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Geological interpretation of the CROP-04 seismic line (Southern Apennines, Italy)

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ABSTRACT

This paper presents a geological interpretation of the CROP-04 reflection seismic line based on a 10 sec TWT reprocessed stack section.

The achieved major results may be synthesized in the following points:

1) In the western part of the line, a well-structured reflective unit rising from 7-8 sec TWT in correspondence to the Tyrrhenian coast to 4-5 sec TWT in correspondence to Monte Marzano fixes the Apennine sole thrust at a depth exceeding 8 sec TWT, i.e. at a depth of at least 20 kilometers. This depth is independent from the geological attribution of the deep-seated reflective unit since it depends only on the climbing geometry of the reflectors that implies displacement in the hangingwall of a contractional fault.

2) The top of the Apulia carbonates rises from about 5 sec TWT in correspondence to the Tyrrhenian coast to less than 2 sec TWT in correspondence to the crest of the duplex system, where it has been reached by the San Gregorio 1 well, and subsequently deepens towards the NE reaching about 4 sec TWT at the foot of the thrust-and-fold cascade featuring the outer flank of the buried antiform. The space between the crest of the antiform and the sole thrust may be entirely filled with imbricates of sedimentary rocks or with sedimentary rocks and crystalline rocks derived from the Apulia basement. The geometry of the aforementioned deep-seated reflective unit suggests a thin-skin tectonic style with no basement involvement. The duplex internal architecture appears to be featured by two major thrust sheets, both lying on top of long thrust flats. This structural architecture agrees with other geological data indicating a minimum cumulative shortening of the duplex system of 90-100 kilometers after the early Pliocene, i.e. after the transport of the allochthonous sheets on the western margin of the Apulia Platform.

3) Well-organized reflectors dubitatively attributed to the lower crust of Apulia have been recognized at 9-10 10 sec TWT in correspondence to the front of the mountain chain. The CROP-04 line cannot provide information on the extent of this reflective unit the 10 sec TWT of time record of the re-processed stack are insufficient for this purpose.

4) As concerns the backstop of the orogenic system, the CROP-04 profile indicates that it must be located somewhere in the Tyrrhenian Sea, west of the line termination. Also the trailing edge of the Apulia-carbonate duplex system must be searches in the offshore west of the line termination.

KEY WORDS: *Italy, Southern Apennines, CROP-04 seismic line, deep structure, tectonic style.*

RIASSUNTO

Interpretazione geologica della linea sismica CROP-04 (Appennino Meridionale, Italia).

In questo lavoro viene presentata un'interpretazione geologica del profilo CROP-04 basata su una sezione stack riprocessata fino a 10 secondi TWT. I principali risultati raggiunti possono essere sintetizzati nei seguenti punti:

1) Nella metà occidentale della linea un'unità sismica con riflettori ben strutturati risale da una profondità di 7-8 sec TWT in corrispondenza della costa tirrenica fino a 4-5 sec TWT in corrispondenza del Monte Marzano. La geometria di questa unità consente di fissare il thrust basale della catena appenninica ad una profondità superiore ad 8 sec TWT, vale a dire ad una profondità di almeno 20 chilometri. Questa profondità è indipendente dall'attribuzione geologica dell'unità riflettiva dal momento che si basa unicamente sulla geometria in salita dei riflettori secondo una superficie parallela ad altre strutture geologiche più superficiali che implica una dislocazione al tetto di una faglia contrazionale.

2) Il top dei carbonati apuli risale da circa 5 sec TWT in corrispondenza della costa tirrenica a meno di 2 sec TWT in corrispondenza della cresta del sistema duplex, dove è stato raggiunto dal pozzo San Gregorio Magno 1, per poi approfondirsi sino a 4 sec TWT in corrispondenza del piede della cascata di pieghe e thrust che caratterizza il fianco esterno dell'antiforme sepolta. In una sezione geologica lo spazio tra la cresta dell'antiforme e il thrust basale del sistema può essere riempito interamente da embrici di rocce sedimentarie oppure può essere riempito in parte da rocce sedimentarie e in parte da rocce cristalline del basamento apulo. La geometria dell'unità riflettiva suggerisce uno stile tettonico con scollamento delle coperture senza coinvolgimento del basamento. La struttura interna del sistema duplex appare dominata da due maggiori corpi sovrascorsi, entrambi al di sopra di una lunga superficie piatta di thrust. Questa struttura geologica è in accordo con altri dati geologici che indicano un accorciamento cumulativo minimo del sistema duplex di 90-100 chilometri dopo il primo trasporto dell'alloctono sul margine interno della Piattaforma Apula avvenuto nel Pliocene inferiore.

3) Riflettori ben organizzati riconosciuti a 9-10 sec TWT in corrispondenza del margine esterno della catena sono stati dubitativamente attribuiti alla crosta inferiore apula. Non è possibile dire quanto questa unità sismica si spinga verso ovest perché dieci secondi di registrazione sono insufficienti.

4) Il backstop del sistema deve trovarsi nell'area tirrenica ad ovest della terminazione della linea. Lo stesso vale anche per il trailing edge del duplex apulo sepolto che in corrispondenza della costa non è stato ancora raggiunto dal profilo.

TERMINI CHIAVE: *Italia, Appennino meridionale, linea sismica CROP-04, struttura profonda, stile tettonico.*

1. FOREWORD

The CROP-04 line extends about 150 kilometers from the Tyrrhenian coast (Agropoli) to the Adriatic coast (Barletta). The seismic section was recorded between November, 1989 and April, 1990 using both vibroseis and dynamite as source types. A standard processing of the whole line was completed in March, 1991. The experiment was aimed at providing information on the following major points:

– Depth of the sole thrust of the tectonic wedge beneath the Apennine mountain chain;

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– Structural architecture of the deepest portion of the buried Apulia-carbonate duplex system;

– Involvement or non-involvement of the crystalline basement of Apulia in the post-Tortonian compressional deformation;

– Identification of the lower crust of Apulia and recognition of its extent towards the Tyrrhenian coast;

– Location and nature and the backstop of the orogenic system.

Due to the poor quality of the field data, the processing of the CROP-04 line was not successful in providing an interpretable seismic profile. After a long pause in which frustration and discouragement prevailed, additional investigations were planned, aimed at determining the causes of the very low signal/noise ratio of the field data and at exploiting as much as possible the signal content. The re-analysis of the data and the re-processing sequence, the latter making also use of some a priori geological knowledge of the area, are described in Mazzotti *et alii* (2000) and in other pages of this volume (Mazzotti *et alii,* Analysis *of the CROP-04 seismic data* and MAZZOTTI *et alii,* Re-*processing of the CROP-04 seismic data*). The interpretations of the CROP-04 seismic profile proposed in this paper and in other two papers of this volume (ANELLI *et alii*, *Integrated interpretation of the magnetic and gravity data along the seismic line CROP-04* and CIPPITELLI, *The CROP-04 seismic profile. Interpretation and structural setting of the Agropoli-Barletta geotraverse*) are based on the first 10 seconds TWT of the field data the re-processing of which was focused on vibroseis data with a few dynamite recordings just used as a guide and reference, e.g. in the refraction static computation. The quality of the new stack section (see Plate 1) is comparable to good commercial lines available in the region. However, records in commercial lines usually do not exceed 5-6 seconds TWT whilst in the CROP-04 line continuous and well-structured events are recognizable up to 8-9 seconds TWT.

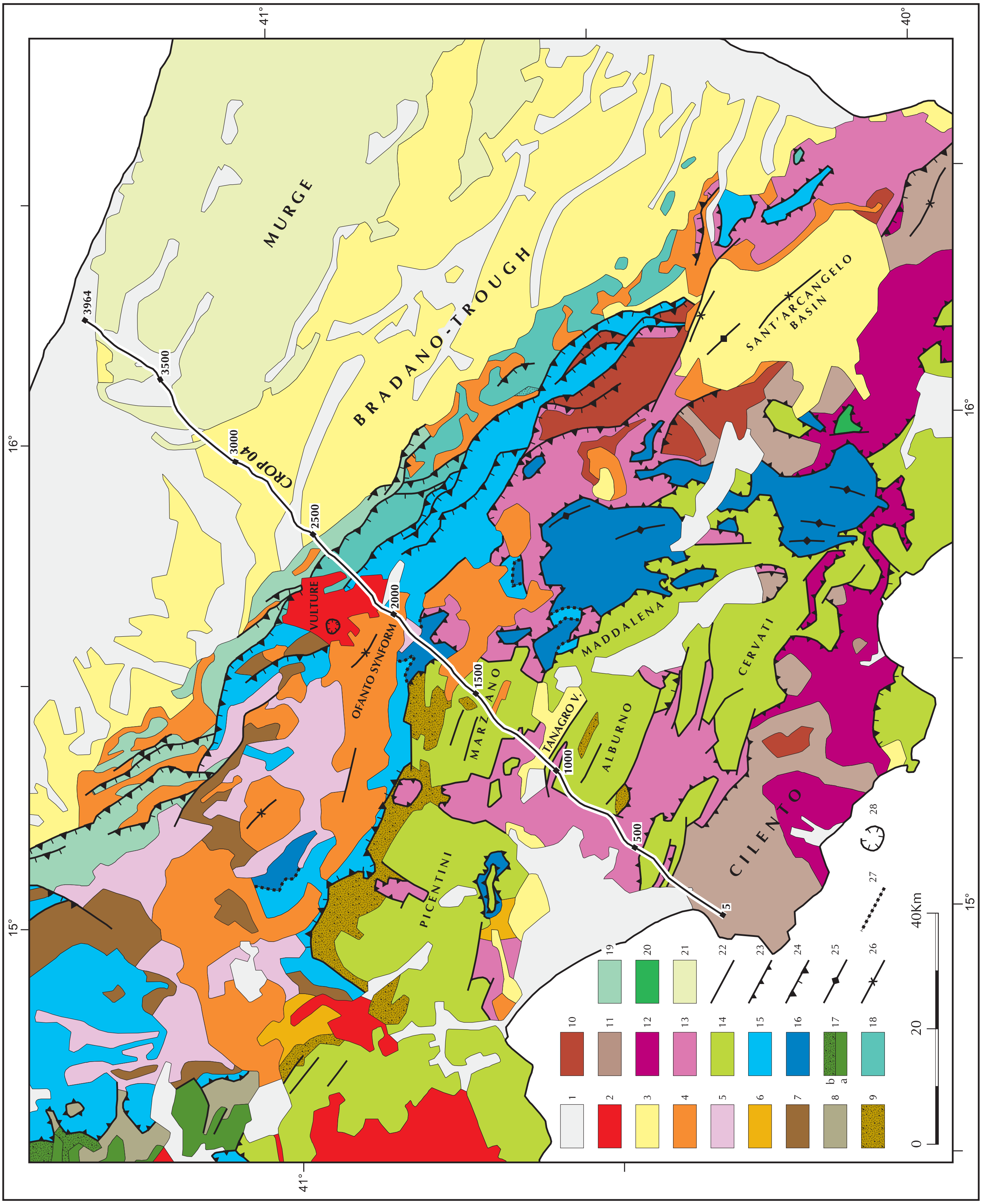
2. GEOLOGICAL FRAMEWORK OF THE AREA CROSSED BY THE CROP-04 LINE

The CROP-04 seismic profile cuts across the entire Southern Apennine thrust belt-foredeep-foreland system (fig. 1) from the Tyrrhenian margin of the mountain chain to the Apulia foreland.

The thrust belt is basically featured In the whole study area by a deep-seated, huge carbonate duplex system («Inner Apulia Platform» of the geological literature, see MOSTARDINI & MERLINI, 1986) buried under a stack of NE-verging rootless nappes (MOSTARDINI & MERLINI, 1986; CASERO *et alii*, 1988, 1991; PATACCA & SCANDONE 1989, 2001; PATACCA *et alii*, 1992; ROURE *et alii*, 1991; MATTAVELLI *et alii*, 1993; ROURE & SASSI, 1995; LA BELLA *et alii,* 1996; LENTINI *et alii*, 1996, 2002; CORRADO *et alii*, 1997, 1998a, b; SPERANZA *et alii*, 1998; MONACO *et alii*, 1998; CELLO & MAZZOLI, 1999; DI BUCCI *et alii*, 1999; SCROCCA & TOZZI, 1999; MENARDI NOGUERA & REA 2000; IMPROTA *et alii*, 2000; MAZZOLI *et alii*, 2000, 2001). The buried duplex system, made up of Mesozoic-Tertiary shallow-water carbonates disconformably overlain by Pliocene terrigenous deposits, forms the backbone of the entire Southern Apennine mountain chain (fig. 2). The subsurface distribution of these carbonates in the thrust belt is well known thanks to the extensive oil exploration in the area (see NICOLAI & GAMBINI, *Structural architec-*

Fig. 1 - Geological-structural map of the area crossed by the CROP-04 line (after PATACCA *et alii*, 2000) with slight modifications. 1) Continental and subordinate shore deposits (Holocene). 2) Volcanic rocks and volcaniclastic deposits (middle Pleistocene-Holocene). 3) Terrigenous marine and paralic deposits filling the Bradano Trough and unconformable overlying the Apennine units (lower Pleistocene-middle Pleistocene *p.p.*). 4) Pliocene thrust-sheet-top deposits. 5) Calaggio Chaotic Complex (uppermost Messinian/lowermost Pliocene). 6) Upper Tortonian-Messinian thrust-sheet-top deposits, including the Braneta Formation and the Gessoso-Solfifera Formation. 7) Upper Tortonian(?)-lower Messinian thrust-sheet-top deposits unconformably overlying the Sannio Unit (San Bartolomeo Formation). 8) Upper Tortonian(?)-lower Messinian thrust-sheet-top deposits unconformably overlying the Matese Unit (San Massimo Sandstone). 9) Middle Miocene thrust-sheet-top deposits unconformably overlying the Alburno-Cervati and Monti della Maddalena Units (Castelvetere Formation). 10) Middle Miocene thrust-sheet-top deposits unconformably overlying the Sicilide Unit (Gorgoglione Formation). 11) Lower Miocene thrust-sheet-top deposits unconformably overlying the North-Calabrian Unit (Albidona Formation). 12) North-Calabrian Unit (Cretaceous-Paleogene). 13) Sicilide Unit (Cretaceous-lower Miocene). 14) Alburno-Cervati, Monti della Maddalena and minor tectonic units derived from the Apenninic Platform (upper Triassic-lower Miocene). 15) Sannio Unit (lower Cretaceous-middle Miocene). 16) Lagonegro Units (middle Triassic-lower Cretaceous). 17) Matese Unit: *a*) shallow-water carbonates (upper Triassic-Tortonian *p.p.); b*) siliciclastic flysch deposits (Tortonian *p.p.).* 18) Tufillo-Serra Palazzo Unit (Paleogene-upper Miocene) 19) Daunia Unit (Paleogene-upper Miocene). 20) Monte Alpi Unit (Jurassic-upper Miocene carbonates) and overlying lower Pliocene(?) thrust-sheet-top deposits (emergence of the Apulia-carbonate duplex system). 21) Cretaceous carbonates of the Murge foreland. 22) Normal faults and strike-slip faults. 23) Thrust flat. 24) Thrust ramp. 25) Anticline axis. 26) Syncline axis. 27) Detachment surface at the base of the Sannio Unit. 28) Caldera rim (Vulture Volcano).

– Carta geologico-strutturale semplificata dell'area attraversata dalla linea CROP-04 (da PATACCA *et alii, 2000) con lievi modifiche. 1) Depositi continentali e subordinatamente di spiaggia (Olocene). 2) Rocce vulcaniche e depositi vulcanoclastici (Pleistocene medio-Olocene). 3) Depositi terrigeni marini e paralici che riempiono la Fossa Bradanica e ricoprono in discordanza le coltri appenniniche (Pleistocene inferiore e medio). 4) Depositi pliocenici discordanti sulle coltri appenniniche. 5) Complesso Caotico del Torrente Calaggio (Messiniano terminale/Pliocene basale). 6) Depositi del Tortoniano superiore-Messiniano discordanti sulle coltri appenniniche comprendenti la Formazione Gessoso-Solfifera e la Formazione del Torrente Braneta. 7) depositi del Tortoniano superiore(?)-Messiniano inferiore discordanti sull'Unità Sannio (Arenarie di San Bartolomeo). 8) Depositi del Tortoniano superiore(?)-Messiniano inferiore discordanti sull'Unità Matese (Arenarie di San Massimo). 9) Depositi del Miocene medio discordanti sull'Unità Alburno-Cervati e sull'Unità Monti della Maddalena (Formazione di Castelvetere). 10) Depositi del Miocene medio discordanti sull'Unità Sicilide (Formazione di Gorgoglione). 11) Depositi del Miocene inferiore discordanti sull'Unità Nord-Calabrese (Formazione di Albidona). 12) Unità Nord-Calabrese (Cretaceo-Paleogene). 13) Unità Sicilide (Cretaceo-Miocene inferiore). 14) Unità Alburno-Cervati, Unità Monti della Maddalena e unità tettoniche minori derivanti dalla Piattaforma Appenninica (Trias superiore-Miocene inferiore). 15) Unità Sannio Unit (Cretaceo inferiore-Miocene inferiore). 16) Unità Lagonegresi (Trias medio-Cretaceo inferiore). 17) Unità Matese:* a) *carbonati di mare basso (Trias superiore-Tortoniano* p.p.*);* b) *depositi silicoclastici di tipo flysch (Tortoniano* p.p.*). 18) Unità Tufillo-Serra Palazzo (Paleogene-Miocene superiore) 19) Unità Daunia (Paleogene-Miocene superiore). 20) Unità Monte Alpi (carbonati del Giurassico superiore-Miocene superiore) e depositi terrigeni discordanti assegnati al Pliocene inferiore (emergenza del duplex di carbonati apuli sottostante le coltri appenniniche). 21) Carbonati cretacei dell'avampaese murgiano. 22) Faglie normali e faglie trascorrenti. 23) Thrust flat. 24) Thrust ramp. 25) Asse di anticlinale. 26) Asse di sinclinale. 27) Superficie di scollamento alla base dell'Unità Sannio. 28) Bordo di caldera (Vulture).*


MURGE
BRADANO-TROUGH
CROP 04
3964
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VULTURE
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TANAGRO V.
ALBURNO
MADDALENA
CERVATI
SANT'ARCANGELO BASIN
CILENTO
PICENTINI
41°
40°
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Fig. 1

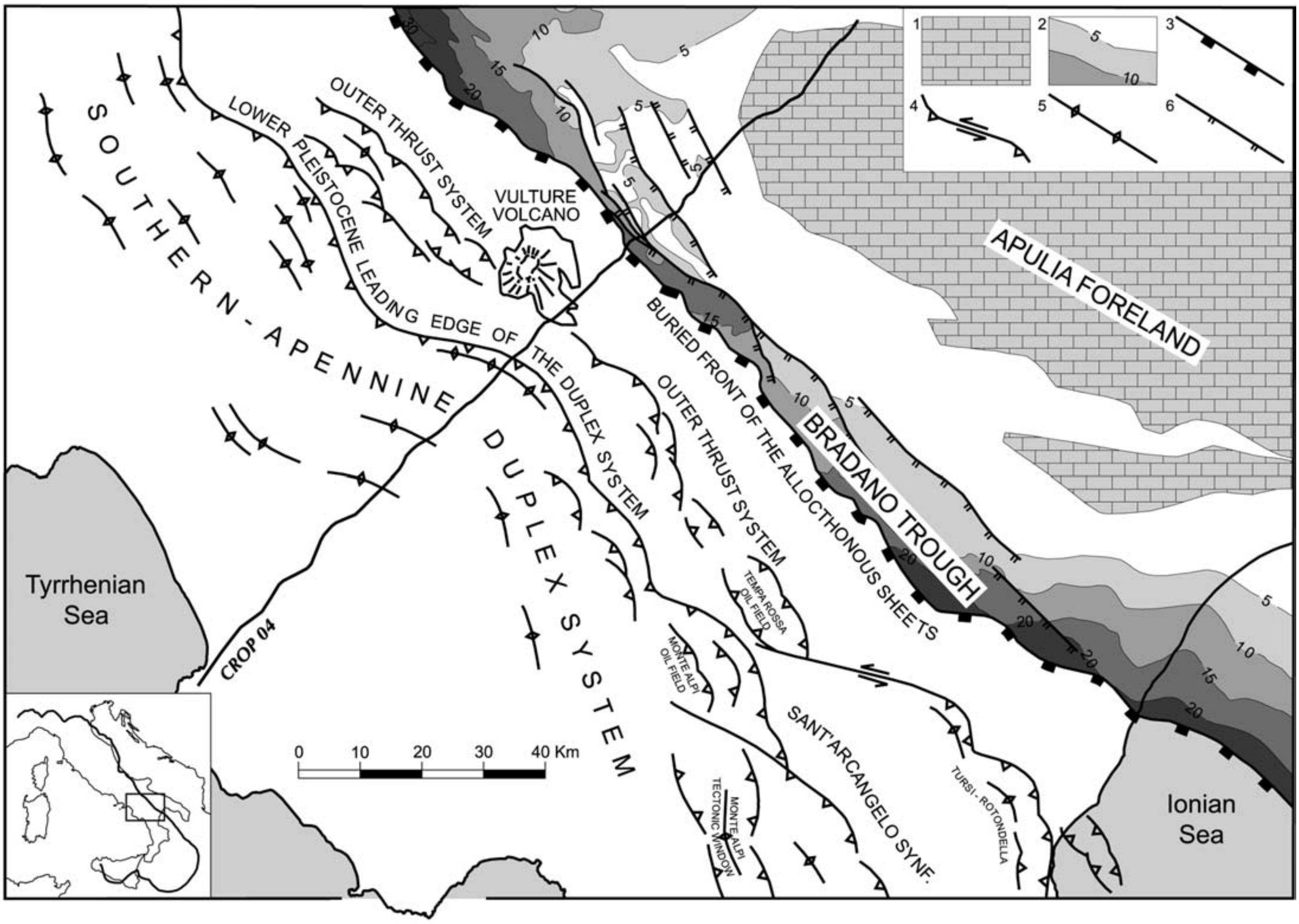


Fig. 2 - Simplified structural map showing the major tectonic features at the top of the buried Apulia carbonates in the area crossed by the CROP-04 line (after PATACCA & SCANDONE, 2001 with slight modifications). 1) Autochthonous Mesozoic carbonates of the Apulia foreland. 2) Base of the Plio-Pleistocene deposits in the foredeep basin (isobaths in hundreds of meters). 3) Front of the Apennine allochthonous sheets. 4) Thrust faults (frontal, oblique and lateral ramps). 5) Anticlines, antiformal stacks and axial culminations of the Apennine duplex system, including its emergence in the Monte Alpi tectonic window. 6) Normal faults.

– Principali strutture tettoniche al top dei carbonati apuli sepolti nell'area attraversata dal profilo CROP-04 (da PATACCA & SCANDONE, 2001 con lievi modifiche). 1) Carbonati mesozoici autoctoni dell'avampaese pugliese. 2) Base dei depositi plio-pleistocenici nel bacino di avanfossa (isobate in centinaia di metri). 3) Fronte delle coltri appenniniche. 4) Faglie inverse e sovrascorrimenti (rampe frontali, oblique e laterali). 5) Anticlinali, antiformal stacks e culminazioni assiali del sistema duplex sepolto, inclusa l'emergenza dei carbonati apuli nella finestra tettonica del Monte Alpi. 6) Faglie normali.

ture of the Adria platform-and-basin system, in this volume). On the surface, a small outcrop of Mesozoic-Tertiary carbonates belonging to the Apulia-carbonate duplex system is exposed in the Monte Alpi tectonic window (southern Basilicata, SW of the Sant'Arcangelo synform, see fig. 1). The thick pile of allochthonous sheets lying on top of the Apulia-carbonate duplex system is basically made up of Mesozoic-Tertiary sedimentary sequences, derived from platform and basin paleogeographic domains. The geometrical relationships between the Apennine tectonic units are schematized in fig. 3. Due to the direction of the tectonic transport principally towards the NE, i.e. from the Tyrrhenian region towards the Adriatic-Apulia foreland, the geometric order of the Apennine units shown in fig. 3 from the highest unit to the lowest one roughly follows the pattern of the corresponding paleogeographic domains from the most internal domains (SW) to the most external ones (NE). Fig. 4 provides synthetic information on the depositional characteristics and ages of the stratigraphic sequences representative of the thrust sheets and thrust-sheet-top deposits of the area crossed by the CROP-04 seismic line. The onset of the siliciclastic flysch deposits in the different tectonic units and the base of the unconformably overlying thrust-sheet-top deposits, both getting younger from the Tyrrhenian to the Adriatic regions, describes the eastward time/space migration of the thrust belt-foredeep-foreland system.

The autochthonous portion of the Apulia platform crops out in the Murge foreland. Between the Murge region and the buried leading edge of the duplex system, the flexured Apulia carbonates gently dip towards the mountain chain giving origin to a structural depression the southern portion of which is known in the geological literature as the Bradano Trough (see fig. 1). This depression represents the youngest foredeep basin of the Southern Apennines, active in late Pliocene and early Pleistocene times.

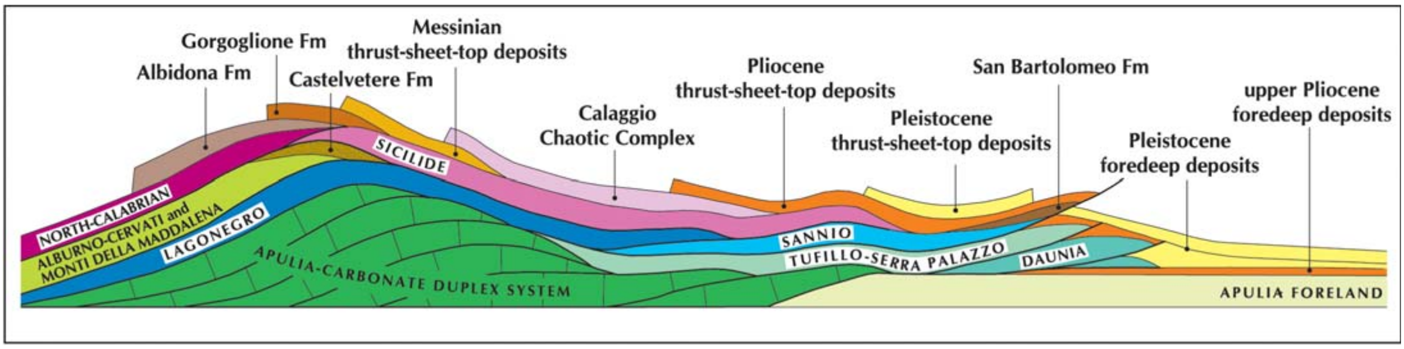


Fig. 3 - Geometric relationships between the Apennine tectonic units in the area crossed by the CROP-04 line.
– Rapporti geometrici tra le varie unità tettoniche appenniniche nell'area attraversata dalla linea CROP-04.

In the Southern Apennines, the bulk of the nappe stacking took place in Miocene times. Subsequently, during the early Pliocene, the entire pile of nappes overthrust the Apulia Platform. In middle-late Pliocene times, the Apulia Platform too was reached by the compression front and underwent severe tectonic shortening. This shortening is recorded by duplex structures in the Apulia carbonates and by the considerable forward displacement of the allochthonous sheets after the early Pliocene. Around the early Pleistocene-middle Pleistocene boundary, flexure-hinge retreat ceased suddenly along the whole Apulia margin, together with shortening in the mountain chain, and the entire Southern Apennine region began to undergo generalized uplift processes (CINQUE *et alii*, 1993; HIPPOLYTE *et alii*, 1994a).

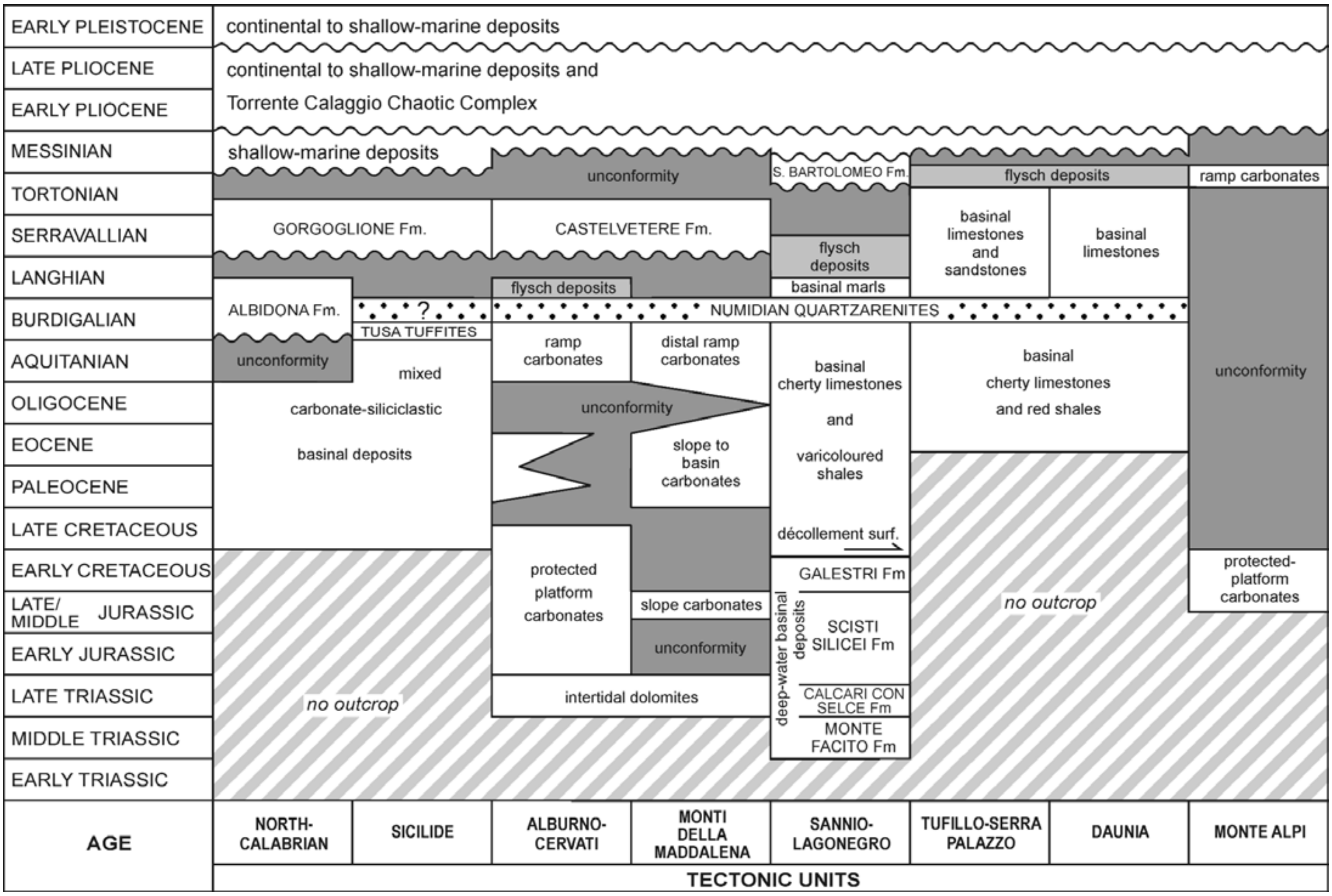


Fig. 4 - Sedimentary characteristics and ages of the stratigraphic sequences representative of the tectonic units and of the thrust-sheet-top deposits cropping out in the area crossed by the CROP-04 line.
– Caratteristiche principali ed età delle sequenze stratigrafiche rappresentative delle unità tettoniche e dei depositi discordanti sulla catena nell'area attraversata dalla linea CROP-04.

3. GEOLOGICAL INTERPRETATION OF THE CROP-04 PROFILE

Fig. 5 is a base map showing the trace of the CROP-04 seismic profile together with the location of commercial lines and wells that contributed to the geological interpretation proposed in this paper. In the description of the CROP-04 profile, we will move from the Adriatic coast to the Tyrrhenian coast starting from the stable Apulia-foreland region.

3.1. The Murge foreland

Two exploration wells, the Canosa 1ax and Puglia 1 wells, penetrated the Mesozoic carbonates of the Murge foreland in correspondence to the CROP-04 transect. Canosa 1ax crossed the Turonian-Barremian Bari Limestone and underlying lower Cretaceous-Jurassic shallow-water carbonates but was abandoned at 4003 meters without reaching the upper Triassic evaporites and associated dolomites of the well-known Burano Formation widespread in the whole Apulia-Adriatic region. The deeper Puglia 1 well (total depth: 7070 m) crossed the entire Apulia Platform, including the upper Triassic evaporites, and drilled from 6112 to 7070 m a Permo-Triassic unit made up of continental to shallow-marine siltstones and sandstones with subordinate clastic carbonates containing fragments of fusulinids. Coeval carbonate/terrigenous deposits at the base of the Apulia Platform have also been reached by the Gargano 1 well, located several tens of kilometers north of Puglia 1, out of the area mapped in fig. 1. In the Gargano 1 and Puglia 1 wells, the contact between the upper Triassic dolomites plus anhydrites and the underlying Permo-Triassic terrigenous deposits coincides with a sudden decrease in the Δt values and with a change in the GR and resistivity curves both featured by a relatively smooth cylinder-shaped profile in the upper Triassic massive dolomites plus anhydrites and by a quite ragged signature in the Permo-Triassic clastic deposits. Several commercial lines located between Gargano 1 and Puglia 1, not far from the CROP-04 transect, show that the Permo-Triassic deposits reached by the aforementioned wells represent only the uppermost portion of a layered seismic unit that in some cases has been recorded for more than 3 seconds TWT without reaching the base. This unit, which strongly contrasts with the almost reflection-free image of the overlying platform carbonates plus anhydrites, is imaged by discontinuous packages of parallel reflectors with variable amplitude and frequency. The top of the reflective unit is often lined by a band of subparallel, discontinuous stronger reflectors. Fig. 6 contains the stratigraphic logs of Puglia 1 and Gargano 1 together with a short segment of commercial line located not far from the CROP-04 profile showing the entire carbonate platform above the reflective layered unit the uppermost portion of which has been reached by drilling. The bulk of the layered sequence is supposed to represent the Paleozoic sedimentary cover, perhaps affected by low-grade metamorphism, of a Precambrian basement (Baikalian-Panafrican crystalline basement, see Vai, 1994, 2001) that was part of the foreland of the Hercynian mountain chain.

Between the Puglia 1 and Canosa 1ax wells, sets of discontinuous parallel reflectors at about 2 sec TWT have been correlated with the seismic signature that usually marks the boundary between the Paleozoic-Triassic terrigenous sequence and the upper Triassic dolomites plus evaporites of the Apulia Platform. An average P-wave velocity of 6 Km/sec in the Apulia Platform (Cretaceous-upper Triassic carbonates plus upper Triassic anhydrites) fits the depth (6112 m) at which the Puglia 1 well crossed the base of the platform. Fig. 7 is a detail of the CROP-04 line between the CDP 3606 and 3786 showing the layered sedimentary unit, imaged by discontinuous sets of well-organized parallel reflectors, that extends from 2 sec to more than 5 sec TWT. Thus, the CROP-04 profile confirms the indication given by commercial lines in the area according to which the Paleozoic sedimentary sequence reaches a minimum record time of 3 seconds TWT. This fact implies a thickness that exceeds 8 kilometres assuming velocity values not smaller than 5.5 Km/sec, which would be unrealistic in sedimentary rocks lying at depths greater than 6000 metres. Below 5.5 sec TWT, the lack of reliable signal does not allow the recognition of any crustal structure. The boundary between an upper crust and a lower crust at about 9 sec TWT indicated in Plate 2 is a mere suggestion derived from the existence of discontinuous sets of well organized deep reflectors between the CDP 2666 and 2886 possibly representative of a layered lower crust.

3.2. The foredeep basin

Between the inner margin of the Murge hills and the front of the allochthonous sheets (i.e. between the CDP 3200 and 2606 in Plates 1 and 2), the top of the Apulia carbonates deepens towards the mountain chain downthrown by a westward-dipping normal fault, which reaches the surface at about the CDP 2826. The base of the Apulia Platform and the underlying layered unit are quite well recognizable, mainly in correspondence to the Apennine nappe front. At major depths, from the CDP 2686 to the CDP 2886, sets of well-organized, subparallel subtle reflectors at 9-10 sec TWT suggest the existence of a layered lower crust.

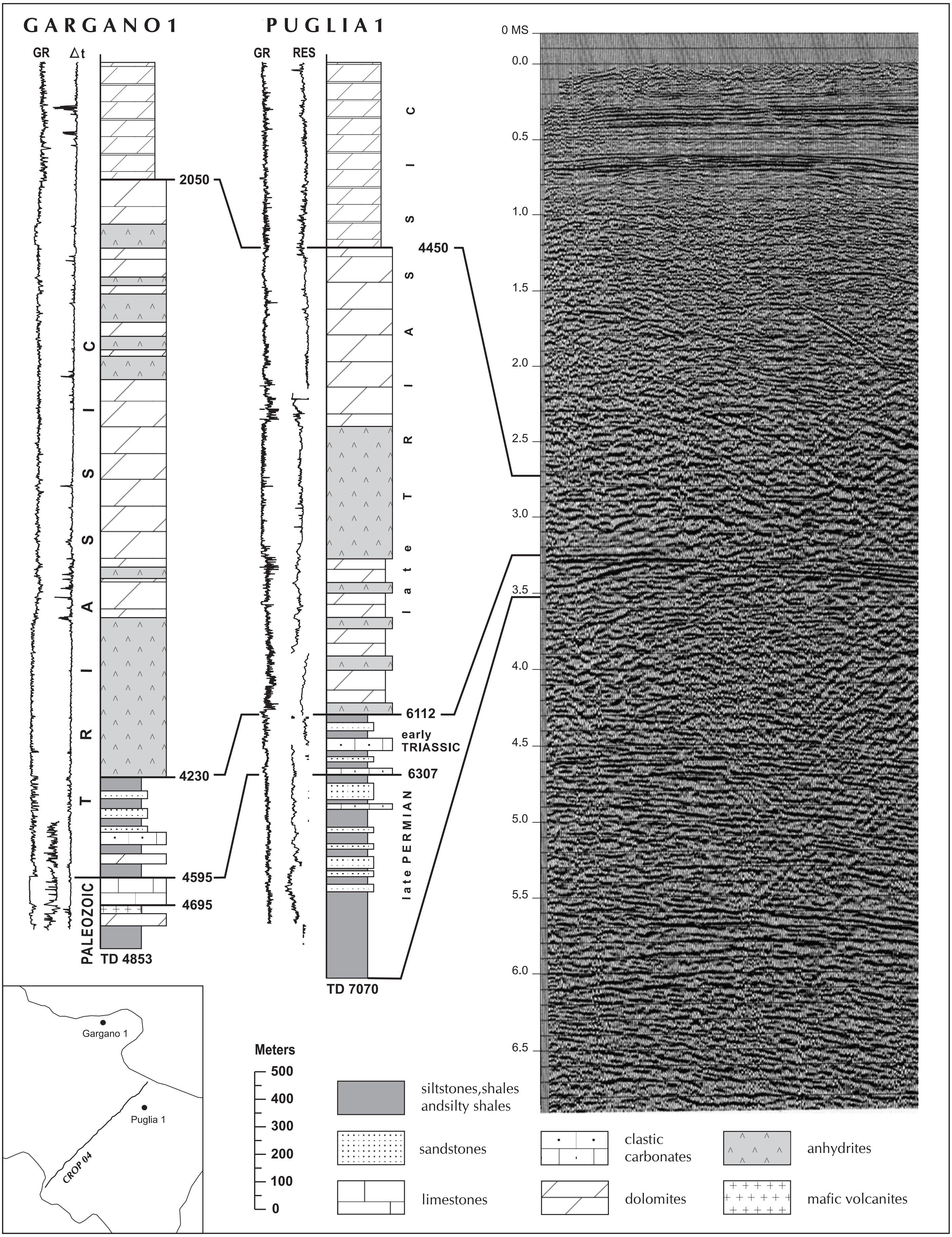
Due to the modest quality of the seismic data at shallow depths, the CROP-04 profile does not provide a good image of the Plio-Pleistocene deposits filling the foredeep basin and unconformably overlying the front of the allochthonous sheets. Nevertheless, several commercial lines cutting across the Apennine nappe front and the foredeep basin describe in detail the stratal architecture of the foredeep deposits in the CROP-04 transect. Fig. 8 is a line drawing of a merged line located at about twenty kilometers NW of the CROP-04 line that crosses at about 90° the trends of the tectonic structures. The top of the Apulia carbonates, usually marked by a couple of high-amplitude/low-frequency reflectors, is highlighted in this profile by the presence of a drape of Pliocene condensed deposits (3.70-3.30 Ma). Above the condensed deposits three intervals have been distinguished, which have been deposited before the arrival of the allochthonous sheets in the area (3.30-1.83 Ma interval), during the growth of the frontal ramp of the allochthonous sheets (1.57-1.50 Ma interval) and after the deactivation of the ramp (interval overlying the 1.50 Ma surface, which sutures the frontal ramp). The 1.83-1.57 Ma deposits are represented by a condensed muddy section, well recognizable in the whole foredeep basin, deposited during the forward transport of the allochtho-

Fig. 5 - Base map showing the trace of the CROP-04 reflection seismic profile and the location of the commercial lines and wells contributing to the geological interpretation proposed in this paper. 1) Normal faults and strike-slip faults. 2) Thrust flat. 3) Thrust ramp. 4) Anticline axis. 5) Syncline axis. 6) Caldera rim (Vulture Volcano). 7) Trace of the CROP-04-89 seismic line. 8) Trace of commercial lines used to constrain the interpretation of the CROP-04 transect. 9) Commercial wells providing useful information on the geometry of the Apennine units and on the stratigraphy of the Plio-Pleistocene deposits in the subsurface.
– Mappa mostrante la traccia del profilo sismico a riflessione CROP-04 e l'ubicazione delle linee commerciali e dei pozzi che hanno contribuito all'interpretazione geologica proposta in questo lavoro. 1) Faglie normali e faglie trascorrenti. 2) Thrust flat. 3) Thrust ramp. 4) Asse di anticlinale. 5) Asse di sinclinale. 6) Bordo di caldera (Vulture). 7) Traccia della linea sismica CROP-04. 8) Traccia delle linee sismiche commerciali usate per vincolare l'interpretazione del transetto CROP. Pozzi che hanno fornito utili indicazioni sulla geometria delle unità appenniniche e sulla stratigrafia dei depositi plio-pleistocenici in sottosuolo

nous sheets over a long thrust flat. A description of the Plio-Pleistocene foredeep and thrust-sheet-top deposits in the area aimed at constraining structural and kinematic restorations of the CROP-04 transect is available in other pages of this volume (see PATACCA & SCANDONE, *Constraints on the interpretation of the CROP-04 seismic line derived from Plio-Pleistocene foredeep and thrust-sheet-top deposits*).

3.3. THE APENNINE THRUST BELT

Between the nappe front and the Ofanto synform (Atella toponym in Plates 1 and 2), the Apulia Platform and the underlying Paleozoic-Triassic terrigenous deposits are cut across and displaced by a system of extensional faults with listric geometry. Between the CDP 2266 and 2586, a faulted rollover anticline is clearly depicted


GARGANO 1
GR
Δt
TRIASSIC
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2050
4230
4595
4695
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PUGLIA 1
GR
RES
late TRIASSIC
early TRIASSIC
late PERMIAN
4450
6112
6307
TD 7070
0 MS
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
Gargano 1
Puglia 1
CROP 04
Meters
500
400
300
200
100
0
siltstones,shales andsilty shales
sandstones
limestones
clastic carbonates
dolomites
anhydrites
mafic volcanites

Fig. 6.

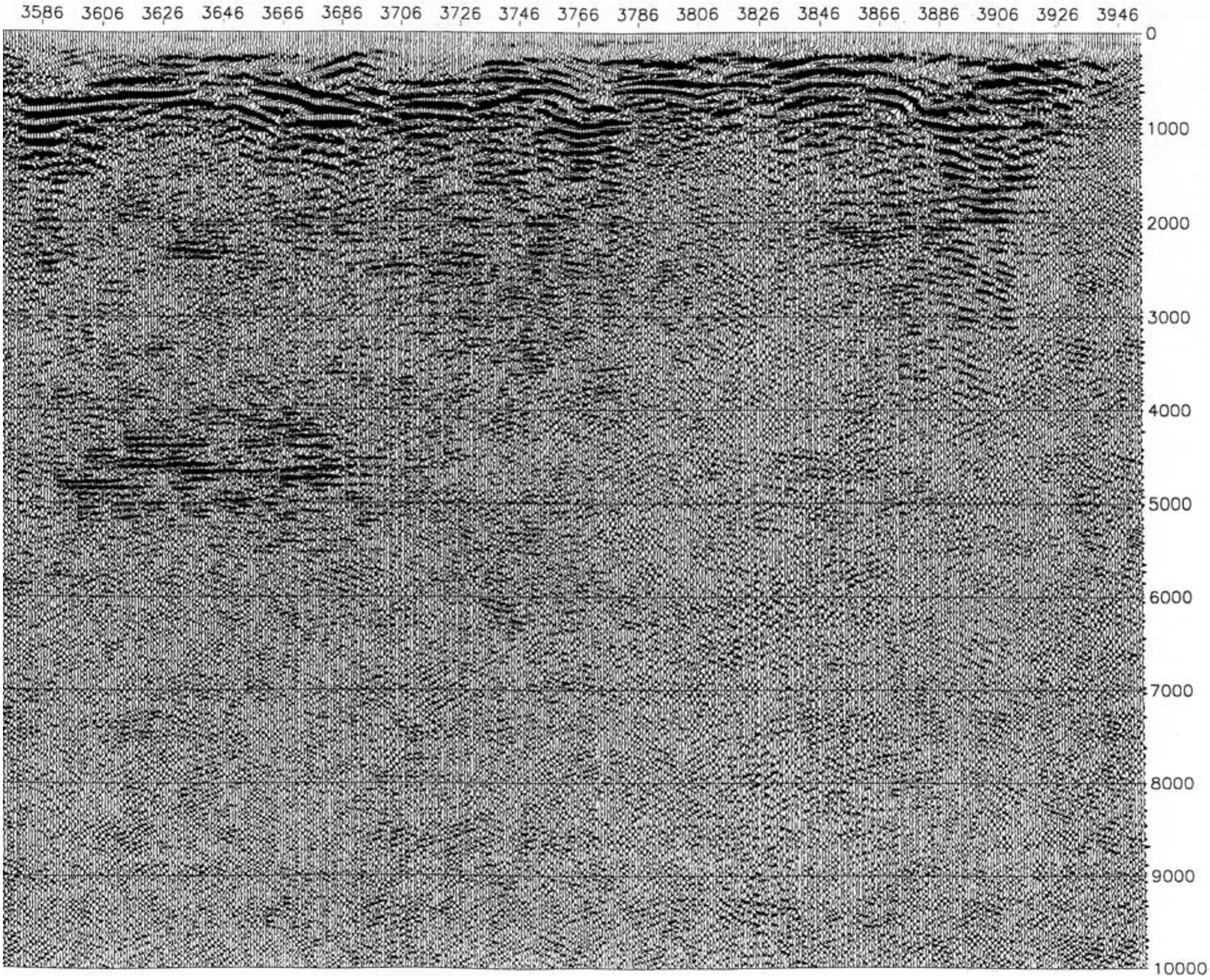
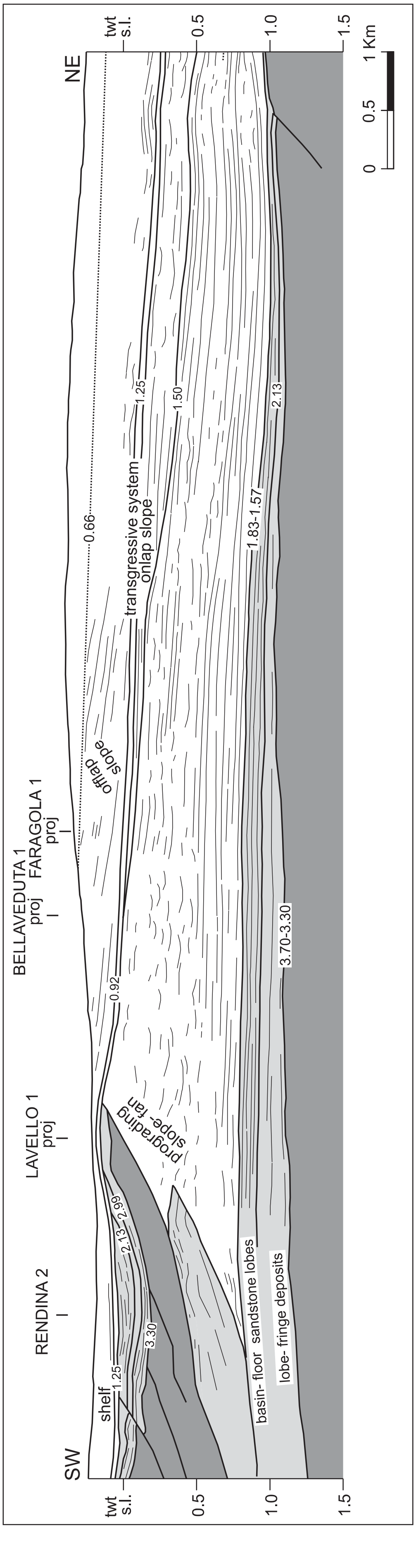


Fig. 7 - Easternmost portion of the CROP-04 line in the Murge foreland. Between 0 (Datum Plane = 400 m) and 2 sec TWT, the profile shows the seismic response of the Jurassic-Cretaceous platform carbonates and of the upper Triassic dolomites and anhydrites. Between 2 and 5.5 sec TWT, discontinuous sets of parallel reflectors displaying different amplitude and frequency evidence a seismic unit revealed also by commercial lines, which has been interpreted as a thick Paleozoic-Triassic sedimentary sequence unconformably overlying a Precambrian crystalline basement. The top of this sequence has been reached by the wells Puglia 1 and Gargano 1.
– Parte orientale della linea CROP-04 attraverso l'avampaese murgiano. Tra 0 e 2 secondi TWT (lo = corrisponde ai 400 metri sul livello del mare) il profilo mostra la risposta sismica dei carbonati di piattaforma giurassico-cretacei e delle dolomie ed associate anidriti triassiche. Tra 2 e 5.5 secondi, riflettori discontinui ma ben organizzati, aventi diversa ampiezza e frequenza, mettono in evidenza un'unità sismica riconosciuta anche nelle linee commerciali esistenti nell'area che è stata interpretata come una potente successione sedimentaria paleozoico-triassica discordante su un basamento cristallino precambriano. La sommità di questa successione è stata raggiunta dai pozzi Puglia 1 e Gargano 1.

by the reflector marking the top of the shallow-water carbonates. Immediately west of the CDP 2186, a deep-seated fold possibly represents an inverted structure related to the reactivation as a contractional fault of the westernmost extensional fault. Between the CDP 1986 and the CDP 2166, the stack of strong reflectors in the allochthonous sheets overlying this structure has been interpreted as a wedge of carbonate/siliciclastic deposits of the Tufillo-Serra Palazzo Unit tectonically covered by the Lagonegro and Sannio Units, which has been transported by a backthrust over the northeastern flank of the San Fele structure.

The San Fele structural high is a thick antiformal stack of Lagonegro imbricates that has been penetrated for more that 5300 meters by the San Fele 1 well (see fig. 9). In other pages of this volume the reader will find a description of the borehole stratigraphic data (PATACCA E., *Subsurface constraints on the CROP-04 seismic line interpretation: San Fele 1, Monte Foi 1 and San Gregorio Magno 1 wells*. *Southern Apennines, Italy)* and a discus-

Fig. 6 - Stratigraphic logs of Puglia 1 and Gargano 1, the only wells in the study area that have reached the Permo-Triassic terrigenous deposits beneath the Triassic evaporites, and detail of a commercial line located not far from the CROP-04 profile showing the top and the bottom of the Apulia Platform and the underlying layered unit recorded for more than 3 sec TWT.
– Logs stratigrafici dei pozzi Puglia 1 e Gargano 1, gli unici pozzi nell'area di studio che hanno raggiunto i depositi terrigeni permo-triassici alla base della Piattaforma Apula, e dettaglio di una linea sismica commerciale ubicata non lontano dal profilo CROP-04 nella quale sono visibili la sommità e la base della Piattaforma Apula e la successione sedimentaria triassico-paleozoica che in questa sezione supera i 3 secondi (tempi doppi) di registrazione.



sion on the kinematic relationships between the growth of the antiformal stack and the internal shortening of the Apulia-carbonate duplex system during the late Pliocene (Patacca E. & Scandone P., *Constraints on the interpretation of the CROP-04 seismic line derived from Plio-Pleistocene foredeep and thrust-sheet-top deposits*). The resolution of the CROP-04 seismic data is insufficient for reconstructing the internal geometry of this complex tectonic feature, but high-quality commercial lines cutting through the antiform provide a good picture of its structural configuration. Fig. 10 shows our interpretation of a seismic line running parallel to the CROP-04 profile at a distance of about one kilometer. This line, as other commercial lines available in the San Fele region, has a very good resolution but is not long enough to show the location of the trailing edge of the antiformal stack and consequently to identify the point where the breach nucleated from the buried Apulia-carbonate duplex system. This breach was obviously expected at the termination of a long thrust flat in the Apulia carbonates. By integrating the information coming from the commercial lines with the information coming from the CROP-04 profile, as well as with the stratigraphic data of the San Gregorio Magno 1 well (see fig. 11) in which the Lagonegro Units do not show any trace of duplexing, we reached the conclusion that the branch line joining the main thrust at the base of the Apennine nappes to the breach that cuts through the allochthonous sheets allowing the generation of a shallower duplex system in the Lagonegro Units has to be localized at the tip of the carbonate thrust sheet drilled by the San Gregorio Magno 1 well. The latter is exactly located in correspondence to the crest of the Apulia duplex system where the top of the carbonates lie at a depth of 3168 m below sea level.

Moving from San Gregorio Magno 1 towards the Tyrrhenian coast, the bulk of the recognizable reflectors gently dip towards the southwest displaying a quite coherent internal organization. The rocks cropping out in the area are basically represented by the Mesozoic shallow-water carbonates of the Alburno-Cervati Unit tectonically overlain, in the structural depressions, by the basinal calcareous/siliciclastic deposits of the Silicide Unit (Tanagro Valley near Contursi; synform between the Alburno and Soprano mountains). West of Monte Soprano, the Alburno-Cervati carbonates disappear beneath the deposits of the North-Calabrian Unit plus Albidona Formation, but have been reached by Cicerale 1 at a depth of 2432 meters below sea level.

In the CROP-04 line, a well-layered reflective unit underlies the carbonates of the Alburno-Cervati Platform and can be easily followed from the Tyrrhenian coast to the northern margin of Monte Alburno for a distance of about 40 kilometers. This unit, evident also in several commercial lines in the area, has been interpreted in other pages of this volume as a Verrucano-type sedimentary sequence stratigraphically underlying the Triassic

Fig. 8 - Line drawing of a merged commercial line cutting across the front of the Apennine chain a few tens of kilometers NW of the CROP-04 profile. Depths in seconds TWT. After Patacca & Scandone, 2001 with slight modifications.
– *Line drawing di una linea sismica commerciale composita che passa attraverso il fronte della catena appenninica qualche decina di chilometri a NW del profilo CROP-04. Profondità in secondi, tempi doppi. Da* Patacca & Scandone*, 2001 con lievi modifiche.*

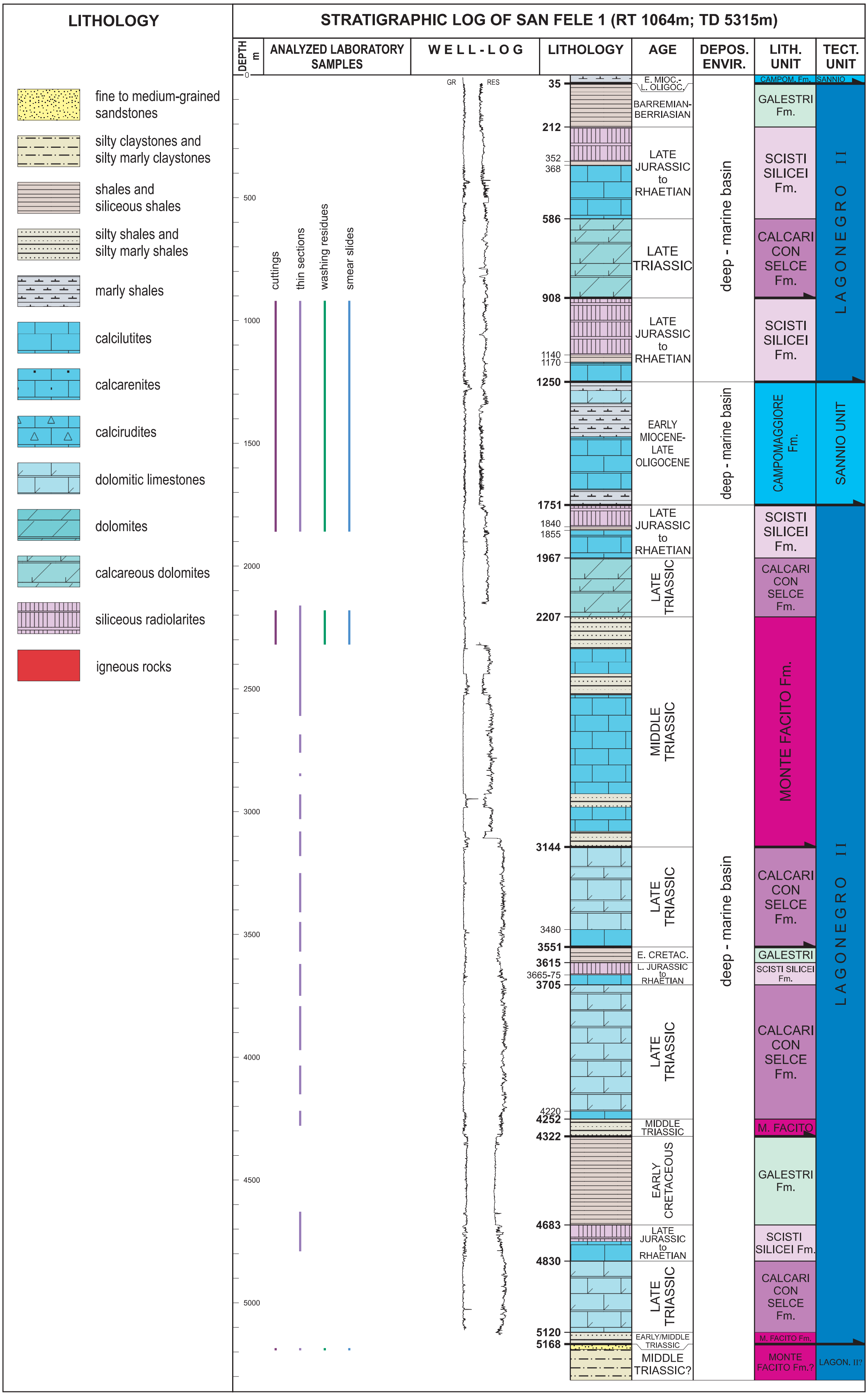


Fig. 9 - Simplified composite log of the San Fele 1 well (T.D. 5315 m).
– *Log composito semplificato del pozzo San Fele 1 (profondità finale: 5315 m).*

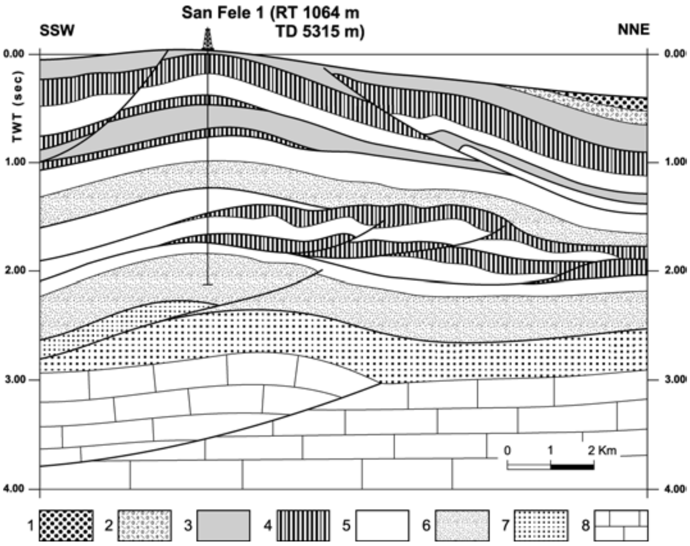


Fig. 10 - Interpretation of a commercial line cutting across the San Fele antiformal stack. The line, tied to the stratigraphic log of the San Fele 1 well, runs parallel to the CROP-04 profile at a distance of about one kilometer. Depths in seconds TWT. 1) Thrust-sheet-top deposits of the $P1_{-2}$ depositional sequence. 2) Upper Messinian-Lower Pliocene thrust-sheet-top deposits (Calaggio Chaotic Complex). 3) Sannio Unit. 4-6) Lagonegro Unit II: 4 Galestri Formation (lower Cretaceous); 5) Scisti Silicei and Calcari con Selce Formations (upper Jurassic-upper Triassic); 6) Monte Facito Formation (middle Triassic). 7) Lower Pliocene deposits overlying the buried Apulia carbonates. 8) Mesozoic-Tertiary Apulia carbonates.

– Interpretazione di una linea sismica commerciale che taglia trasversalmente l'antiformal stack di San Fele. La linea, calibrata sul log stratigrafico del pozzo San Fele 1, corre parallela al CROP-04 ad una distanza inferiore al chilometro. Profondità in secondi, tempi doppi. 1) Depositi discordanti della sequenza deposizionale $P_{1\text{-}2}$. 2) Depositi del Messiniano superiore-Pliocene inferiore (Complesso Caotico del Torrente Calaggio). 3) Unità Sannio. 4-6) Unità Lagonegrese II: 4 Formazione dei Galestri (Cretaceo inferiore); 5) Formazione degli Scisti Silicei e Formazione dei Calcari con Selce (Giurassico superiore-Trias superiore); 6) Formazione di Monte Facito (Trias medio). 7) Depositi del Pliocene inferiore che ricoprono i carbonati apuli. 8) Carbonati mesozoico-terziari apuli.

carbonates of the Alburno-Cervati Unit, unknown on the surface (see CIPPITELLI, *The CROP-04 seismic profile: interpretation and structural setting of Agropoli-Barletta geotraverse*). These deposits, in other words, have been supposed to represent an equivalent of the Permo-Triassic carbonate/terrigenous deposits reached by Puglia 1 at the base of the upper Triassic dolomites plus anhydrites of the Apulia Platform. We do not agree with this interpretation introducing a sort of *deus ex machina* and are inclined to believe that the reflective unit is made up of Mesozoic-Tertiary deposits of the Lagonegro-Molise Basin which in surface sections and in subsurface explored sections are systematically present between the Alburno-Cervati plus Monti della Maddalena carbonates and the buried Apulia deposits. A correlation between the layered unit underlying Monte Alburno and the layered unit underlying Monte Marzano, the latter reached by the San Gregorio Magno 1 and Contursi 1 wells and certainly represented by Lagonegro deposits, seems to us very likely. In addition, the existence of a seismic unit representative of Mesozoic-Tertiary deposits of the Lagonegro-Molise Basin in quite internal areas of the mountain chain justifies the occurrence of a pile of Lagonegro deposits more than 3000 meters thick in the Acerno 1 well. The latter is located about 25 kilometers west of the CROP-04 trace, not far from the Tyrrhenian coast, on a structural trend probably intersecting the CROP profile at the CDP 1025-1046. The interpretation of the layered unit as Lagonegro deposits has obviously guided the reconstruction of the top of the Apulia carbonates between the Tyrrhenian coast and Contursi.

Let us now discuss the internal architecture of the buried Apulia-carbonate duplex system. When we have described the San Fele antiformal stack, we have remarked that the nucleation of the causative breach was expected at the tip of a thrust flat in the Apulia carbonates long enough to compensate the telescopic shortening of the Lagonegro Units. The evaluated shortening in this structure measures at least 40-50 kilometers (see PATACCA & SCANDONE, *Constraints on the interpretation of the CROP-04 seismic line derived from Plio-Pleistocene foredeep and thrust-sheet-top deposits*). The CROP-04 line confirms the theoretical speculations showing at the expected place a very important seismic feature represented by a well structured package of high-frequency/low-amplitude reflectors that extends from the crest of the Apulia duplex system to the Tyrrhenian margin of the mountain chain deepening from about 4 sec TWT in correspondence to San Gregorio Magno 1 to 7-8 seconds in correspondence to the end of the line and depicting as a whole a gently dipping homocline. Figs. 12-15 provide images of this seismic unit in the Monte Soprano (fig. 12) and Monte Alburno (figs. 13-14) areas and in the Tanagro Valley (fig. 15). The unit imaged in these figures correspond, in our opinion, to the Permo-Triassic carbonate/terrigenous deposits explored by Puglia 1 and Gargano 1 at the base of the Apulia Platform. The quite smooth geometry of the gently dipping couple represented by the reflective unit and the almost reflection-free overlying unit featuring the Apulia carbonates plus anhydrites fits very well the geometry of a thrust sheet on top of a long flat. In the CROP-04 profile, this thrust sheet exceeds 50 kilometers in length and therefore the amount of minimum displacement is in the same order of magnitude as the minimum telescopic shortening related to the growth of the San Fele antiformal stack.

Another long thrust flat in the Apulia carbonates was expected to emerge at the foot of the thrust-and-fold cascade featuring the northeastern flank of the Apulia-carbonate duplex system. A long flat is required to justify the forward transport of the allochthonous sheets over the upper Pliocene and lower Pleistocene deposits of the foredeep basin. The minimum amount of this transport averages 40 kilometers, without taking into consideration the tight imbricates developed at the rear of the nappe front (see again the aforementioned paper of PATACCA & SCANDONE in this volume). Our interpretation of the CROP-04 line shows beneath the carbonate thrust sheet explored by San Gregorio Magno 1 a deeper thrust sheet the tip of which lies at about 4 sec TWT in correspondence to the CDP 1986. The total displacement of this structure averages 45 kilometers, in a good agreement with the minimum forward transport of the allochthonous sheets over the upper Pliocene-lower Pleistocene deposits and with the 47 kilometers measured between the ramp-to-flat change in the thrust trajectory around the CDP 1486 and the tip of the allochthonous sheets at about the CDP 2626.

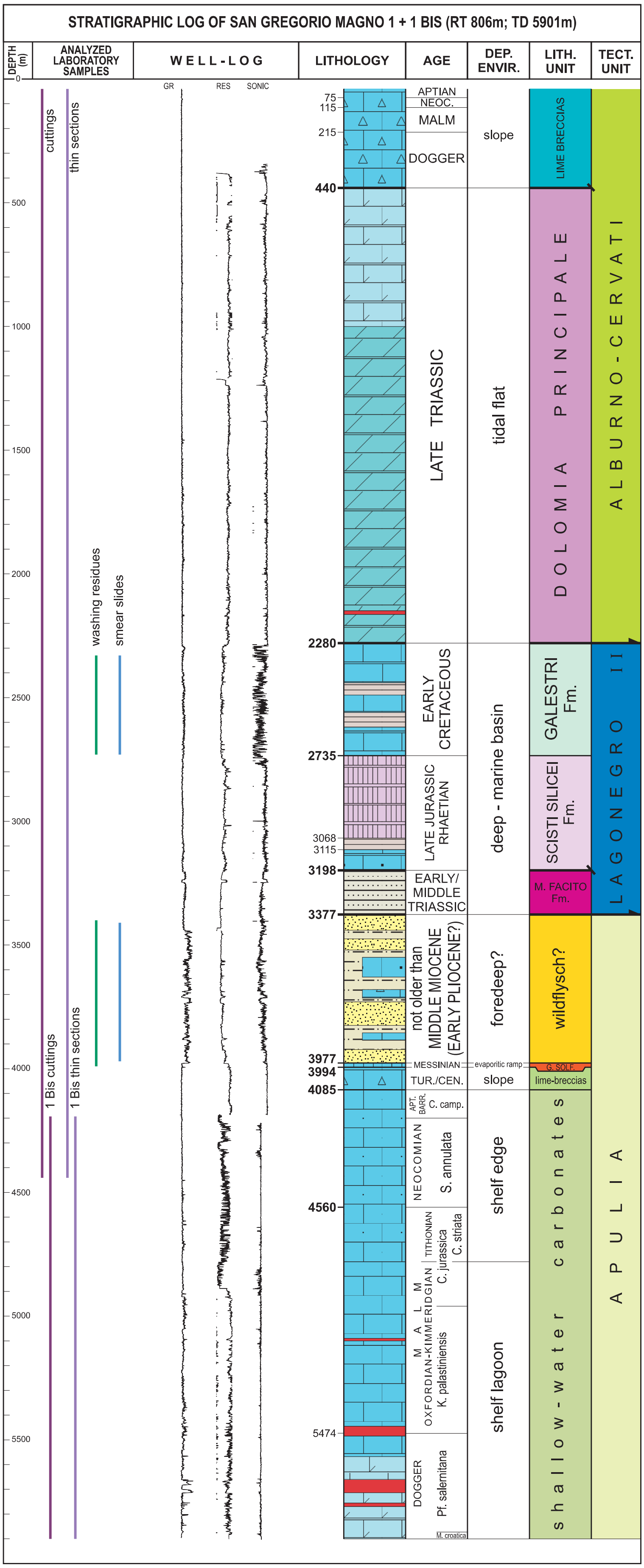


Fig. 11 - Simplified composite log of the San Gregorio Magno 1 well (T.D. 5901 m). Lithology legend in fig. 9.
– *Log composito semplificato del pozzo San Gregorio Magno 1 (profondità finale: 5901 m). Legenda delle litologie in fig. 9.*

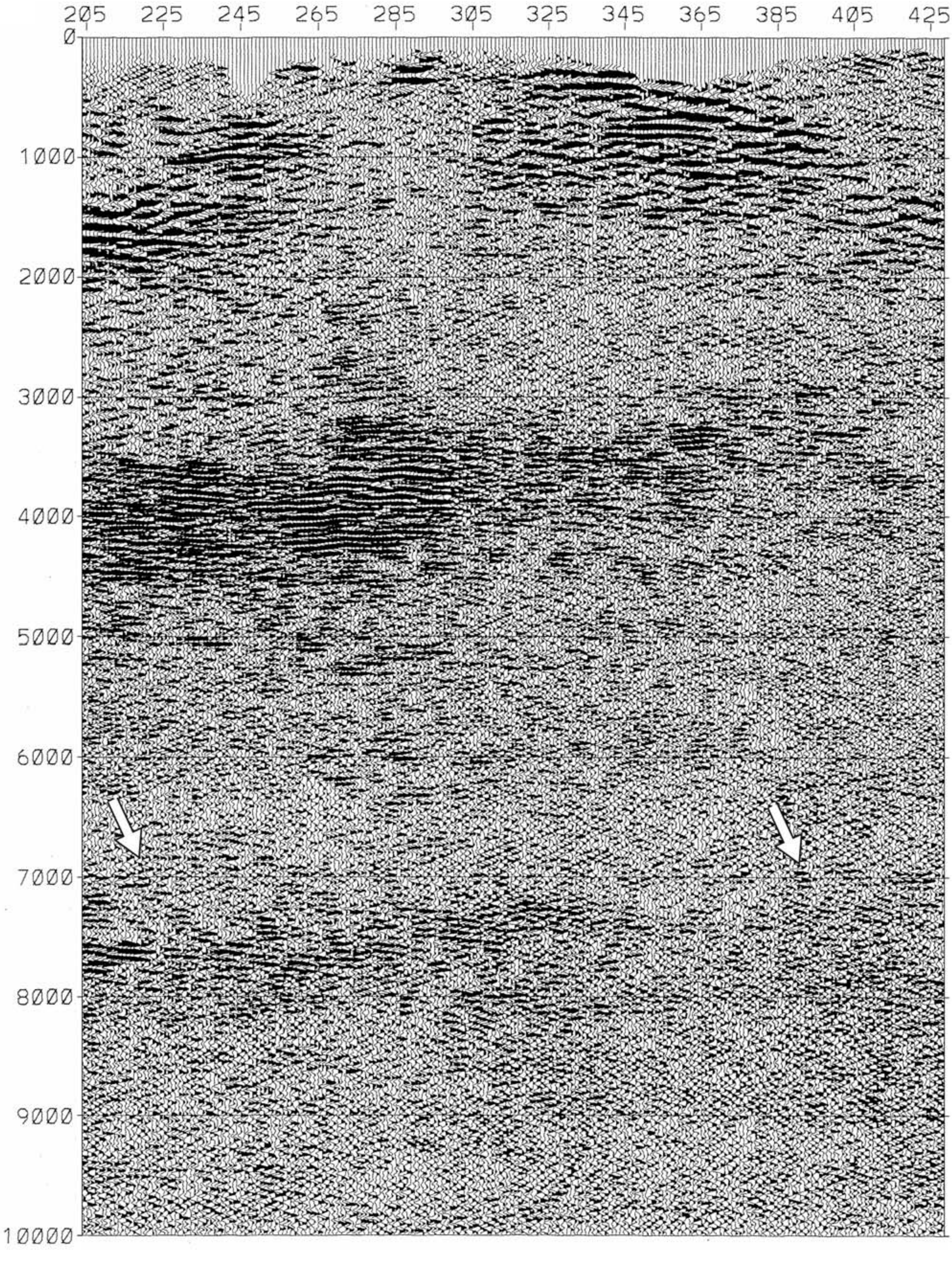


Fig. 12 - Segment of the CROP-04 line located in correspondence to Monte Soprano, not far from the Tyrrhenian coast, showing at a depth of 7-8 sec TWT the reflective seismic unit considered in this paper representative of the Permo-Triassic deposits stratigraphically underlying the Upper Triassic dolomites plus anhydrites of the Apulia Platform.
– *Segmento della linea CROP-04 ubicato in corrispondenza di Monte Soprano, non lontano dalla costa tirrenica, mostrante ad una profondità di 7-8 secondi tempi doppi l'unità sismica considerata in questo lavoro rappresentativa dei depositi permo-triassici sottostanti le dolomie e le anidriti del Trias superiore della Piattaforma Apula.*

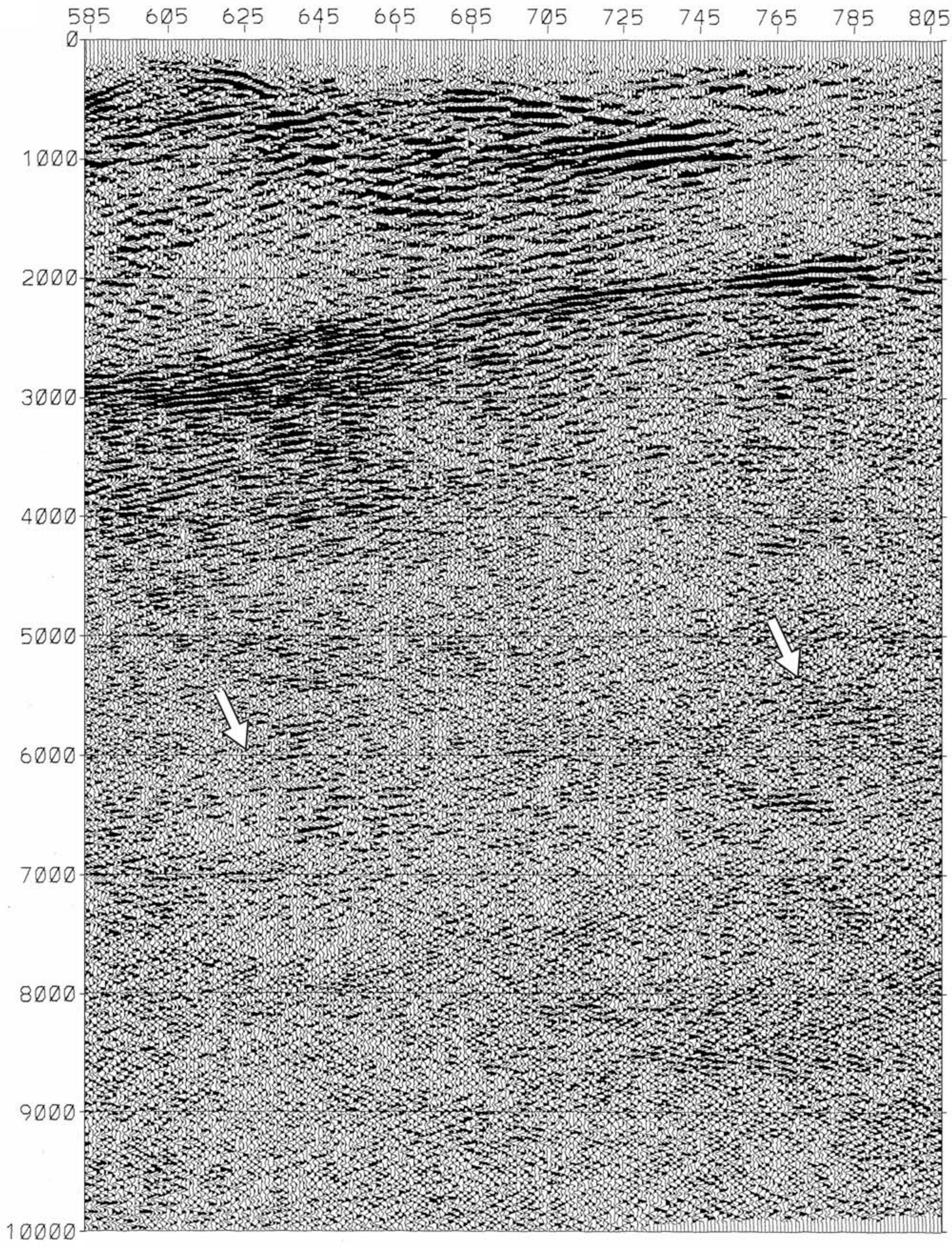


Fig. 13 - Same seismic unit as in fig. 12, at a depth of 6-7 sec TWT in correspondence to the southwestern margin of Monte Alburno, gently rising towards the crest of the Apulia-carbonate duplex system lying parallel to the regional dip of the surface and subsurface tectonic structures in the area.

– Stessa unità sismica della fig. 12, alla profondità di 6-7 secondi tempi doppi in corrispondenza del margine sud-occidentale dell'Alburno, in dolce risalita verso la cresta del sistema duplex sepolto di carbonati apuli e con giacitura parallela alle strutture tettoniche di ordine maggiore riconosciute nell'area in superficie e in sottosuolo.

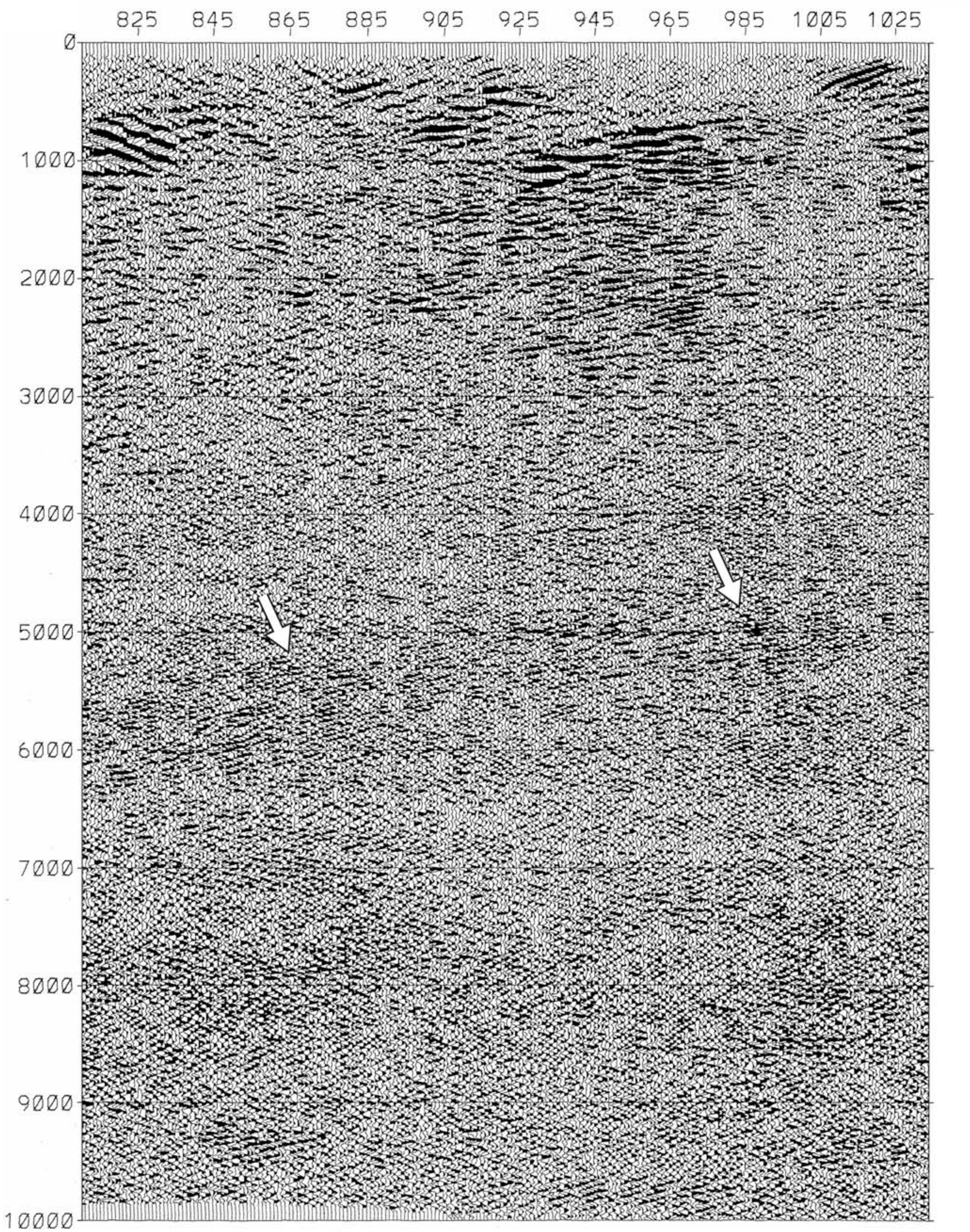


Fig. 14 - Moving towards the NE, same seismic unit and same geometry as in fig. 13 beneath the Alburno Mountain. The reflector package lies here at a depth of 5-6 sec TWT.
– Stessa unità e stessa configurazione geometrica delle fig. 2 con il pacco di riflettori ancora in salita riconoscibile alla profondità di 5-6 secondi tempi doppi.

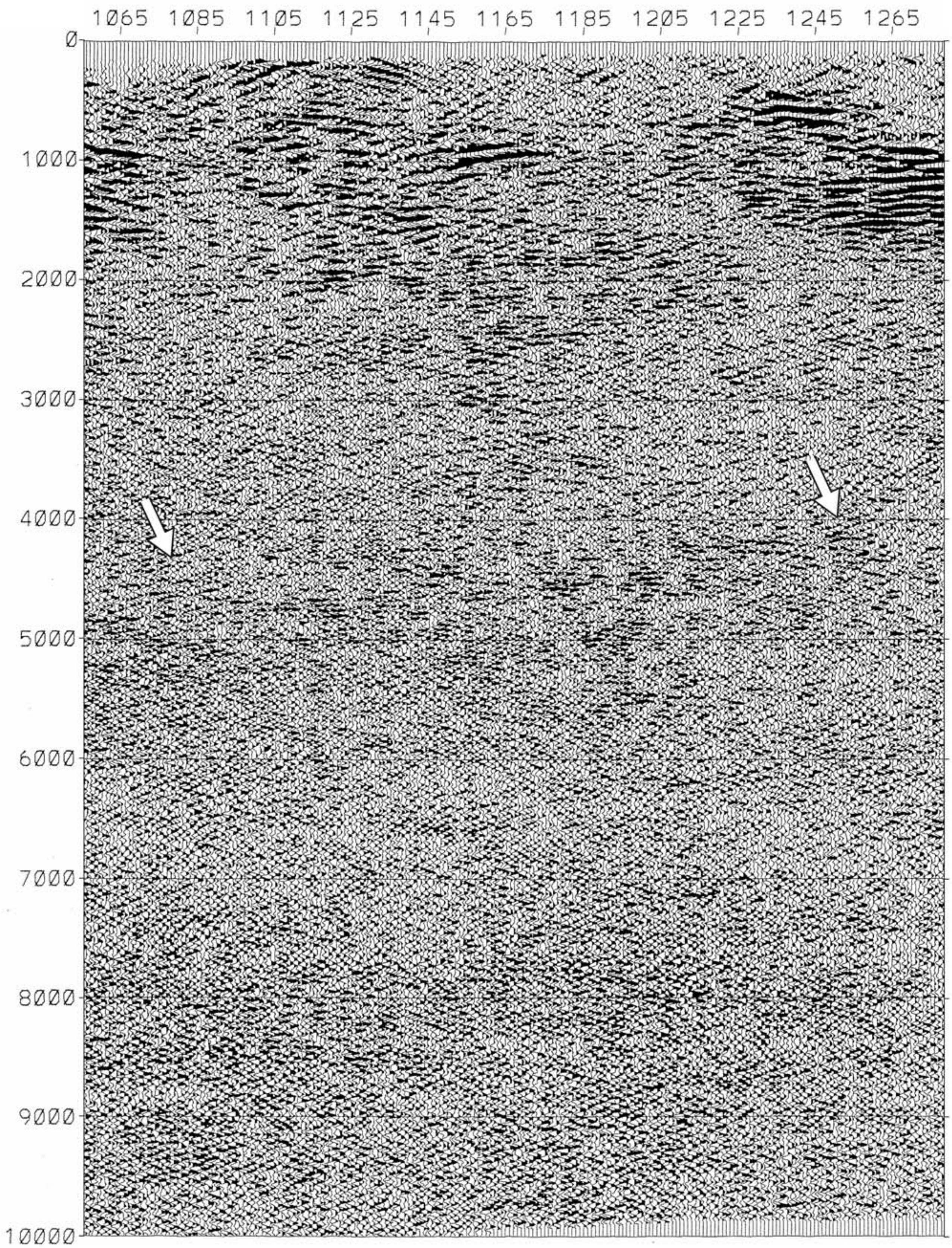


Fig. 15 - The seismic unit of shown in figs. 12-14 reaches structural culmination at 4-5 sec. TWT in correspondence to Monte Marzano before disappearing at about the CDP 1405. The highly reflective shallow unit between the CDP 1125 and 1345 and the upper half portion of the underlying more transparent unit correspond to the Lagonegro basinal deposits and to the Apulia shallow-water carbonates, respectively, crossed by the San Gregorio 1 well (see Plate 2).

– L'unità sismica mostrata nelle figg. 12-14 raggiunge la minima profondità (4-5 sec.) sotto il Monte Marzano per poi scomparire non lontano dal CDP 1405. L'unità fortemente riflettiva più superficiale e la metà superiore della sottostante unità trasparente corrispondono rispettivamente ai depositi bacinali lagonegresi e ai carbonati di piattaforma apuli attraversati dal pozzo San Gregorio Magno 1.

4. CONCLUSIONS

The acquisition of the CROP-04 line was aimed at providing information on: 1) the depth of the sole thrust of the tectonic wedge beneath the Apennine mountain chain; 2) the internal architecture of the buried Apulia-carbonate duplex system; 3) the involvement or non-involvement of the crystalline basement of Apulia in the post-Tortonian compressional deformation; 4) the identification of the lower crust of Apulia and the recognition of its extent towards the Tyrrhenian coast and finally 5) the identification of the backstop of the orogenic system.

Due to the very low signal/noise ratio, the first conventional processing of the CROP-04 line did not produce any interpretable seismic profile. A subsequent re-analysis and non-standard re-processing of the line brought to a new 10 sec TWT stack showing the quality a quality comparable with that of good commercial lines available in the area the record of which, however, usually does not exceed 5-6 sec TWT.

The interpretation of the reprocessed CROP-04 line provide new elements to give, or at least to suggest, realistic solutions to the principal open problem identified before the acquisition of the seismic line.

Depth of the sole thrust of the tectonic wedge. The well-structured reflective unit recognized in the western part of the line that rises from 7-8 sec TWT in correspondence to the Tyrrhenian coast to 4-5 sec TWT in correspondence to Monte Marzano constrains the location of the Apennine sole thrust at a depth exceeding 8 sec TWT, i. e. at a depth of at least 20 kilometers. Note that the depth of the sole thrust is independent from the geological attribution of the deep-seated reflective unit since it depends only on the climbing geometry of the reflectors that implies displacement in the hangingwall of a contractional fault.

Internal architecture of the buried Apulia-carbonate duplex system; involvement or non-involvement of the crystalline basement of Apulia in the post-Tortonian compressional deformation. The top of the Apulia carbonates rises from about 5 sec TWT in correspondence to the Tyrrhenian coast to less than 2 sec TWT in correspondence to the crest of the duplex system and subsequently deepens towards the NE until it reaches about 4 sec TWT at the foot of the thrust-and-fold cascade featuring the outer flank of the antiform. This geometry admits a lot of space between the crest of the antiform and the sole thrust. This space may be filled with imbricates of sedimentary rocks, and this would require a quite considerable amount of shortening of the Apulia Platform, or may be filled partly with sedimentary rocks and partly with rocks derived from a crystalline basement. Again the deep-seated reflective unit suggests with its geometry a thin-skin tectonic style, without any basement involvement. In our interpretation, a duplex internal architecture dominated by two major thrust sheets lying on top of long thrust flats fits independent geological data indicating a minimum cumulative shortening of the duplex system of 90-100 kilometers after the early Pliocene, i.e. after the transport of the allochthonous sheets on the western margin of the Apulia Platform.

Identification of the lower crust of Apulia and recognition of its extent towards the Tyrrhenian coast. The CROP-04 line cannot provide information on this point because the 10 sec TWT of time record of the re-processed stack are insufficient. Well-organized reflectors dubitatively attributed to the lower crust of Apulia, in fact, disappear below 10 sec TWT already in correspondence to the front of the mountain chain.

Identification of the backstop of the orogenic system. The CROP-04 profile indicates that the backstop of the Apennine thrust system must be located somewhere in the Tyrrhenian Sea, west of the line termination. Perhaps the Crop-Mare profiles will be able to image this important feature usually thought as a shallow asthenospheric wedge.

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