsica mostly consists of Hercynian granitoids (with the development of the Miocene Bonifacio Basin in its southernmost part), the northern coast of Sardinia is more heterogeneous. In the central part (Gallura) Hercynian granitoids with a small Miocene basin (Santa Teresa di Gallura) crop out, whereas a different geological setting is observed to the west, along the northern coast of Sardinia. A large area characterized by Oligocene-Miocene deposits bounds to the west the Hercynian granites and is bordered to the west by a Mesozoic succession (mostly carbonates) covering the Hercynian basement (Nurra-Asinara ridge). In summary, it is thus possible to identify in the study area three major lithological associations: the Hercynian basement, the Mesozoic carbonates of the Nurra and the Oligo-Miocene successions (Fig. 1, 6).

The Hercynian granitoids consist of different intrusive bodies (granodiorite, leucomonzogranite, monzogranite, rare gabbro and diorite) with ages spanning from about 300 to 270 Ma (DEL MORO *et alii*, 1972). Locally volcanic and volcaniclastic deposits are preserved. In the western part of the Hercynian ridge, the granitoids intrude metamorphic rocks, mostly consisting of paragneiss, ortogneiss, quartzites and metasandstones. Variscan metamorphic rocks and minor intrusive bodies (CARMIGNANI *et alii*, 1979) irregularly crop out also in North-Western Sardinia (Asinara Island). These units are non-conformably covered by an Upper Permian/Triassic to Cretaceous succession, extensively outcropping in the Nurra region, north of Alghero (CHERCHI & SCHROEDER, 1985a).

The base of the sedimentary succession consists of siliciclastic deposits associated with evaporites of uncertain age (Upper Permian or Triassic), covered by shallow-water limestone (Muschelkalk, Middle Triassic) covered by massive peritidal dolostones (Late Triassic; CASSINIS *et alii*, 1996; POSENATO, 2002; CASSINIS *et alii*, 2003). The Jurassic succession of Northern Sardinia mostly consists of bedded carbonates with marly intervals, representing sedimentation in a lagoonal/brackish to coastal setting, under tropical climate conditions (CHERCHI & SCHROEDER, 1985a; CHERCHI *et alii*, 2010). Dolostone prevails in the Late Jurassic. The lower Cretaceous (PECORINI, 1965 CHERCHI & SCHROEDER, 1985b) is characterized by a 50-60 m thick marly interval (“Purbeckian Facies”) that predates the deposition of a thick, shallow-water carbonate succession ("Urgonian facies"), rich in rudists (CHERCHI & SCHROEDER, 1985a; Fig. 6). This succession is topped (Albian-Cenomanian) by a karst surface with bauxites that documents a phase of subaerial exposure and tectonic tilting (CHERCHI & SCHROEDER, 1985a; CARANNANTE & SIMONE, 2002). The Upper Cretaceous units unconformably (PECORINI, 1965) cover Late Jurassic to Aptian sediments, which are locally tilted up to 30-35°. The succession consists at the base of limestones with fresh-water influxes (Cenomanian?) covered by rudist-bearing limestones (Coniacian-Santonian) passing upward to hemipelagic marls (Santonian-Campanian). The situation is different in the Anglona area (on the western side of the Permian complex) where scattered Upper Cretaceous carbonates (Cenomanian-Coniacian) directly cover a very thin succession of Triassic Muschelkalk limestones (CHERCHI & SCHROEDER, 1976). This different evolution of the Nurra with respect to the Anglona area suggests a possible gradual onlap of the Jurassic-Cretaceous succession toward the east and/or a major erosion (down to the Muschelkalk) related to the "middle Cretaceous" unconformity observed in the Nurra.

The Cenozoic (mostly Oligocene-Miocene) succession is preserved differently in Sardinia and Corsica. In southern Corsica, a thin, irregular volcanic Oligocene succession is covered by a thick, mixed siliciclastic-carbonate succession in the Bonifacio Basin (BRANDANO *et alii*, 2009; REYNAUD *et alii*, 2013), preserved in a fault-controlled basin. A similar, but smaller, Miocene succession is preserved in the northermost Sardinia (Santa Teresa di Gallura). A larger Oligo-Miocene basinal area (FUNEDDA *et alii*, 2000) is preserved south of the Asinara gulf (Porto Torres Basin and Logudoro Basin), where a thick succession of mostly Oligocene continental to shallow marine conglomerates, sandstone and marls, associated with volcanic deposits (mostly developed to the west of the Hercynian granitoid) is covered by riolite and riodacite (Aquitanian to Burdigalian). Miocene marine carbonates and sandstones, similar to those preserved in the Bonifacio Basin, unconformably cover the Mesozoic units of the Nurra area.

The described units record three major tectonic events. The oldest is related to the Hercynian orogenesis, documented by the metamorphic rocks of northern Sardinia and southern Corsica, intruded by post-collisional granitoids that build the backbone of these two islands. After this event, northern Sardinia and southern Corsica have been considered a generally stable domain, partly affected by faraway effects of diverse geodynamic events (COCOZZA *et alii*, 1974). Fault systems characterized by different stress fields and kinematics reflect two different Cenozoic tectonic events: a first event is documented by a complex system of strike slip faults (NE-SW and E-W oriented in northern Sardinia and Southern Corsica, responsible for local compression and extension; CARMIGNANI *et alii*, 1992; 1994; OGGIANO *et alii*, 1995; 2009; PASCI, 1997; PASCI *et alii*, 1998) of Oligocene-Aquitanian age (DIENI & MASSARI, 1965; DIENI *et alii*, 2008). The distribution of the strike-slip faults was controlled by inherited Hercynian surfaces, coherent with N-S shortening direction (PASCI, 1997). Where extension occurred, strike slip basins hosting Oligocene-Aquitanian volcanic and sedimentary deposits (OGGIANO *et alii*, 1995) developed. This strike-slip event is followed since the Burdigalian by a generally E-W directed extension, responsible for the development of the Miocene basins (OGGIANO *et alii*, 1995; FUNEDDA *et alii*, 2000) of northern Sardinia and southern Corsica. Evidence of extensional tectonics is also documented in the offshore of northern Sardinia, in the Asinara Gulf, where seismic interpretation (THOMAS & GENNESSEAUX, 1986) of AGIP lines provides the evidence of a two-stages (Oligocene-Aquitanian and Burdigalian) extensional event.

4) Interpretation

4.1) Seismic facies

The geological interpretation focused on the shallowest part of the seismic line (less than 3 sec TWT). The lowest seismic faces in the considered succession is homogeneous with minor, faint, discontinuous reflectors, suggesting minor changes in acoustic impedance. This seismic facies (Seismic facies 1) is shallowest in the central part of the seismic line (where it is close to the sea-bottom), whereas it is covered by overlying units both to the east and to the west. In the westernmost part of the line, this facies is sharply uplifted along a normal, E-dipping major fault. The top surface of this seismic facies reflects the existence of an irregular morphology, controlled by erosional processes and, probably, by faults. In the central-western part of the seismic line, Seismic facies 1 is covered by a wedge-shaped seismic facies (Seismic facies 2) that exhibits internal continuous, parallel reflectors that onlap eastwards Seismic facies 1. To the west, the upper boundary of this facies is represented by an erosional surface. In the central part of Seismic facies 2, two high-amplitude reflectors document a major impedance contrast, suggesting a major lithological change. The space between these two reflectors is around 50-60 ms (TWT), likely representing a lithological thickness ranging between 50-80 meters. Within the seismic facies, minor throws of seismic reflectors indicate faulting: the distance between the reflectors remains constant across these faults, suggesting post-depositional faulting.

A different seismic facies (Seismic facies 3) covers the Seismic facies 2 and, in the central and eastern part of the seismic line, directly Seismic facies 1. In this unit, reflectors become steeper in the eastern and western part of the seismic line, suggesting clinostratification in a prograding sedimentary wedge. In general, Seismic facies 3 shows lower amplitude and higher frequency with respect to Seismic facies 2. The seismic facies rapidly thickens eastwards and westwards. Seismic facies 3 shows changes in thickness and deformation of the reflectors close to some faults, documenting syndepositional tectonic activity. Most of the faults appear to have been active between the end of the deposition of Seismic facies 2 and the beginning of the deposition of Seismic facies 3. Fault recognition is complex when faults cross Seismic facies 1 (Hercynian granitoids). Their presence is deduced by throw in the overlying reflectors (Seismic facies 2 and 3), which suggests steep fault surfaces. According to the deduced displacement, these faults have both normal and reverse throws. The coherent distribution of the faults, their geometry and their displacement are similar to those observed for outcropping faults in Northern Sardinia and central Corsica, where NE-SW and E-W oriented Oligocene strike slip tectonics dominates (CARMIGNANI *et alii*, 1992; PASCI, 1997; OGGIANO *et alii*, 2008), with documented occurrence of compressional and extensional events also along the same fault (e.g.; Nuoro Fault, Tavolara Fault; OGGIANO *et alii*, 2008).

4.2) Geological reconstruction

The interpretation of the seismic profile is based upon the identification of the three major seismic facies (divided in subfacies) and the discussion of their possible similarities with the lithological units cropping out in southern Corsica and northern Sardinia.

Reflectors are frequently displaced by faults along the seismic line. Faults are identified in Seismic facies 2 (where the displacement of reflectors is evident) and 3, whereas in homogeneous Seismic facies 1 their identification is complex, due to the absence of identifiable displaced reflectors. The steep fault surfaces, the type of displacement (both normal and reverse) and the possible connection of different faults at depth suggest they are strike slip faults, producing both positive and negative flower structures. The existence of major strike slip faults is documented in outcrop by the presence of SW-NE trending fault systems (PASCI, 1997), with an extensional component which controlled the development of depressions where Neogene to Quaternary deposits accumulated. The constant distance of reflectors across these faults in Seismic facies 2 indicate that these faults were active after its deposition. A limited number of faults crosses the erosional surface at the top of seismic facies 2 and displaces reflectors in Seismic facies 3, suggesting a partial reactivation of existing faults or a new tectonic event. The kinematic interpretation of the fault systems identified in the re-processed seismic line is different from that proposed in a previous interpretation (FINETTI *et alii*, 2005), where low-angle thrust surfaces, cut by later subvertical faults (mostly strike-slip faults), had been recognized. The common and diffuse overthrust of basement above the sedimentary cover (in the interpretation by FINETTI *et alii*, 2005) cannot be confirmed in the re-processed seismic line. Although local overthrusts with limited throw can be observed in outcrop (OGGIANO *et alii*, 1995), they are rare and related to the Cenozoic strike slip tectonics.

In the central part of the seismic line (Bonifacio Strait) Seismic facies 1 is close to the sea-bottom: this part of the seismic line corresponds to the area of outcrop of Hercynian intrusive rocks, rhyolites and, locally, metamorphic basement, both in southern Corsica and northern Sardinia. This observation and the characteristics of the seismic facies indicate that Seismic facies 1 represents the Hercynian basement of the Corso-Sardinia block (including intrusive rocks, volcanic flows and metamorphic basement), non-conformably covered by a sedimentary succession. Seismic facies 2, preserved in the western part of the seismic line, is characterized by a general parallel reflection configuration, with amplitude and continuity higher in its middle-upper part. Within this facies, a very high amplitude reflector is observed in the middle part of the unit, suggesting a strong difference of acoustic impedance at a specific stratigraphic level. The reflection configuration of Seismic facies 2 clearly indicates a sedimentary origin of this lithological association with limited lateral environmental changes, whereas a major lithological change corresponds to the high-amplitude reflector. The reflectors in Seismic facies 2 gradually pinch out toward the east (COSTAMAGNA, 2016), suggesting a gradual onlap of this sedimentary succession on the Hercynian basement high (Seismic facies 1). Considering the onlap relationships with the Hercynian substrate and the erosional surface below Seismic facies 3, the Seismic facies 2 is considered to represent the seaward continuation of the Mesozoic units of the Nurra region. In detail, within Seismic facies 2 it is possible to identify a lower interval with relatively discontinuous reflectors (2a) and an upper part with laterally continuous reflectors (2b), containing a very high amplitude, continuous reflector (2c). Seismic facies 2a could represent the Triassic succession whereas Seismic facies 2b is considered to represent the Jurassic-Lower Cretaceous bedded units. The high-amplitude reflectors (2c) document a major physical and lithological contact: in the Nurra succession the two strong changes in the acoustic impedance are interpreted as the lower and upper boundary of the Purbekian Marls (50-60 m thick). Seismic facies 2, at shallower depth, is less defined in the central-eastern part of the seismic profile: this fact can be related to acquisition or, doubtfully, to the presence of a possible angular unconformity in the Cretaceous succession (base of Seismic faces 2d?). The reflector at the top of Seismic facies 2 documents an erosional truncation to the west, where Seismic facies 2 is covered by clinostratified deposits of Seismic facies 3.

Previous interpretation of this and other (mostly from ENI) seismic profiles by THOMAS & GENNESSEAUX (1986**)** and FINETTI *et alii* (2005) do not clearly recognize a Mesozoic succession (FINETTI *et alii*, 2005, suggest a presence of a thin Mesozoic succession in one of the ENI lines) and refer most of the sedimentary succession to the Cenozoic. Seismic facies 2 clearly pre-dates the tectonic activity that characterized the identification of the Cenozoic basins in Northern Sardinia. The reprocessing and interpretation of the CROP M-2A/I profile thus allows the probable identification, for the first time, of Mesozoic sediments in the Bonifacio Strait. Close to the Asinara Island, THOMAS & GENNESSEAUX (1986) recognize the presence of a thick Cenozoic succession, directly resting on the Hercynian basement. Considering the position of the lines interpreted by THOMAS & GENNESSEAUX (1986), it is likely that the Mesozoic succession, preserved to the east, is not crossed by their lines that are located westward with respect to the buried Mesozoic succession.

Seismic facies 3 is represented by clinostratified converging reflectors, prograding over both Seismic facies 2 and 1. The geometry of the reflectors (locally gently folded) suggests syndepositional activity: some faults are sealed by Seismic facies 3, whereas others were still active at the beginning of the deposition of Seismic facies 3. Most of the Seismic facies 3 is characterized by continuous, planar to clinostratified, high-frequency and high-amplitude reflectors. In detail, Seismic facies 3 can be separated into three subfacies (Fig. 7). The lowermost part, mostly preserved in depressions in the Hercynian basement both in the eastern and western part of the line, is characterized by a more homogeneous seismic facies. This sub-facies is covered by prograding units, both eastward and westward, with similar internal architecture. Nevertheless, this seismic sub-facies is tilted eastward on the Tyrrhenian side of the seismic profile, whereas it is horizontal on the Balearic side. This geometry suggests a post-depositional tilting of this succession eastward, likely related to the Tyrrhenian extension (a rift stage is well documented in seismic profiles; SARTORI *et alii*, 2004), younger than the extension on the Balearic side. The proposed interpretation suggests that the seismic facies filling basement depressions could represent the Oligocene-Lower Miocene volcanoclastic and coarse-grained succession (Seismic facies 3a), whereas the overlying westward prograding unit (Seismic facies 3b) is interpreted as the Upper Miocene succession, likely consisting of mixed carbonate to siliciclastic deposits, analogue to those cropping out extensively in Northern Sardinia and Southern Corsica (Bonifacio Basin). Seismic facies 3b pinches out toward the central part of the seismic profile. The situation is probably different on the eastern part of the seismic profile. Here a first tilted unit can be observed, later followed by the progradation of an overlying seismic facies. Geological constraints indicate that the opening of the Tyrrhenian basin occurred since the end of the Miocene (the oldest-known basaltic crust of Tyrrhenian Sea, eastern rim of Vavilov bathyal plain drilled in DSDP well-373 is Late Tortonian/Early Messinian in age: SAVELLI, 2015) , therefore after the deposition of the Seismic facies 3b, interpreted as the Miocene succession. Consequently, the post-tilting, prograding wedge toward the east (Seismic facies 3c) should be younger (Pliocene-Quaternary) than the westward prograding unit (Seismic facies 3b). The presence of Mesozoic sediments (preserved in central Sardinia) is not suggested by the seismic facies identified in the seismic profile. If present, these sediments should be preserved more to the east (DOGLIONI *et alii*, 2004). Erosional and onlap/downlap surfaces within Seismic facies 3 reflect the possible effects of tectonics or base level changes.

According to the seismic evidence, no major expression of the Messinian unconformity is observed in Seismic facies 3b.

5) Discussion: geological evolution

The geological evolution of the succession crossed by the M-2A/I seismic profile indicates the presence of a persisting Hercynian high in the central part of the seismic profile that is covered in the central and eastern part directly by prograding Cenozoic sediments. In the western part of the seismic profile a bedded unit is present between the Hercynian basement and the Cenozoic succession: this unit is interpreted as a subsurface equivalent of the Mesozoic succession of the Nurra region, according to its internal architecture. The onlap geometry of the Mesozoic succession confirms that the Hercynian high persisted throughout the Mesozoic, being gradually transgressed by sediment since the Triassic (Late Permian?) in the west and only in the Late Jurassic (DIENI & MASSARI, 1985; LANFRANCHI *et alii*, 2011) to the East (Tavolara and Orosei carbonates, not observed in the seismic line). Field data (Anglona region) confirm the gradual onlap of the Mesozoic sediments on the Hercynian high. The Hercynian basement is uplifted in the westernmost part of the seismic profile along an E-dipping normal fault. Here the seismic facies are poorly defined: on this uplifted area, the Mesozoic succession is probably deeply eroded or absent. The proposed interpretation suggests that part of the Mesozoic succession may be probably preserved in small fault-controlled depressions. This high may represent the northward continuation of the ridge of the Asinara Island. In southern Corsica there is no evidence of preserved Mesozoic sediments.

The seismic profile does not show a recognisable evidence of the major Cretaceous unconformity that can be recognized in the Nurra region, where an angular unconformity of 20-30° is observed in outcrop. Dubitatively, a possible angular unconformity could be placed at the base of Seismic facies 2d. The nature of this angular unconformity is still debated. The Mesozoic succession is poorly deformed but deeply eroded, documenting a post-Cretaceous erosional event, probably associated with a regional uplift. In post-Cretaceous time a strike slip fault system developed, as documented by negative and positive (less common) flower structures. Cenozoic strike slip tectonics is well documented in outcrop (PASCI, 1997). The tectonic activity probably continued also during the deposition of the overlying units, as suggested by the geometry of the seismic facies. Deposition after the post-Cretaceous erosion starts in depressions with volcanic and continental facies (mostly Oligocene in age), extensively cropping out in northern Sardinia (Sassari and Logoduro Basin). This unit is eventually covered by a thick wedge of sediments that onlap the Hercynian high from west and east: the similar facies on the east and west of the Hercynian high probably represent prograding sedimentary wedges of different age (mostly Miocene toward the Balearic basin, mostly Pliocene-Pleistocene toward the Tyrrhenian Sea).

The tectonic history of the study area is characterized by a dominance of strike slip and extensional tectonics (clearly recognized in outcrop; CARMIGNANI *et alii*, 1992; PASCI, 1997; OGGIANO *et alii*, 2008), whereas evidence of E-verging thrusting, cannot be observed in the re-processed seismic profile.

6) Conclusions

The reprocessed CROP M-2A/I seismic profile was interpreted after a detailed study of the units cropping out along the coast of Southern Corsica and Northern Sardinia. The re-processing procedure improved the signal-to-noise ratio and the resolution of the seismic image, allowing the identification of different seismic facies: regional geology and the geometry of the reflectors in the re-processed lines suggest a correspondence between geological units cropping out in the surroundings of the seismic line and the seismic facies. The availability of a newly processed “old” line (applying up to date geophysical techniques) and improved knowledge of the regional geology supported a new interpretation of the existing CROP M-2A/I seismic profile in its shallowest part. The new interpretation suggests the presence of a Mesozoic succession, previously undescribed, on the Balearic side of the Corso-Sardinia block, gradually onlapping the Variscan basement (granites and metamorphic rocks) toward the east. The Mesozoic succession is unconformably covered (along an evident erosional surface) by Cenozoic units, according to the constraints from the outcrops preserved north and south of the seismic line. Tectonic activity is mostly recorded by strike slip faults (identified according to the geometry of the interpreted fault planes and in agreement with outcrop studies by previous authors), frequently with a transtensional component.

The re-processing of the seismic line with the proposed work-flow significantly improved the quality of the seismic image with respect to that obtained in the past. In addition, the improved regional geological knowledge permitted a more reliable correlation of the seismic facies with the lithological units exposed on land. The results obtained by this joint effort clearly indicate that the re-processing of existing seismic lines, partly «forgotten» after their original use, represents an important resource for improving the geological knowledge without acquiring new, expensive seismic data.

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Figures

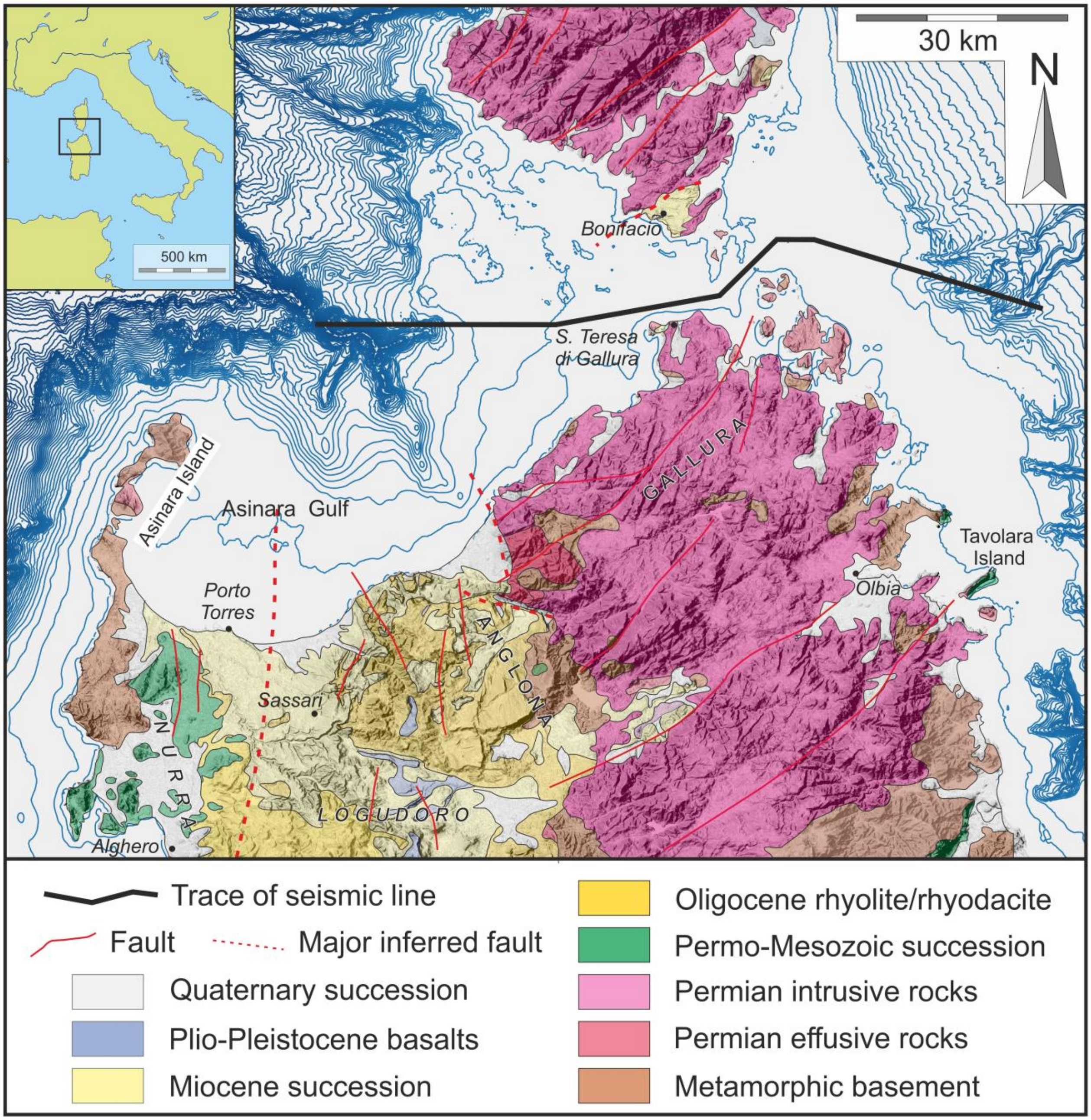

Figure 1) Location map of the marine seismic profile M-2A/I (black line), approximately E-W oriented, lying between Sardinia (South) and Corsica (North) island. Geological map modified from CARMIGNANI *et alii*, 2001.

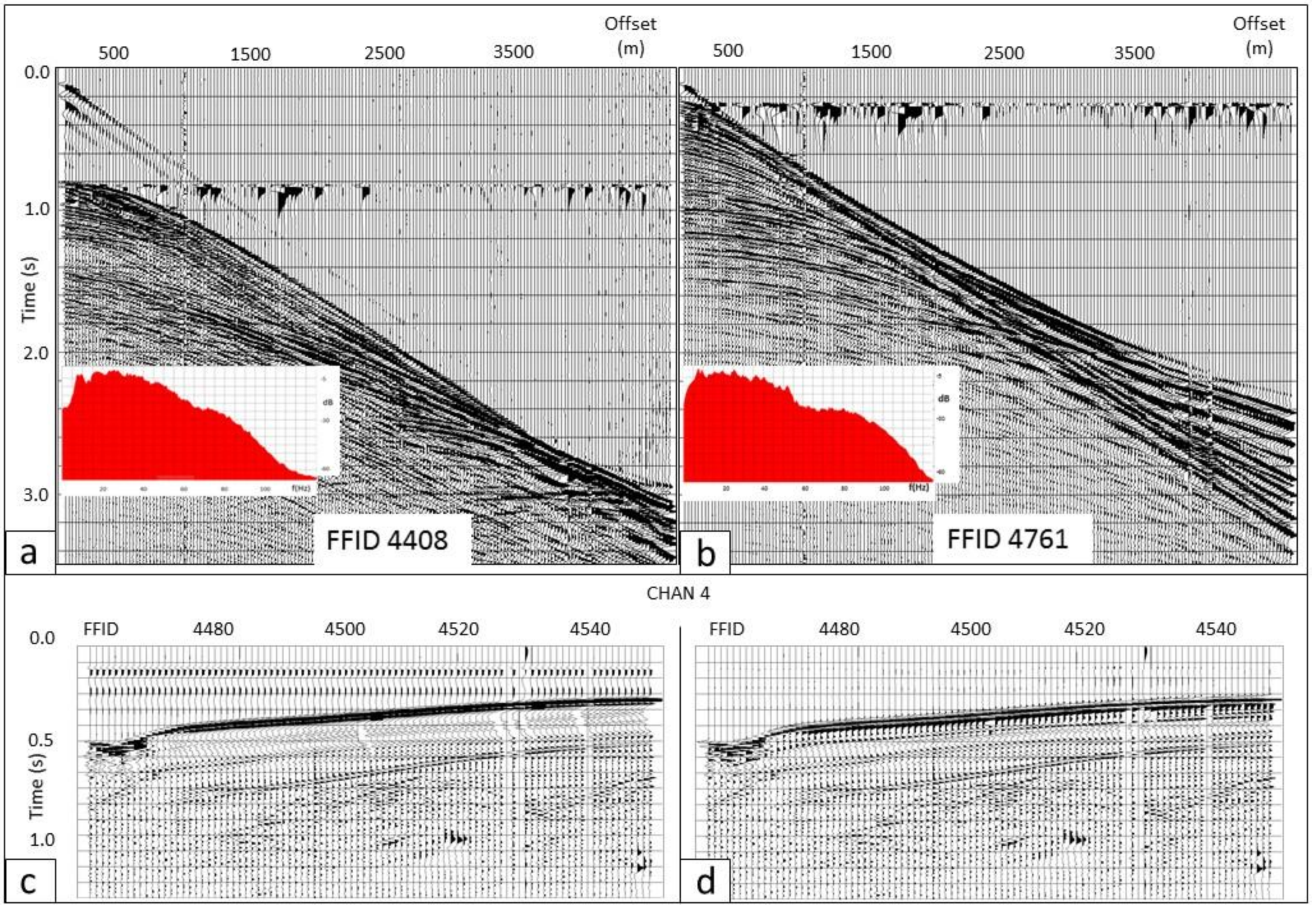

Figure 2) a) The FFID 4408 shot gather is placed near the western end of the seismic line. Note the bursts of noise that originate at the sea bottom reflection located at about 0.8 s TWT. In the inset, the amplitude spectrum characterised by a bandwidth between 5-65 Hz at -25 dB is displayed. b) The FFID 4761 gather, located approximately 17.5 km East of the 4408 shot, is characterised by a shallower sea bottom reflection at about 0.2 s TWT. In this case, the secondary lobes of the source wavelet interfere with the sea-bottom reflection as a consequence of the shallow bathymetry. In the inset, the amplitude spectrum of the 4761 shot is shown. c) Raw data of the channel number 4 (FFID 4460-4550) at the beginning of the line. The burst of noise that starts in correspondence of the sea bed arrival is responsible for the negative values observed for approximately 200 ms after the sea bed reflection (i.e.; no black wiggle area). Note also the secondary lobe of the source wavelet that interferes with the shallow sea bed reflection. d) The noises are largely attenuated after the estimation and subtraction process based on the cross-correlation procedure.

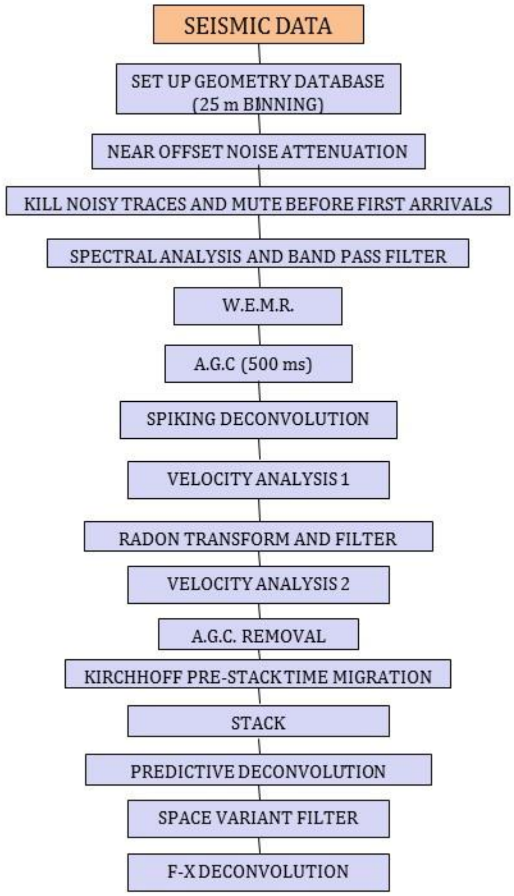

Figure 3

Figure 3) Reprocessing flow chart of the M-2A/I profile.

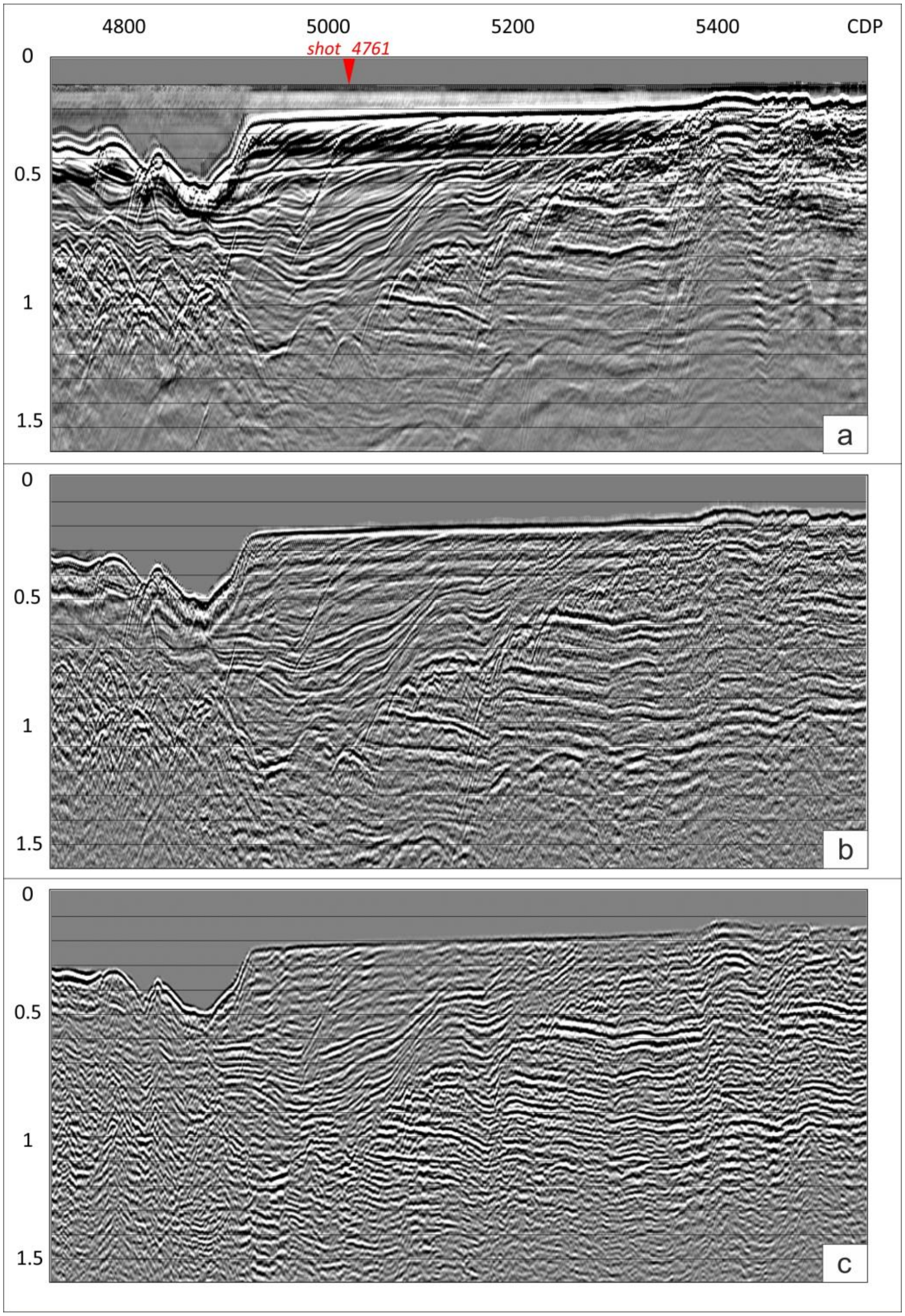

Figure 4) Part of the stack section on the western side built using the final velocity field: a) raw seismic data (only band-pass filtered) displayed for comparison purposes (the red triangle shows the position of the 4761 shot); b) stack of the seismic data as in a) after the application of the Radon transform (AGC not removed). Note the reduced reverberations, in particular the sea-bottom multiple between 0.4 and 0.5 s, and the better visibility of the deeper events due to the gain applied; c) final pre-stack time-migrated section. The pre-stack time migration collapses the many diffractions visible on the stacked section in a) and b), allowing a better definition of the location of the contact between different lithologies.

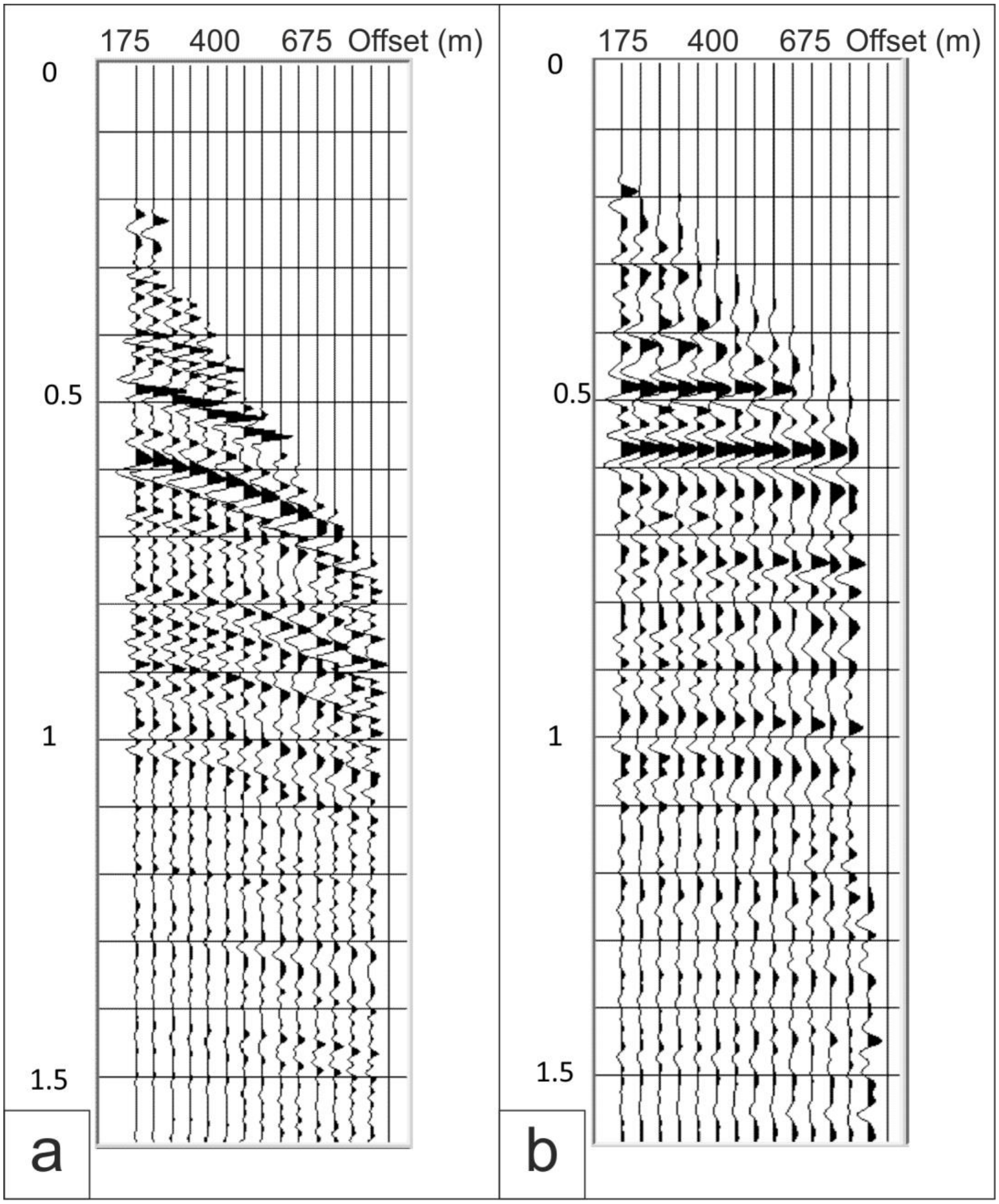

Figure 5) CDP gather number 5291 before (a) and after (b) the pre-stack time migration. In this seismic domain, the alignment of the events is an indicator of the good estimate of the velocity field in time (root mean square velocity). As can be observed, the alignment can be considered satisfactory in particular for the strong events at 0.5 and 0.6 s TWT, which reflect a major change in the acoustic impedance and are interpreted as due to the marly Purbekian interval within the carbonate succession.

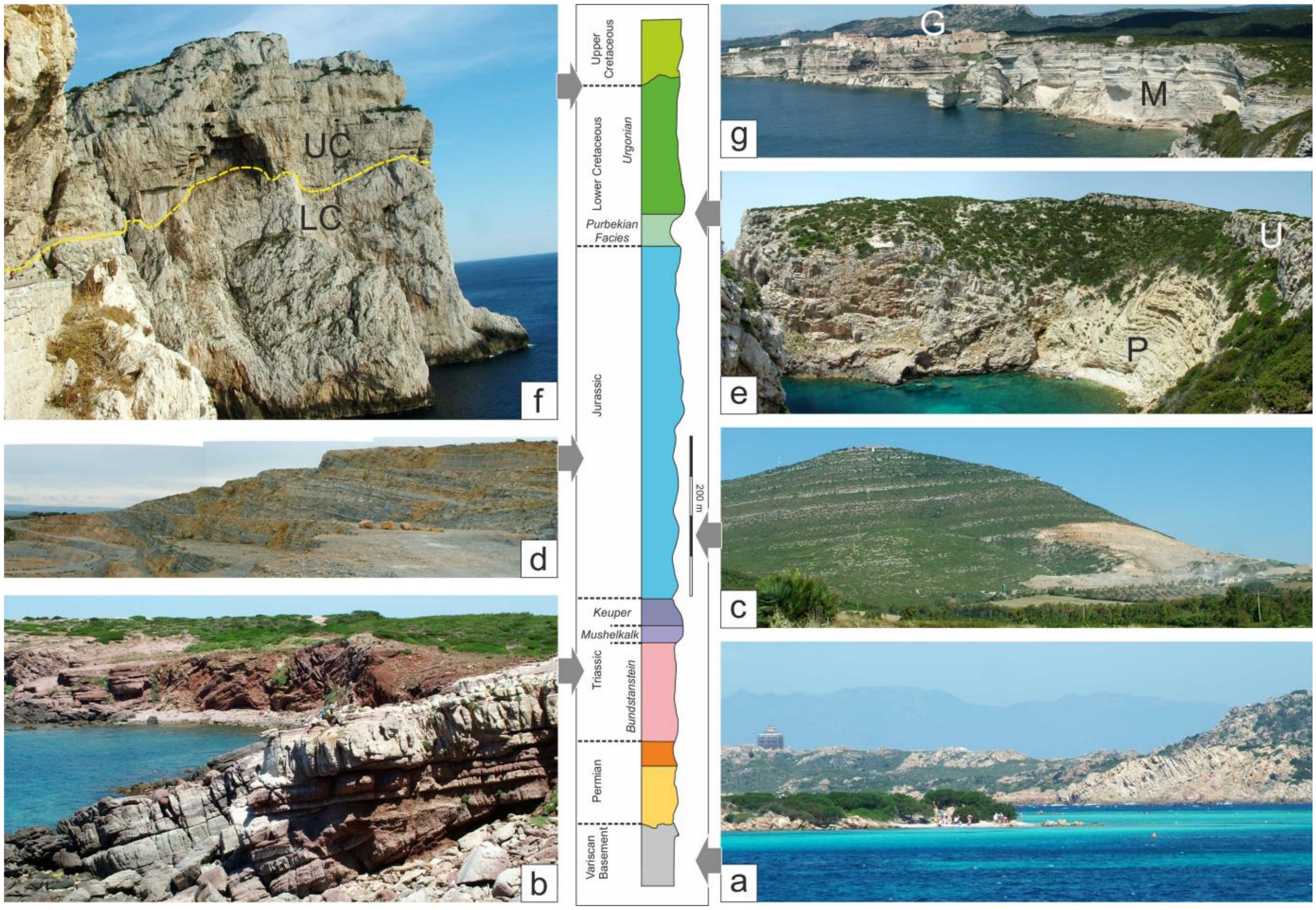

Figure 6) Outcrops in northern Sardinia and southern Corsica, in the surroundings of the seismic profile M-2A/I: a) Hercynian granitoids along the northern coast of Sardinia; b) Permo-Triassic siliciclastic succession directly covering the Hercynian metamorphic rocks and Lower Permian granites and volcanic rocks; c; d) Jurassic succession of the Nurra: the succession mostly consists of bedded alternation of limestone and marls; e) Purbekian interval (P), consisting of marls and limestone (about 60 m thick) between more massive carbonate units; f) angular unconformity between the Lower Cretaceous (LC) and Upper Cretaceous (UC)carbonate platform facies; g) Miocene succession of the Bonifacio basin (Southern Corsica). In the back, Hercynian granitoid (G) borders the depression filled by shallow-water, flat-lying Miocene carbonates and mixed sediments (M).

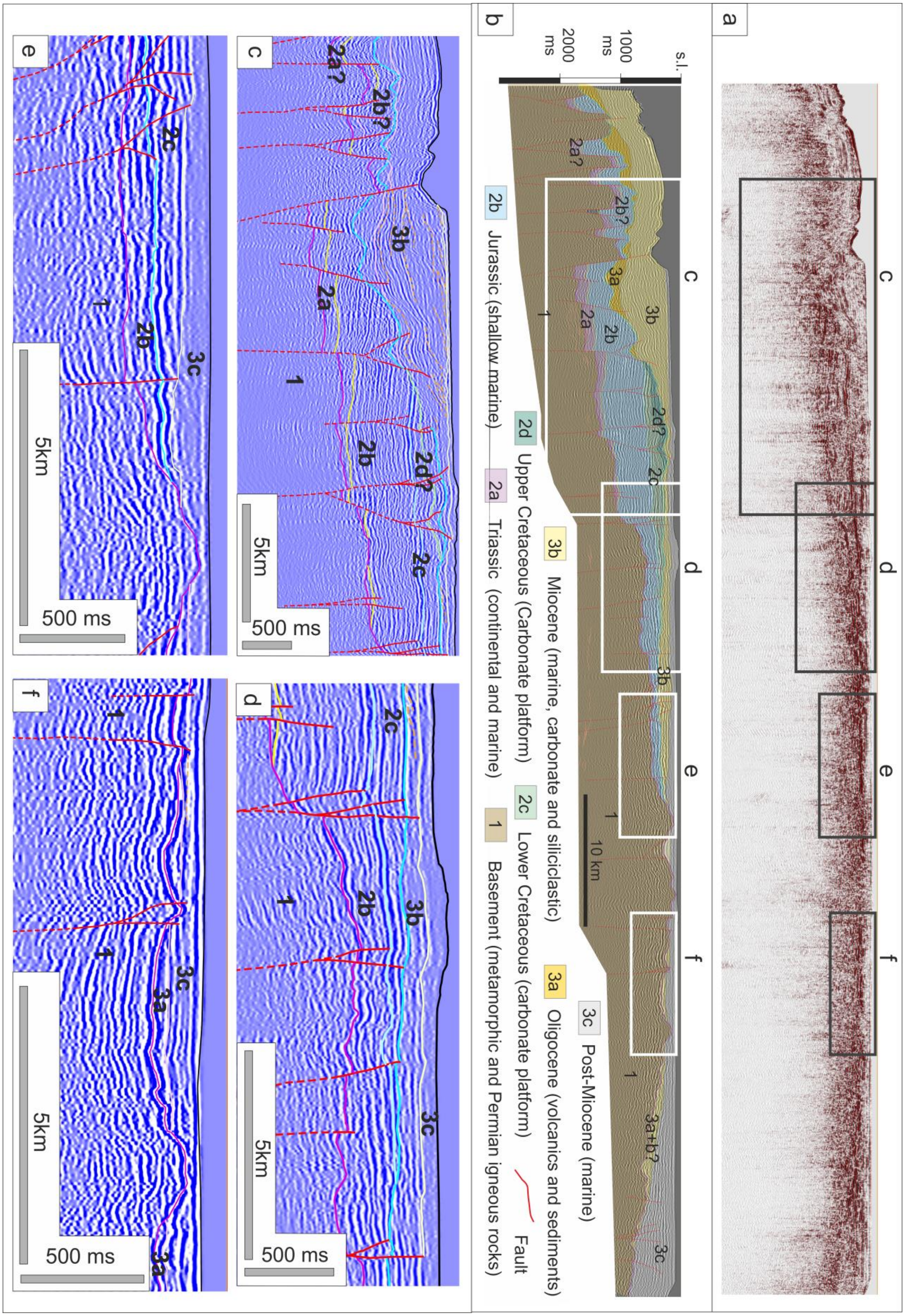
a
b
c
d
e
f
s.l.
1000 ms
2000 ms
10 km
5km
500 ms
3c Post-Miocene (marine)
3b Miocene (marine, carbonate and siliciclastic)
3a Oligocene (volcanics and sediments)
2d Upper Cretaceous (Carbonate platform)
2c Lower Cretaceous (carbonate platform)
2b Jurassic (shallow marine)
2a Triassic (continental and marine)
1 Basement (metamorphic and Permian igneous rocks)
Fault

Figure 7 (previous page) Seismic profile after the reprocessing (a) and proposed geological interpretation (b), with details of selected parts of the profile: (c) detail of the erosional surface between the Mesozoic succession (Seismic facies 2a to 2d) and the overlying Miocene succession (Seismic facies 3b): the high-amplitude reflector between Seismic facies 2b and 2c is interpreted as the subsurface equivalent of the Purbekian marls of the Nurra; the surface between Seismic facies 2c and Seismic facies 2d could dubitatively correspond to the angular unconformity between lower and upper Cretaceous observed in the Nurra region; (d) detail of the onlap geometry of the Mesozoic succession (Seismic facies 2b) on the granites of the Hercynian high (Seismic facies 1): steep, strike slip faults are suggested by reflector discontinuities; (e) easternmost lateral closure of the Mesozoic succession (2a and 2b) on a granite high; (f) possible Ologocene volcanics (Seismic facies 3a) filling depression in the Hercynian granites (Seismic facies 1), covered by sediments (Seismic facies 3c), probably post-Miocene, dipping toward the Tyrrhenian Sea (interpretation produced with MOVE).

Recording Parameters	
Contractor	O.G.S.
Vessel	OGS Explora
Record length	17000 ms
Filter L.C.	OUT
Filter H.C.	77Hz 70 dB/OCT
Sampling Interval	4 ms
Coverage	45
Source	
Energy Source	Airgun
Source Depth	8 m
Shot Interval	50 m
N. of Subarrays	9
N. of Gun for Subarray	8
Total Volume	4906 cu inc
Cable	
Single Streamer	4500 m
N. of Groups	180
Hydrophones per Group	32
Group Interval	25 m
Cable Depth	14 m
Minimum offset	150 m

Table 1) Acquisition parameters of the seismic line M-2A/I.