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The contribution of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) to "Adria LithosPHere investigAtion (ALPHA)" active seismic experiment

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Abstract

During the winter 2012, from 20 January to 4 February, the German oceanographic FS METEOR cruise (M86/3) took place in the central-southern Adriatic Sea in the frame of "Adria LithosPHere InvestigAtion" (ALPHA [Kopp et al., 2013]). The primary goal of the project was high-resolution tomographic imaging of the crust and lithospheric mantle underneath the southern Adriatic Sea, the Apulia eastern margin and the external zone of the Dinaric thrust-belt by collecting offshore-onshore seismic data along three multi-fold wide-aperture profiles. The definition of reliable velocity models of the Adriatic lithosphere was considered crucial for a better understanding of the structure, fragmentation, geodynamic evolution, and seismotectonics of the Adria-Apulia microplates.

The ALPHA Project was coordinated by Helmholtz Centre for Ocean Research Kiel, Germany (GEOMAR), former Leibniz Institute of Marine Sciences (German: Leibniz-Institut für Meereswissenschaften, IFM-GEOMAR) and conducted in close cooperation with different European institutions of Germany, Albania, Croatia, Italy and Montenegro. The Istituto Nazionale di Geofisica Vulcanologia (INGV) participated by deploying land stations along two transects in the Apulia and Gargano Promontory to extend westwards the seismic profiles. The primary goal was to record shallow-to-deep seismic phases travelling along the transition between the Adriatic basin and the Apulia foreland.

In this paper we present the field work related to the two Italian onshore transects, the recorded data, and the processing flow developed to highlight crustal and mantle refractions and wide-angle reflections.

1. The ALPHA Project and the 2012 active seismic survey

The "Adria LithosPHere InvestigAtion" (ALPHA [Kopp et al., 2013]) active seismic experiment was performed during the winter 2012 (20 January – 04 February) in the central-southern Adriatic Sea and surrounding onshore regions. The ALPHA Project was coordinated by GEOMAR (Kiel, Germany) and conducted in close cooperation with German and European institutions (GFZ, ETH, Seismological Observatory of Montenegro, University of Tirana, Istituto Nazionale di Geofisica e Vulcanologia - INGV, Istituto di Scienze Marine of the Centro Nazionale delle Ricerche – ISMAR). The primary goal of the experiment was high-resolution tomographic imaging of the southern Adriatic crust and lithosphere by using active source marine data. Indeed, the lithospheric structure of Adria still remains mainly unresolved because geophysical and seismic data were mainly acquired along the Periadriatic regions. Consequently, various models of tectonic fragmentation and recent kinematic evolution have been proposed [Bennett et al., 2008].

The project aimed at filling this information gap by collecting mainly three multi-fold wide-aperture seismic refraction profiles in the framework of FS METEOR cruise M86/3 in the central-southern Adriatic Sea (Figure 1). The first profile (P01) entirely ran NW-SE in the middle of the central-southern Adriatic Sea intercepting the Gargano-Dubrovnik shear zone that presumably separates the Adria microplate to the north from the Apulia microplate to the south [D'Agostino et al., 2008]. The remaining two profiles extended SW-NE from the coastline of the Apulia (P02) and W-E from the Gargano Promontory (P03) to the Dinaric external front across the southern Adriatic sea (e.g. across the Apulia microplate). A total number of 36 Ocean Bottom Hydrophones (OBH) and Seismometers (OBS) were deployed along each profile with an average spacing of ~5 km (P02) and ~6.5 km (P01 and P03). The OBH/OBS recorded the signals produced by an array of 6 airguns for a total volume of 84 litres. The approximate shooting interval was 110 m (P02) and 140 m (P01 and P03). The resulting offshore profiles measured a length of 245 km (P01), 180 km (P02) and 220 km (P03). During the acquisition of profiles P02 and P03, land stations were installed both in Italy and in Montenegro/Albania to record the offshore airgun shots. On-land deployments aimed at extending further the maximum offset of observation that is a key parameter to record deep phases from the crust-mantle boundary (Pn refractions and PmP post-critical reflections) and to obtain information on the crustal structure in the Periadriatic zones.

Profiles P02 and P03 were extended westward by INGV's field team that deployed short-period seismic stations across the Apulia and Gargano Promontory, respectively (Figure 1). The goal was to record shallow-to-deep phases travelling across the transition between the Adriatic basin and the Apulia foreland.

In this manuscript we illustrate: *(i)* the onshore experiment, *(ii)* the processing flow developed to improve data quality and highlight crustal and mantle refractions and wide-angle reflections, *(iii)* describe the characteristics of first arrivals and main wide-angle reflected phases identified on the elaborated record sections. In particular, we show that a careful frequency-time analysis of the data allowed to design optimal filters aimed at identifying very weak first arrivals in the intermediate-large offset range. These steps of the developed processing flow were of key importance because the recognition of primary head waves on the record sections was hampered by shadow zones associated to low-Vp layers placed at the base of the Apulian sedimentary cover.

2. The INGV temporary seismic network: instrumentation and deployment

We installed a total of thirteen temporary seismic stations along P02 and P03 profiles in Apulia and in the Gargano Promontory. The deployment has been done in two stages and in close coordination with the offshore activities:

a) the first transect of eight seismic stations was installed in Apulia along the onshore continuation of the offshore profile P02 that strikes NE-SW. The transect extends from the Adriatic coastline (to the north of Brindisi) to the Taranto gulf (to the south of Taranto; see Figure 2);

b) the second deployment consisted of five stations installed in the Gargano Promontory along the onshore continuation of the offshore profile P03 that trends E-W (see Figure 3).

Potential recording sites were preliminarily identified inside a narrow strip surrounding the onshore continuation of each profile by the analysis of aerial photos and geologic maps. Then, the definitive sites were chosen after field inspections in the area of interest. All stations were deployed on limestone outcrops and far from sources of cultural noise. To respect these conditions, the station spacing is not regular but this allowed recording of very good quality data as described in the next paragraphs.

2.1 The onshore segment of profile P02

The onshore segment of profile P02 is approximately 55 km long and has an average station spacing of about 6 km. Stations are 0.1 to 2.7 km distant from the onshore continuation of the profile (yellow line in Figure 2). The first station (R1) was installed 2.7 km to the west of the Adriatic coastline, the last one (R8) at a distance of 5 km to the east of the Ionian coastline. Distances from the closest airgun shot were: 7.8 km (P02_R1), 15.5 km (P02_R2), 22.0 km (P02_R3), 27.2 km (P02_R4), 35.1 km (P02_R5), 40.8 km (P02_R6), 47.1 km (P02_R7) and 55.6 (P02_R8). Station elevations range from 20 m to 210 m.

All stations started recording prior to the expected shooting that would have begun on 20 January from the Montenegro side of the profile. Due to the adverse weather conditions in the Adriatic Sea, the shooting was delayed until 10:00 a.m. of 22 January and ended at 11:46 a.m. of 23 January. The average shot spacing was 114 m. The sea floor depth along profile P02 is reported in Figure 4.

2.2 The onshore segment of profile P03

The onshore segment of profile P03 is about 33 km long. Station spacing was very irregular (the station interval ranges from 2 to 7 km) due to the logistic difficulties and environmental conditions of the Gargano mountainous area (yellow line in Figure 3). The first station (R1) was located 2.3 km to the west of the coastline, the farther one (R5) at a distance of 23.7 km. Distances from the closest airgun shot were: 11.7 km (P03_R1), 17.1 km (P03_R2), 24.6 km (P03_R3), 26.6 km (P03_R4), 33.1 km (P03_R5). Station elevations range from 104 m to 754 m. All stations started recording prior to the shooting that started from

the Gargano coastline at 07:28 a.m. of 27 January and ended at 11:22 a.m. of 28 January. The average source spacing was 140 m. The sea floor depth along profile P03 is reported in Figure 4.

2.3 The instrumentation

We used a Reftek-130 24 bit digitizer (www.reftek.com) equipped with three components Lennartz LE-3Dlite seismometer with a dominant period of 1s (http://www.lennartz-electronic.de) and a GPS antenna. Each station was equipped with a battery of 40 Ah, sufficient for ten days of acquisition and removable disks for local data storage.

The coordinates of the two final profile configurations are listed in Table 1 (profile P02) and Table 2 (profile P03). The sampling rate was fixed at 8 ms. Each seismometer was buried in a hole and deployed on a concrete base.

3. Data analysis and description

3.1 Data processing

In order to define a processing flow aimed at enhancing the main crustal phases, post-critical wide-angle reflections (PmP) and refractions (Pn) generated at the crust-mantle boundary, we first performed a frequency-time analysis on selected good-quality traces by using the Gabor transform-like multi-filter analysis technique [Dziewonski et al., 1969]. We used the Gabor transform algorithm available in the open source software package Seismic Unix developed for the processing of active and passive seismic data by the Center for Wave Phenomena at the Colorado School of Mines [Cohen and Stockwell, 2008]. This algorithm provides a multi-filter representation of the instantaneous amplitude of seismic data in the time-frequency domain. An input waveform is passed through an ensemble of Gaussian filters to produce a collection of seismic traces, each representing a discrete frequency range in the input data. For each of these narrow bandwidth traces, the instantaneous amplitude is related to the real part of the analytic trace, that is just the original narrow bandwidth trace, and to its imaginary part, also called the *quadrature* trace, that is computed by taking the Hilbert transform of the real part. Therefore, after computing the instantaneous amplitude of all narrow bandwidth traces, the output is represented as a function of time and frequency.

We performed the Gabor transform-like multi-filter analysis on selected seismograms extracted from the vertical component record sections arranged in Common Receiver Gather (CRGs). For each seismic station and for different offset ranges, we selected seismic traces that satisfy two criteria: *(i)* best signal-to-noise ratio, *(ii)* the arrival of the target phase (i.e., primary refracted waves or wide-angle reflections) is well separated from secondary phases. The analysis was performed on 10 selected traces at least for each CRGs. Based on the frequency content of the target seismic phases estimated by multi-filter analysis, we designed optimal band-pass filters depending on the offset range and target phase.

We applied an automatic gain (RMS-type function) to outline very weak first arrivals that precede large-amplitude post-critical reflections. Traces were tapered and then plotted with reduced times using different velocities to discriminate crustal and mantle arrivals. All the processing was performed by using the Seismic Unix free software package.

Then, vertical component CRGs were classified according to the signal-to-noise ratio, amplitude, lateral coherence and continuity of the main phases (e.g. first arrivals travelling in sedimentary layers and through the mid- and lower-crust, wide-angle crustal reflections, PmP reflections, Pn refractions).

3.2 Profile P02

All record sections, but CRG8, show usable seismic phases, which are more or less clear depending on the distance from the coastline and local site conditions.

CRG3, located at 22014 m from the closest source, can be considered representative of the onshore seismic data recorded in Apulia (Figure 5). In the following we describe the main phases identified on the record section at increasing source-receiver distances.

First arrivals with apparent velocity comprised between 5.5 and 7.0 km/s are evident up to 50 km offset (Figure 6). These arrivals can be interpreted as refracted waves travelling inside the Meso-Cenozoic carbonate multilayer of the Apulia Platform, which has Vp around 5.5-6.0 km/s in the limestone sequences and Vp around 6.5-6.7 km/s in the basal Triassic evaporites (see the Puglia 1 well sonic log reported by Improta et al., [2000]). Frequency content of these shallow refractions ranges from 2 to 10 Hz.

Beyond 50 km offset, data show an evident decrease of the signal-to-noise ratio (Figure 6). Amplitude and lateral coherence of first arrivals and early reflections are low, while apparent velocities of these arrivals decrease rapidly toward the east (apparent velocity for first arrivals decreases down to 4.5-5.0 km/s). This change in data quality correlates to the abrupt deepening of the sea floor that marks the transition between the Apulia Platform and the Adriatic basin (between shot number 1300 and 1200; Figure 4). In addition, the very low amplitude and apparent velocities of first arrivals may be related to lateral and/or vertical velocity heterogeneities within the Apulian sedimentary cover. Indeed, we expect a lateral Vp change between Mesozoic platform carbonates and coeval pelagic limestones in correspondence to the Apulia steep margin. Furthermore, it is well known that the Apulia Platform overlies a low velocity layer consisting of Permo-Triassic clastic sediments drilled at the base of the Triassic evaporites (Vp around 5.0-5.5 km/s; see Puglia 1 well in Improta et al. [2000]). Such a low-Vp layer should cause a shadow zone in the first-arrival branch, a feature that reconciles with the abrupt decrease in amplitude and apparent velocity for shallow refractions observed between 50 and 60 km offset (Figure 6).

Weak first arrivals with an apparent velocity larger than 7.0 km/s are visible between 65 and 70 km offset with corrected traveltimes around 4.5 s (for reduction velocity of 8 km/s, Figure 5) or 3.5 s (for a reduction velocity of 7 km/s, Figure 6). These arrivals may represent refractions from the top of the crystalline basement, thereby below the low-Vp layer drilled under the base of the Apulia Platform [Improta et al., 2000].

The offset range 70-80 km corresponds to a shadow zone (Figure 7). Even if data quality is quite good, first arrivals are barely visible and coherent arrivals (with apparent velocities of 6.5-7.0 km/s) appear for reduced times larger than 5.5-6.0 s (crustal refracted and wide-angle reflection waves). This shadow zone may be indicative of a low Vp layer or of a low velocity gradient zone in the mid crust. These crustal phases are visible up to 110 km and converge towards large amplitude PmP reflections. The mantle wide-angle reflections exhibit excellent lateral coherence and continuity from 70 km to 120 km and have traveltimes increasing with offset from 7.5 to 8.5 s (reduced times using a reduction velocity of 8 km/s; see Figure 7).

From 80 to 110 km offset, the first P-pulses could correspond to very weak and discontinuous arrivals outlined by blue arrows in Figure 7. This interpretation is based on data recorded by station P2_R2 located at 15503 m from the closest shot (Figure 8). Section CRG2 shows a weak but lateral continuous refracted phase between 80-102 km with apparent velocities of 6.8-7.0 km/s and reduced traveltimes of 4.2-4.5 s (see Figure 9). These crustal refractions again precede deeper crustal refracted phases that in turn tend asymptotically to large amplitude PmP reflections with excellent lateral coherence and continuity from 70 km to 120 km offset (Figures 9 and 10). Frequency content of the weak crustal refracted wave ranges from 4-5 to 8-9 Hz, while PmP reflections range from 2-3 to 12-14 Hz, with a dominant frequency of 7-8 Hz (Figure 10).

Clear, large-amplitude PmP reflections characterize also the other common receiver gathers with the exception of gather CRG8. Mantle wide-angle reflections can be easily picked at source-receiver distances comprised between 70-80 and 100-120 km. Unfortunately, land stations along profile P02 lack mantle refractions.

For what concerns first arrivals, upper crustal refractions travelling within the Apulia Platform can be picked up to 40-50 km offset on CRG1 to CRG5. These first arrival traveltimes carry information on the upper crustal velocity structure under the eastern margin of the Apulia Platform.

3.3 Profile P03

All record sections show crustal phases, mantle wide-angle refractions and mantle refractions. Data recorded by station P03_R3 located at 24.6 km distance from the closest airgun shot shows the best signal-to-noise ratio in the intermediate-large offset range (Figure 11). In the following, we describe the main phases identified on the record section CRG3 at increasing source-receiver distances.

First arrivals with apparent velocities of 6.0-6.5 km/s can be picked from 24.6 km to about 50 km offset (Figures 12). These refractions were travelling within the high-Vp Apulian carbonates and evaporites (see the Gargano 1 well sonic log published by Improta *et al*. [2000]) progressively deteriorate with offset and precede clear arrivals with apparent velocities around 6.7 km/s that could be related to refractions and wide-angle reflections from the crystalline basement (Figure 12). First arrivals are hardly identifiable from 50 km to 60 km, and the basement refractions likely become first arrivals beyond 60 km. The resulting gap in first arrivals around 55-60 km defines a clear shadow-zone (Figure 12) that suggests the presence of a low-Vp layer. Such a layer might corresponds to low-Vp sediments sandwiched between the Apulia Platform carbonate multilayer and the underlying Paleozoic crystalline basement. This interpretation is consistent with: *(i)* the regional-scale low-Vp layer resolved between the upper and mid crust by teleseismic receiver functions computed for all stations of the National Seismic Network (in Italian: Rete Sismica Nazionale – RSN [Michelini et al., 2016]) installed in the Gargano Promontory and Apulia foreland [Amato et al., 2014]; *(ii)* logs of the Gargano 1 well that drilled low-Vp Permo-Triassic clastic deposits underneath the Apulian Triassic evaporites.

Amplitudes and apparent velocities of basement refractions rapidly decrease at offsets beyond 65-70 km (Figure 13). This observation relates strictly to the abrupt deepening of the sea floor to the east of shot points 300-320 (Figure 4). Thus, the 70-85 km offset range is characterized by extremely weak first arrivals, which can be identified after a careful processing, followed by large amplitude crustal refractions/reflections and PmP arrivals (Figure 14). The apparent velocity of these subtle first arrivals, as well as of the deeper crustal phases, is around 6 km/s, but this value is clearly underestimated due to the bathymetry that steeply dips eastward.

Deep crustal refractions become, in turn, first arrivals beyond 95 km (Figure 15). These deep crustal refractions tend asymptotically to PmP arrivals and are characterized by apparent velocities around 7.0 km/s (beyond 95-100 km offset where the sea floor is regular). Frequency content of these weak crustal refractions observed at large offset ranges from 4 to 10 Hz.

At offsets larger than 110 km, first arrivals correspond to mantle refractions that precede large amplitude mantle reflections (Figure 11 and Figure 16). The frequency content is comprised between 3-4 and 8-9 Hz for Pn arrivals and between 3-4 and 11-14 Hz for PmP arrivals (Figure 10b). The Pn branch is outlined by a clear knee point in the first arrival traveltime curve (at around 108 km offset) and by typical apparent velocities of 7.9-8.2 km/s for mantle refractions (Figure 16). The Pn phases have a fair signal-to-noise ratio and lateral coherence between 108-115 km, 123-142 km, 161-177 km. Large amplitude PmP arrivals are evident from 70 km to 140 km offset and have traveltimes increasing with offset from 6.7 to 8.2 s (reduced times using a reduction velocity of 8 km/s; see Figure 11).

First arrivals associated to refracted waves travelling within the Apulia sedimentary layers, having apparent velocities of 5.5-6.5 km/s, can be picked up to 40-45 km offsets on all CRGs.

Fair mantle refractions can be identified on processed common receiver gathers from CRG1 to CRG4 beyond about 100 km offset. Post-critical large-amplitude PmP arrivals, with good lateral continuity and coherence characterize all five common receiver gathers. The PmP branch can be accurately picked at source-receiver distances comprised between 60-80 and 120-150 km.

4. Discussions and Conclusions

The primary goal of ALPHA survey was the high-resolution tomographic imaging of the crust and lithospheric mantle underneath the southern Adriatic Sea along three dense wide-aperture offshore profiles.

To illuminate the crust and crust-mantle boundary underneath the eastern side of the Apulia Platform, we extended the two SW-NE profiles onshore by deploying temporary short-period stations in the Gargano Promontory (profile P03) and Apulia region (profile P02).

We improved the signal-to-noise ratio by applying to the common receiver gather sections a processing flow specifically designed to highlight crustal phases, mantle wide-angle reflections and mantle refractions.

Our analysis of the processed CRG sections illustrates the high quality of the collected data.

The identification of first arrivals is complicated by shadow zones. An evident break in the first-arrival curve observed on record sections of profile P03 at about 50-60 km offset (Figure 12) points to the presence of a low-Vp layer in the upper crust above the crystalline basement. This finding is in agreement with the low-Vp sediments drilled by two deep wells [Improta et al., 2000] and imaged by teleseismic receiver functions as a low-Vs layer sandwiched between the Apulia Triassic evaporites and the crystalline basement in the depth range 4-6 to 8-10 km [Amato et al., 2014].

The five stations of the Gargano transect recorded both clear PmP reflections and Pn arrivals. In addition to the relevant mantle phases that were even recorded from the opposite end of the shot line (Figure 11), crustal refraction and reflected arrivals can be identified and accurately picked on all record sections in the small to intermediate offset range. Thus, the land deployment allows to extend the volume sampled by seismic rays 33 km to west of the closest airgun shot. The recorded onshore data carry information on the upper crustal velocity structure in the Gargano Promontory, while the joint modelling of Pn and PmP phases allows to illuminate a portion of the crust-mantle boundary that extends 35-40 km eastward from the coastline. Preliminary modelling of mantle wide-angle reflections and mantle refractions recorded by OBH/OBS and INGV land stations indicates that the crust-mantle boundary is about 34 km deep under the Gargano coastline and gently dips eastward [Figure 17, Dannowski et al., 2016]. This depth value is in good agreement with the depth of 30-32 km estimated by Amato et al. [2014] by using teleseismic receiver functions recorded at two INGV permanent stations located in the Gargano Promontory.

Along the Apulia transect, seven out of eight stations recorded clear crustal phases and mantle wide-angle reflections characterized by excellent lateral continuity and coherence. The farthest station with usable data P02_R7 is located at 47 km distance from the western ending of the marine seismic profile and recorded PmP arrivals between 70 and 100 km offset (corresponding to a shooting distance of 23-53 km from the beginning of the offshore profile). Therefore, PmP arrivals recorded by station P02_R7 illuminate an about 30 km long portion of the crust-mantle boundary located onshore underneath the Apulia Platform. Taken together, PmP traveltimes picked from the closest station (P02_R1) to the farthest one (P02_R7) provide constraints on the crust-mantle boundary underneath the western side of the Adriatic basin and the Apulia Platform.

Differently from profile P03, no land station recorded mantle refractions along the P02 profile. We speculate that the lack of Pn arrivals might be an effect of a deeper crust-mantle boundary that would shift the knee point between crustal and mantle refractions towards very large offset traces characterized by a lower signal-to-noise ratio. This hypothesis reconciles with PmP traveltimes that are larger for P02 stations: PmP arrival times at about 70 km offset are equal to 6.7 s for station P03_R3 and to 7.5 s for station P02_R3 (see Figures 6 and 12).

The observation of Pn arrivals at far offset (up to 170 km, Figure 16) and of very clear mantle reflections in a large offset range on land record sections (Figures 6 and 12) are not obvious or expected results. We remark that such results are valuable in the light of the energy of the used airgun source (i.e., 84 litres) that is ordinary for academic surveys and of the large distance of land stations from the coastline (47 km and 33 km for profile P02 and P03, respectively). Comparable example of good quality mantle phases recorded by land stations during wide-angle marine seismic surveys in Italian seas are rare [Prada et al., 2015; Dellong et al., 2018]. We believe that the acquisition of good quality data even at very large offset has been possible thanks to excellent local conditions of the recording sites chosen after a careful selection, as well as to low seismic attenuation of the Apulia continental crust.

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TABLES

Table 1. Coordinates of P02 profile land stations (see map in Figure 1 and Figure 2).

Station code	Latitude (°N)	Longitude (°E)	Altitude (m)
R1	17° 44.6948’	40° 42. 5696’	64
R2	17° 39.9490’	40° 40.0390’	141
R2	17° 39.5720’	40° 35.9850’	129
R4	17° 35.6138’	40° 34.5611’	210
R5	17° 33.2460’	40° 30.5966’	161
R6	17° 31.9630’	40° 27.6220’	141
R7	17° 30.4440’	40° 24.3183’	148
R8	17° 25.9484’	40° 21.0378’	20

Table 2. Coordinates of P03 profile land stations (see map in Figure 1 and Figure 3).

Station code	Latitude (°N)	Longitude (°E)	Altitude (m)
R1	16° 08.9233’	41° 51.3008’	104
R2	16° 05.0356’	41° 51.1542’	355
R2	15° 59.7018’	41° 49. 9453’	733
R4	15° 58.2476’	41° 50.0883’	754
R5	15° 53.5240’	41° 50.1910’	330

CATPIONS

Figure 1. The map shows the three seismic refraction profiles collected during the FS METEOR cruise M86/3 in the central-southern Adriatic Sea. Blue triangles are land stations that recorded the airgun shots. Black triangles are OBH/OBS instruments (modified from Kopp et al. [2013]).

Figure 2. Location of INGV stations along the Apulia transect (profile P02). The white and yellow lines indicate the offshore profile P02 and its land prolongation, respectively. Blue symbols and labels (P2_R1 to P2_R8) denote INGV land stations, numbers (01, 02, etc) denote position of OBH/OBS (modified form Google Earth, 2017).

Figure 3. Location of INGV stations in the Gargano Promontory (profile P03). The white and yellow lines indicate the offshore profile P03 and its land prolongation, respectively. Blue symbols and labels (P3_R1 to P3_R5) denote INGV stations, numbers *(01, 02, etc)* denote OBH/OBS (modified form Google Earth, 2017).

Figure 4. Sea floor depth along P02 (top) and P03 (bottom) as a function of the shot number and shot position along the profile.

Figure 5. P02-CRG3: traces are band-pass filtered (f=3-5-9-12 Hz) and plotted with reduced times (Vr=8 km/s). Yellow arrows denote first arrivals (refractions from the Apulian sedimentary sequence and the top of the crystalline basement), blue arrows possible weak first-arrivals (refracted waves through the mid crust), red arrows large amplitude PmP arrivals. The red dashed lines outline the offset range of the data plotted in Figure 6, while the red continous rectangle delimits data showed in Figure 7.

Figure 6. P02-CRG3: zoom on the small-to-intermediate offset range showing refracted waves from the sedimentary layers. Traces are band-pass filtered (f=3-5-9-12 Hz) and plotted with reduced times (Vr=7 km/s). Yellow arrows denote first arrivals.

Figure 7. P02-CRG3: traces in the 65-124 km offset range. Traces are band-pass filtered (f=3-5-9-12 Hz) and plotted with reduced times (Vr=8 km/s). Yellow arrows denote first arrivals, blue arrows possible first-arrivals (refracted waves through the mid-lower crust), red arrows clear PmP arrivals. The shadow zone is outlined by the green circle.

Figure 8. P02-CRG2: traces are band-pass filtered (f=2-3-8-10 Hz) and plotted with reduced times (Vr=8 km/s). Yellow arrows denote first arrivals (refractions from the Apulian sedimentary sequence), blue arrows weak first-arrivals of refracted waves through the mid crust, red arrows high-quality PmP reflections.

Figure 9. P02-CRG2: this zoom on the 73-103 km offset range allows outlining the weak and continuous first-arrivals (grey arrows) that likely correspond to a refracted phase travelling in the mid-crust.

Figure 10. Frequency-time analysis (Gabor Transform) performed on selected seismograms. (a) P02-CRG2, seismogram recorded at 91.1 km offset showing the first arrival of the refracted wave through the mid-crust and the large amplitude, wide-angle PmP reflection; (b) P03-CRG3, seismogram recorded at 134.2 km offset showing both mantle refraction (Pn) and reflection (PmP).

Figure 11. P03-CRG3: traces are band-pass filtered (f = 4-5-9-11 Hz) and plotted with reduced times (Vr = 8 km/s). This plot displays traces up to 170 km offset. Arrows outline first arrivals: refractions from Apulia sedimentary layers (yellow), large-to-weak refractions possibly from the Apulia crystalline basement (blue), refractions/reflections from the mid-lower crust (blue), mantle refractions (Pn, light blue), large amplitude wide-angle mantle reflections (PmP, red). The red dashed rectangle delimits data plotted in Figure 14, the red dotted rectangle data in Figure 15, the red continuous rectangle data in Figure 16.

Figure 12. P03-CRG3: zoom on traces between 24633 m and 63000 m offset. Data are band-pass filtered (f=2-3-10-12 Hz) and plotted with reduced times (Vr=6.5 km/s). Yellow arrows denote refracted waves from the Apulia sedimentary layers (presumably from the high-Vp Triassic evaporites), blue arrows refractions possibly from the Apulia crystalline basement. The "basement" refractions likely become first arrivals beyond 60 km offsets. The yellow circle outlines a shadow zone.

Figure 13. P03-CRG3: traces from 45 to 90 km offset. Data are band-pass filtered (f=4-5-9-11 Hz) and plotted with reduced times (Vr=8 km/s). The yellow circle highlights the region where the amplitude of basement refractions (blue arrows) abruptly decreases. White and red arrows denote large-amplitude crustal refracted/reflected waves and PmP arrivals, respectively. The red rectangle bounds data showed in Figure 14.

Figure 14. P03-CRG3: zoom on traces characterized by very weak first arrivals (dashed line and arrows) likely corresponding to a refracted wave from the crystalline basement. Data are band-pass filtered (f=4-5-9-11 Hz) and plotted with reduced times (Vr=8 km/s).

Figure 15. P03-CRG3: zoom on the large offset data. Arrows denote extremely weak refracted wave from the basement (blue), refractions from the mid-lower crust that become first arrivals beyond 95 km offset (white), mantle wide-angle reflections (red), mantle refractions (light-blue) representing first arrivals beyond 110 km offset.

Figure 16. P03-CRG3: zoom on the far offset data showing Pn arrivals (light-blue arrows). The white arrows indicate deep crustal refracted waves, red arrows mantle reflections. Data are band-pass filtered (f=3-4-8-10 Hz) and plotted with reduced times (Vr=8 km/s). A gain (RMS function, time-window of 1.0 s) is applied to data to evidence weak Pn arrivals.

Figure 17. Vp model along the western portion of the P03 profile determined by preliminary modelling of refraction and wide-angle reflection arrival times using marine and land stations [modified from Dannowski et al., 2016]. Yellow triangles denote marine and land stations used for data modelling. Note that this preliminary model does not include yet a low-Vp layer under the Apulia Platform.

FIGURES

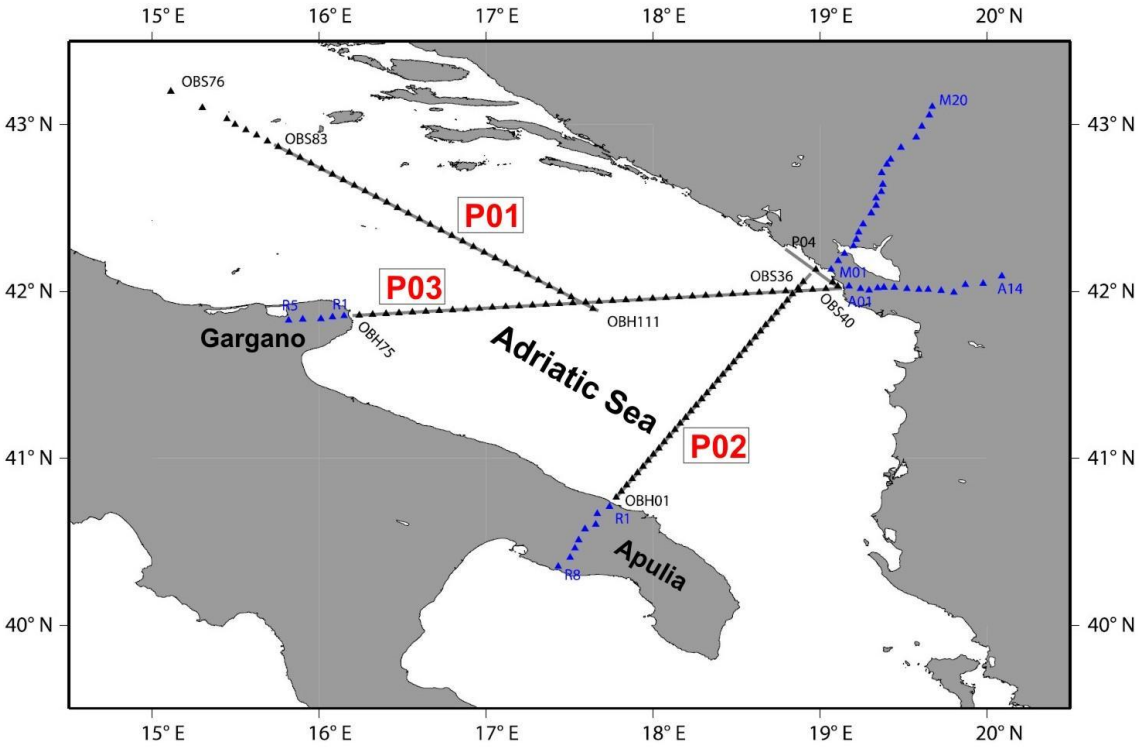


Figure 1

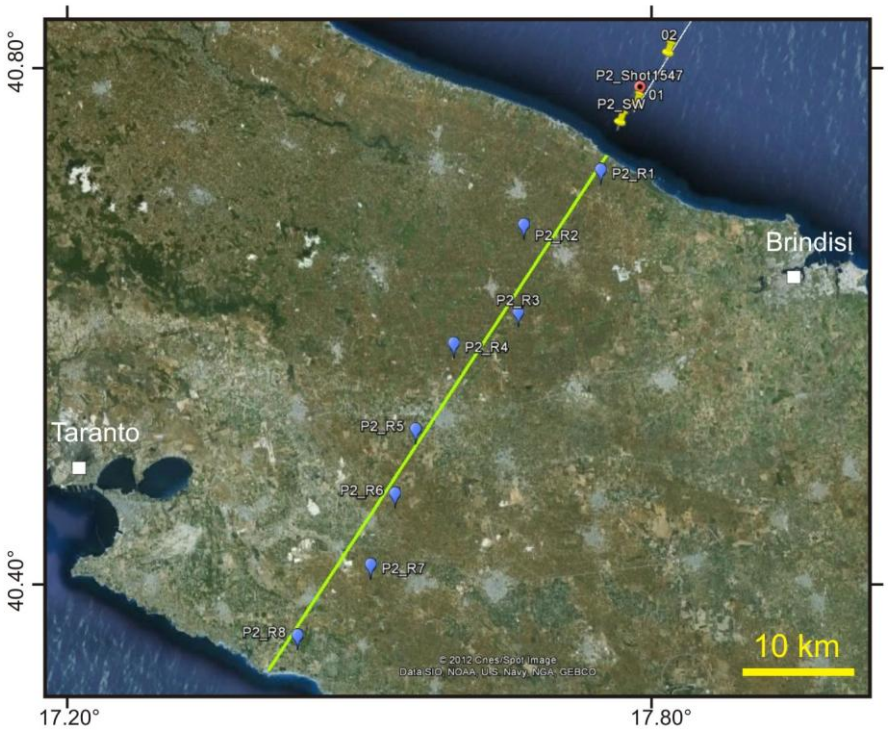
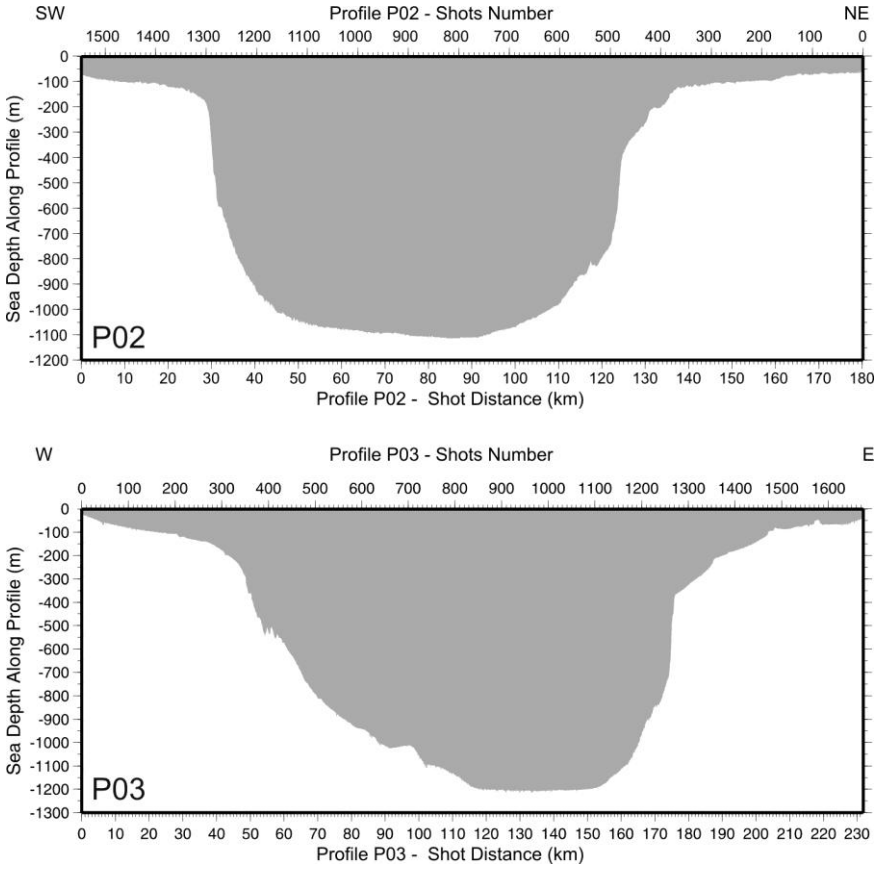


Figure 2

Figure 3



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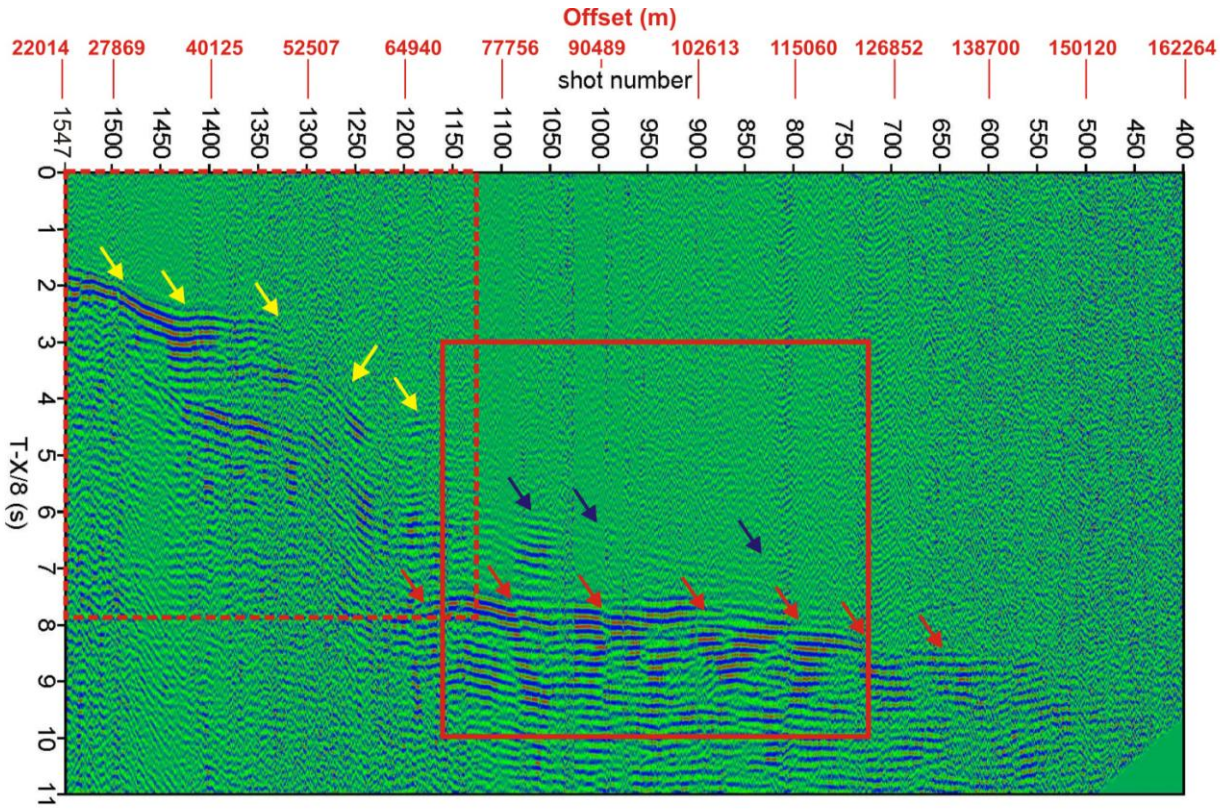

485
486 **Figure 5**
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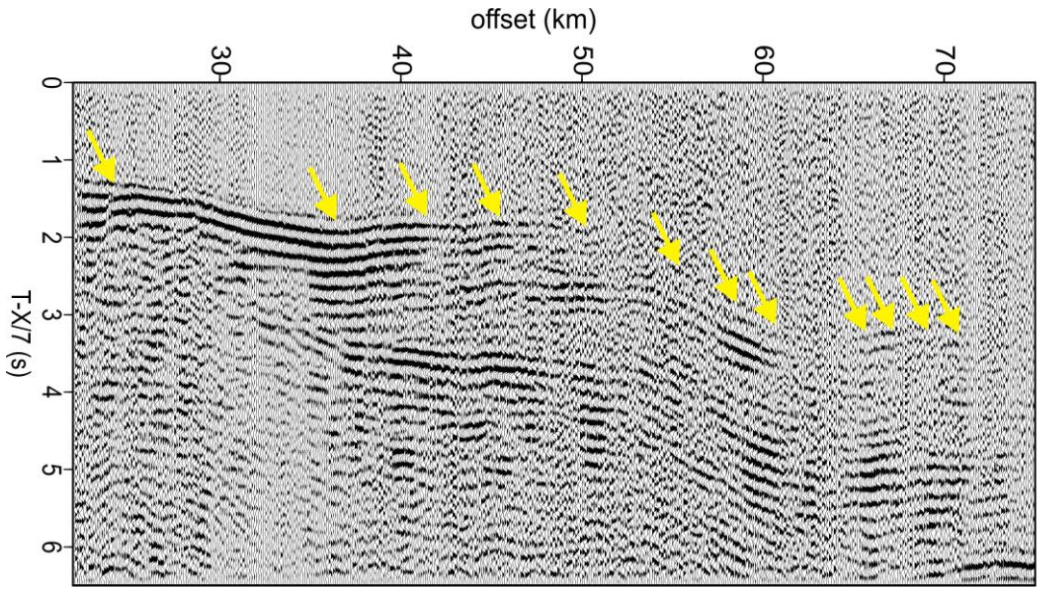

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491 **Figure 6**
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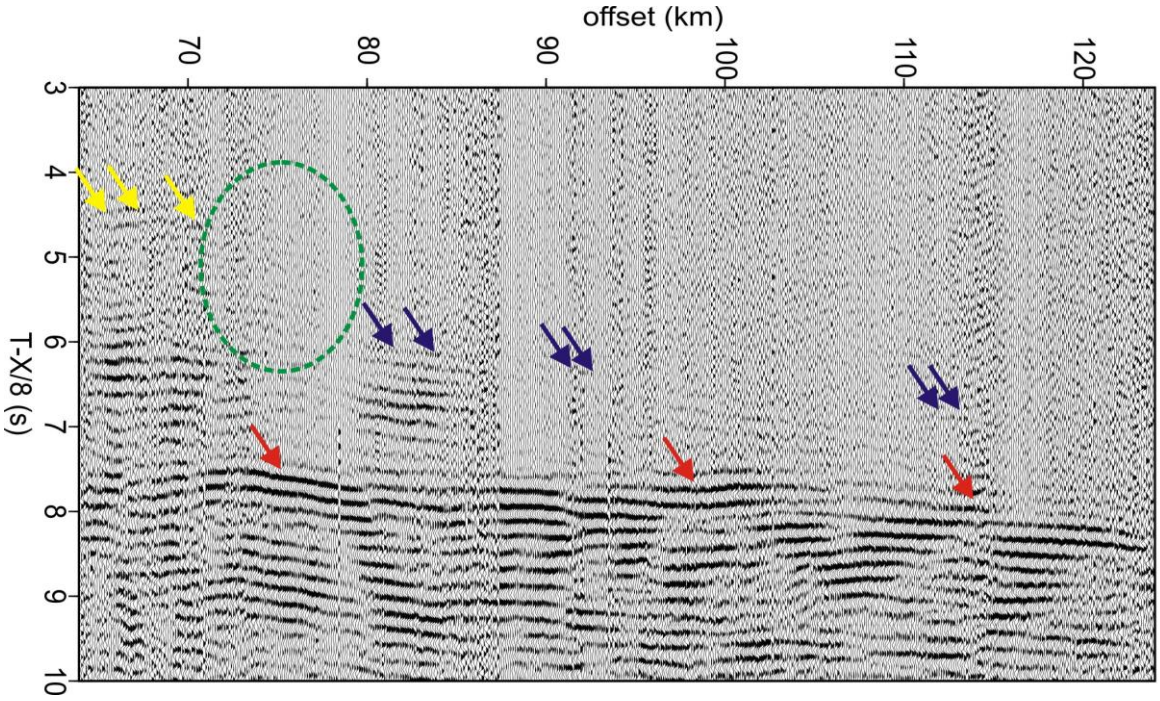

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494 **Figure 7**

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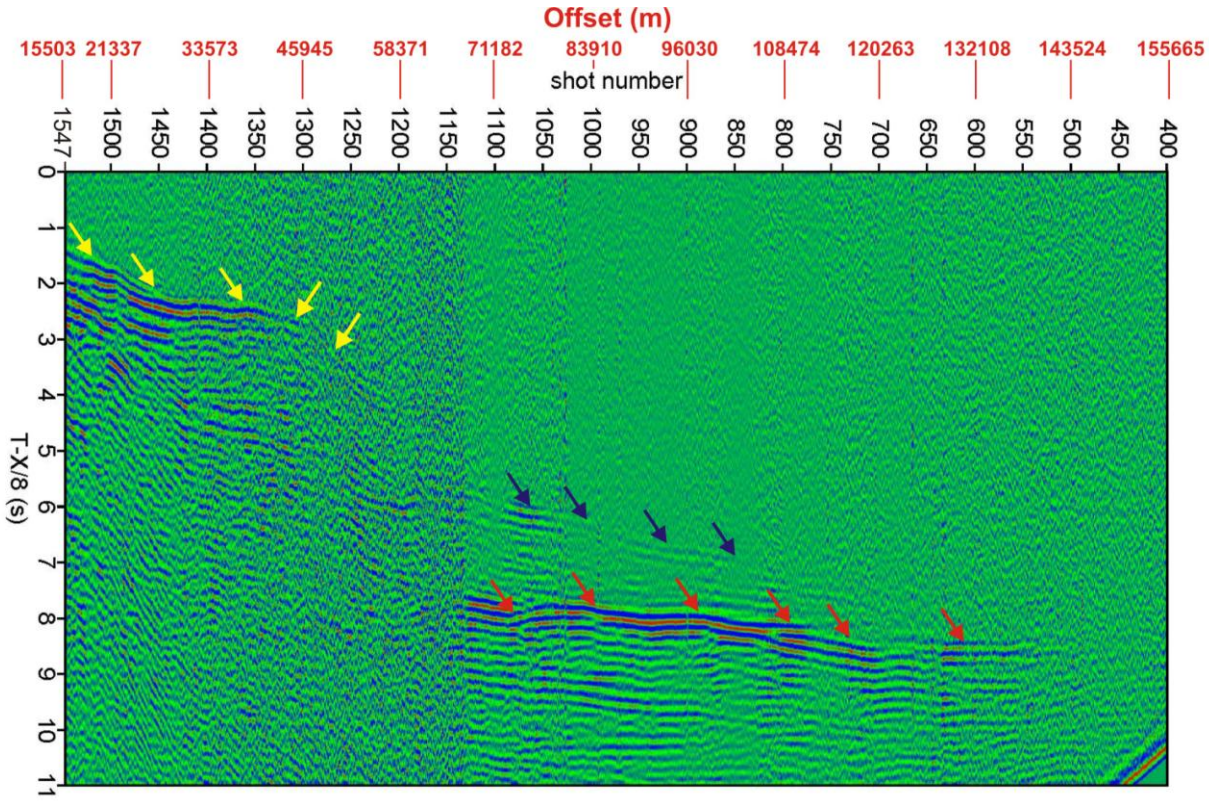

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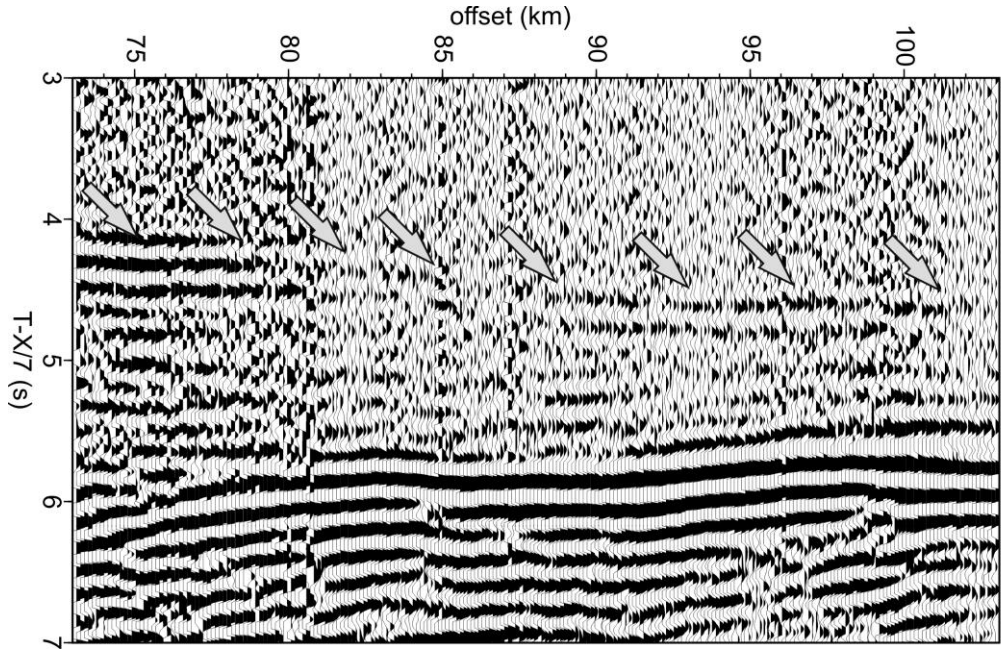
497 **Figure 8**



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499 **Figure 9**
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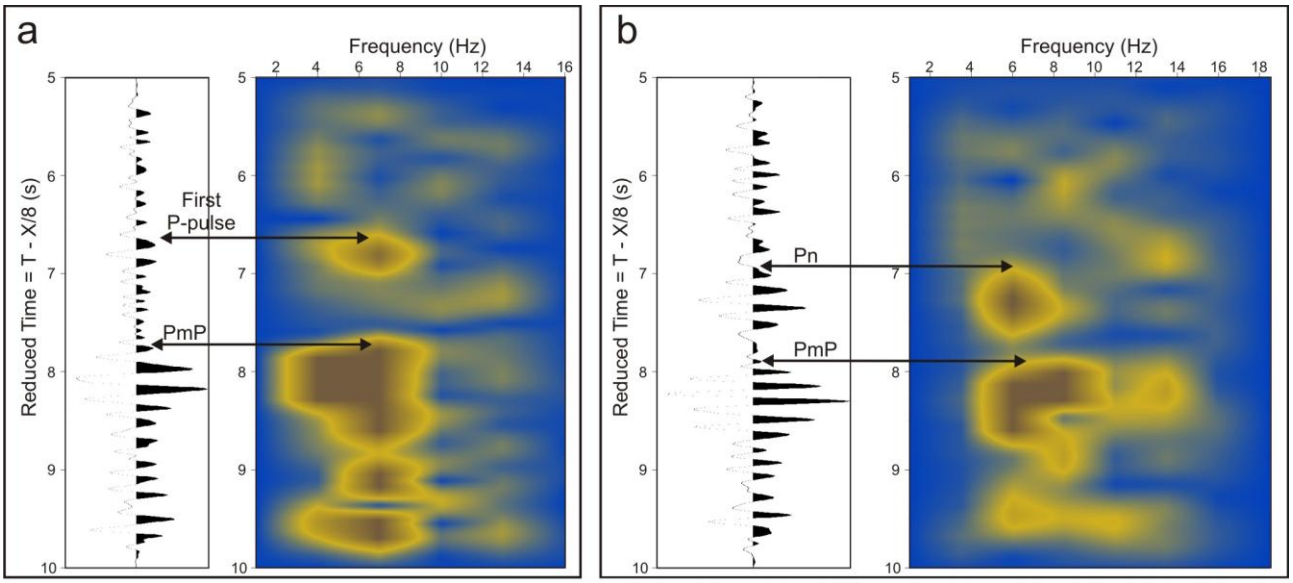

501
502 **Figure 10**
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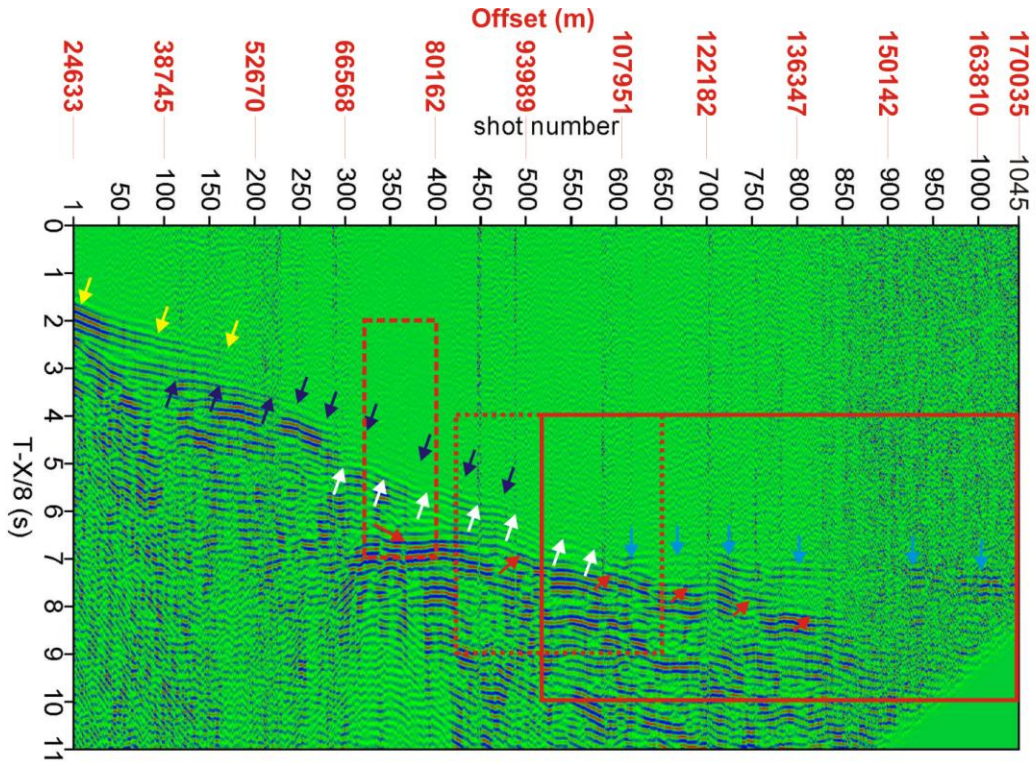


Figure 11

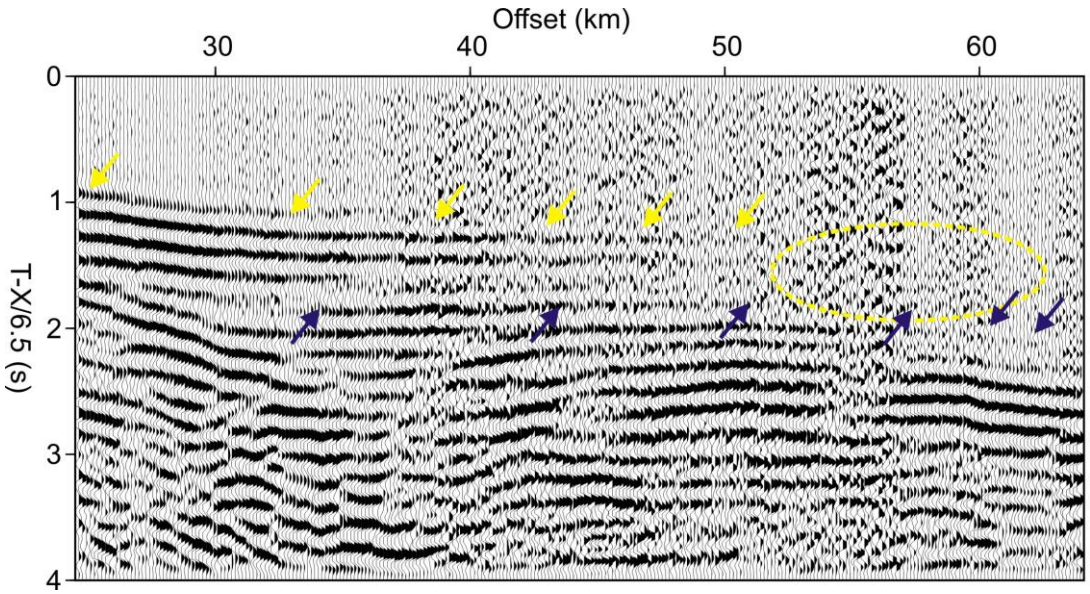
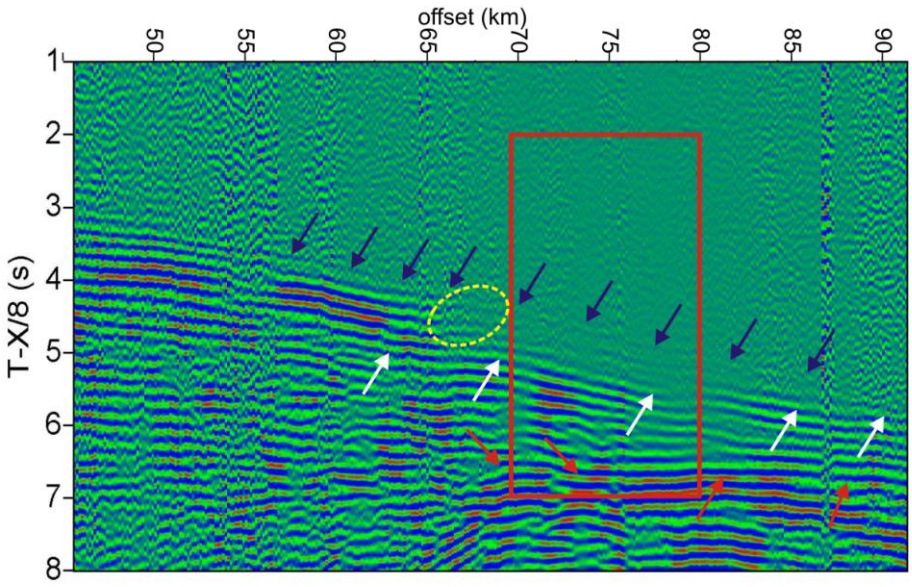


Figure 12



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513 **Figure 13**

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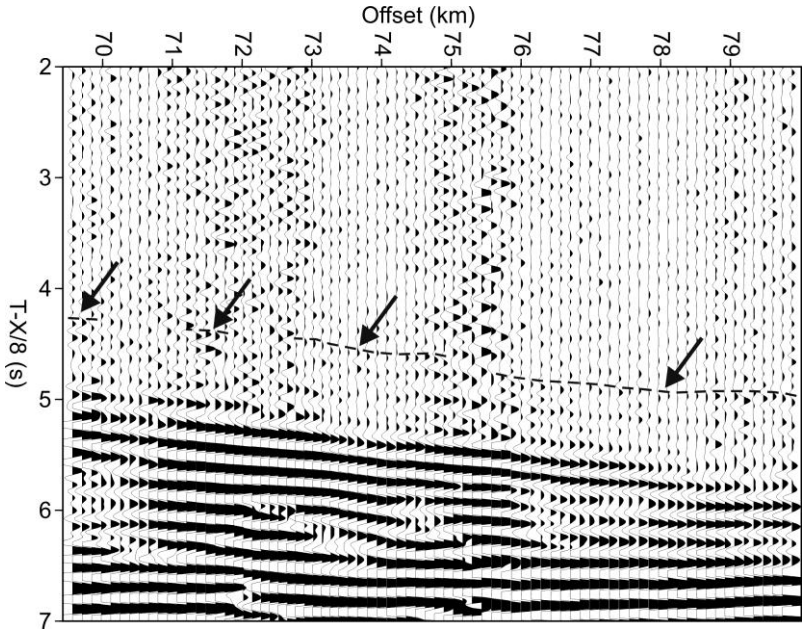

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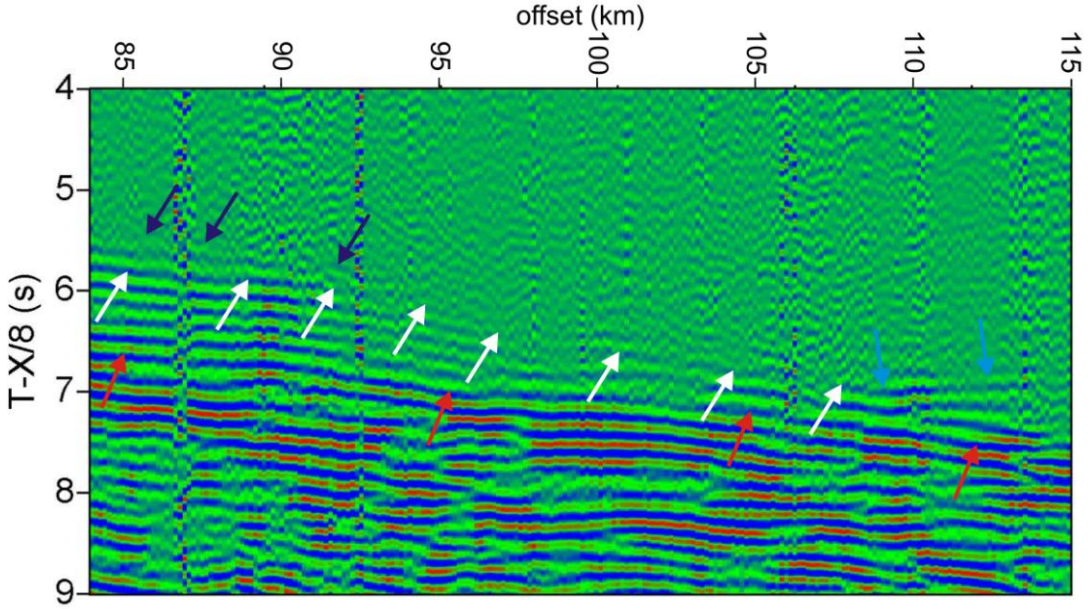
516 **Figure 14**



517
518 **Figure 15**
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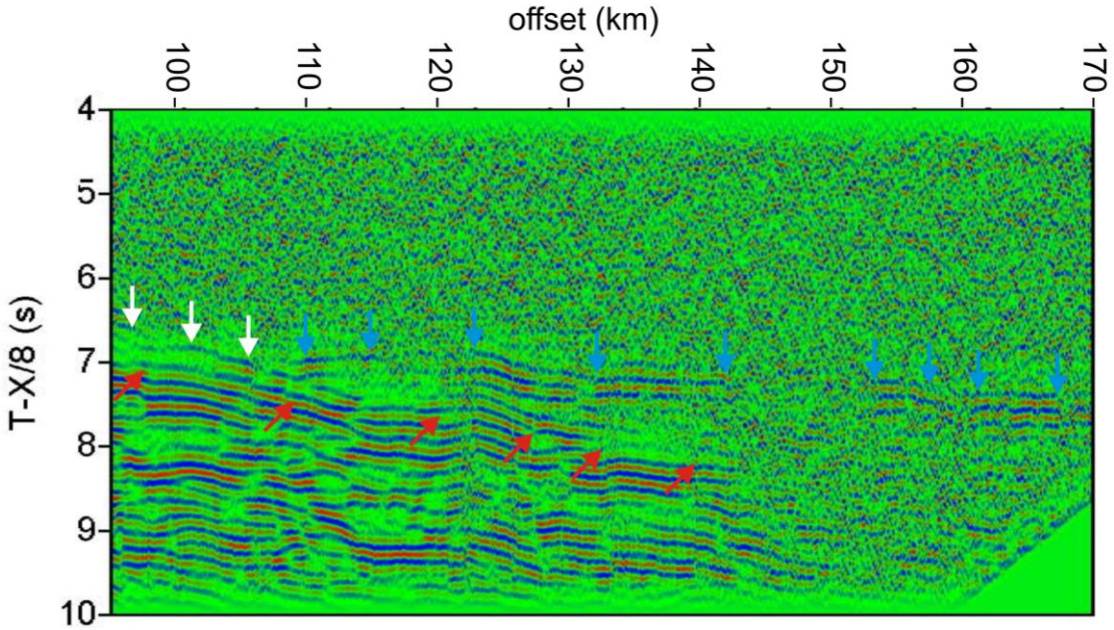

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522 **Figure 16**
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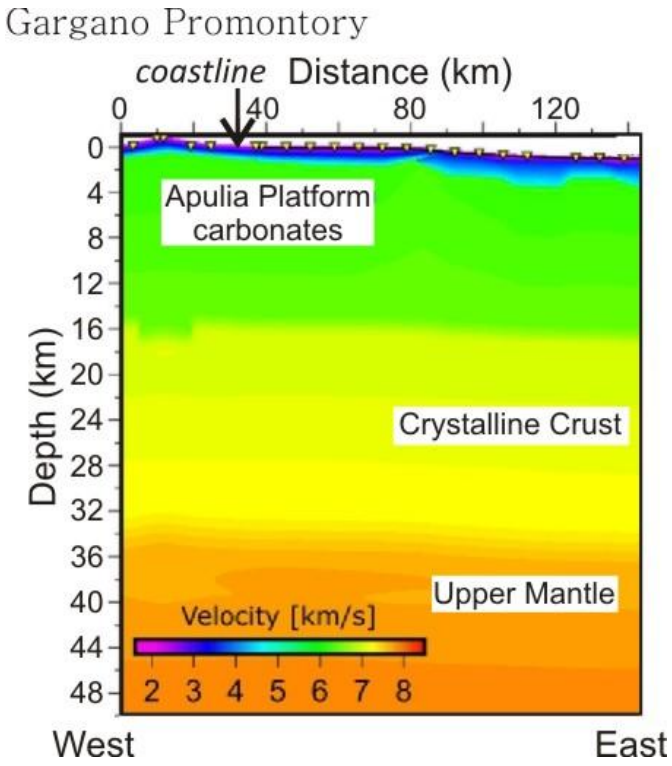
Gargano Promontory
coastline
Distance (km)
0
40
80
120
0
4
8
12
16
20
24
28
32
36
40
44
48
Depth (km)
Apulia Platform carbonates
Crystalline Crust
Upper Mantle
Velocity [km/s]
2 3 4 5 6 7 8
West
East

Figure 17