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Structural architecture of the central Apennines: Interpretation of the CROP 11 seismic profile from the Adriatic coast to the orographic divide

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[1] We present an interpretation of the eastern half portion of the CROP 11 line, a deep reflection seismic profile 265 km long that cuts across the central Apennines from the Tyrrhenian coast to the Adriatic coast. In the study area the line cuts across a pile of thrust sheets that underwent tectonic transport between the Messinian and the Pleistocene. In its easternmost part, the line runs through the Plio-Pleistocene deposits of the Adriatic foredeep. In the foreland region the CROP 11 line integrates previous information on the crustal structure derived from petroleum exploration and from deep seismic sounding refraction experiments. In particular, the CROP 11 line confirms the existence of a very thick sedimentary sequence underlying the Mesozoic-Tertiary carbonates of the Apulia Platform interpreted as the Paleozoic-Triassic sedimentary cover of a pre-Cambrian crystalline basement. In the mountain chain, where the base thrust of the orogenic wedge reaches a depth of about 25 km, this sedimentary sequence appears to be the deepest geological unit incorporated in the thrust system. This interpretation of the CROP 11 profile suggests an unusual thin-skin tectonic style implying the detachment from the original basement and the incorporation in the post-Tortonian tectonic wedge of a very thick Paleozoic-Triassic sedimentary sequence possibly affected by low-grade metamorphism in the lower part. Other new suggestions from the CROP 11 seismic data concern the origin of the Fucino basin, one of the most remarkable Plio-Pleistocene intramontane basins. The normal faults bordering this structural depression, as other important normal faults present in the central Apennines (e.g., the Caramanico fault system in the Majella region), seem to have been controlled by gravitational-collapse processes driven by uplift during crustal shortening rather than by a generalized extension subsequent to the Apennine compression, as usually reported in the geological literature. If this interpretation is correct, the strong seismic activity in correspondence to the Apennine watershed may be related to the very recent increase in the structural relief caused by an out-of-sequence propagation of the active thrusts.

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1. Introduction

[2] The CROP 11 line is a deep reflection seismic profile 265 km long that cuts across the whole central Apennines (southern portion of the Northern Apenninic Arc in Figure 1) from the Tyrrhenian coast near Civitavecchia to the Adriatic coast near Vasto. The CROP 11 Sub-project [*Cavinato et al.*, 1994b; *Parotto et al.*, 1996, 2003] was a task of a national research project called the CROP Project (CROsta Profonda Project, i.e., Deep Crust Project). The CROP Project started in 1984 in the wake of the successful results of the COCORP-Consortium for Continental Reflection Profiling in USA (see, among many others, *Brown et al.* [1986] and *Hauser and Oliver* [1987]) as a joint venture between CNR (National Research Council), AGIP (major Italian Oil Company) and ENEL (Electric Power National Company). The major aim of the Project was the investigation of the deep crustal structure of the Italian Peninsula and surrounding offshore areas by means of reflection seismic profiles and associated deep seismic sounding (DSS) refraction experiments [see *Scrocca et al.*, 2003, and references therein]. Besides the Italian CROP Project, several analogous research ventures flourished in the eighteen in Europe (e.g., BIRPS in UK, CZESLOCORP in Czechoslovakia, DERKORP in West Germany, ECORS in France and NRP20 in Switzerland; see, among many others, *BIRPS and ECORS* [1986], *Bois et al.* [1988], *Blundell* [1988], *Matthews* [1988], *Meissner and Bortfeld* [1990], *Matthews and BIRPS Group* [1990], *Roure et al.* [1990], *Meissner et al.* [1991], *Pfiffner et al.* [1997], and *Meissner and Rabbel* [1999]), as well as in non-European countries, among which Australia, Canada, China, India, Japan, New Zealand and USA [see *Blundell and Wright*, 1989].

[3] The acquisition of the CROP 11 seismic line postdates the acquisition of all other lines of the CROP Project. The western half portion of the profile, from the Tyrrhenian

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coast to the Apennine watershed (CROP11/CNR/ENEL 96 segment in Figure 2, 109 km long), was completed in 1996. Subsequently, near the end of 1999, the field acquisition was extended eastward as far as the Adriatic coast and about 156 km of reflection data were gathered (CROP11/DSTN 99 and CROP11/COGEPRO 99 segments in Figure 2). In the whole profile, the seismic signal was acquired using dynamite (30 kilograms per shot, depth of source 30 m, shot interval 160–180 m, station interval 40–60 m) with coverage 24–32. The data were recorded for 25 s TWT at a sample rate of 2 ms.

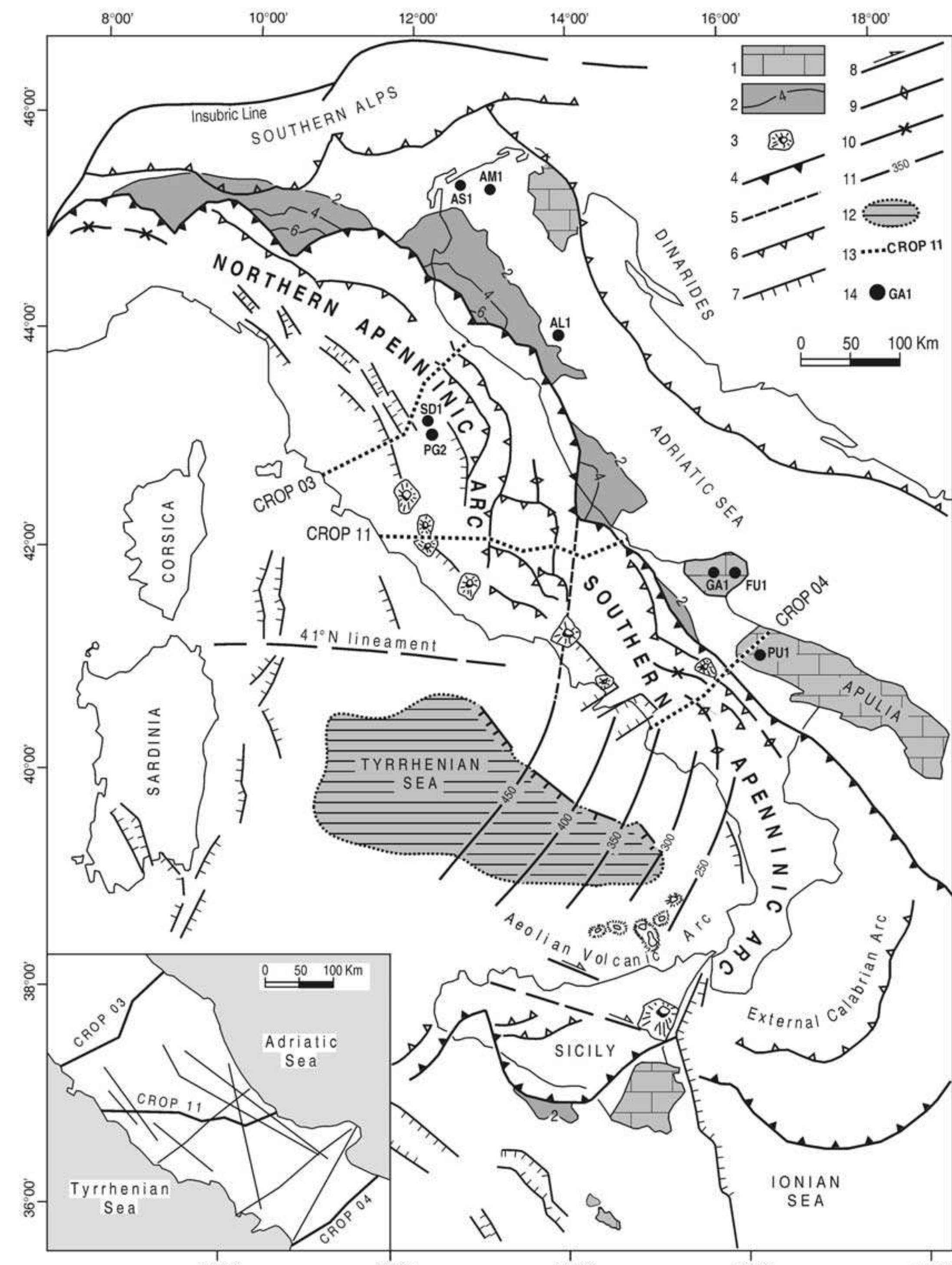


Figure 1

[4] In this paper, we will discuss the deep structural architecture of the central Apennines deduced from the interpretation of the eastern half portion of the CROP 11 profile from the Fucino Plain to the Adriatic coast, i.e., from the orographic divide of the mountain chain to the front of the Apennine thrust sheets. The profile employed in our interpretation was a raw stack section with horizontal scale 1:50.000 and vertical scale 1 s = 2.5 cm (see Foldouts 1–4, showing a reduced copy at the scale 1:100.000). Several commercial lines available in the study area, some of which stratigraphically linked to detailed information coming from exploration wells, were useful for the geological identification of the shallow seismic units and for the structural interpretation of the tectonic features recognizable in the CROP 11 profile between 0 and 5 s TWT. Refraction seismic experiments in the area (see traces of the principal DSS profiles in the lower left insert of Figure 1) provided important information on the P-wave velocities in the crust and established some constraints on the interpretation of the deep structures along the trace of the CROP 11 profile. The absence of seismic information at shallow depths in correspondence to the Majella Mountain, due to a gap in the data acquisition, has been partly replaced with the information deriving from a commercial line that cuts across the massif in its central part in correspondence to the maximum elevations (line A in Figure 3).

[5] The portion of mountain chain that extends from the Apennine orographic divide to the nappe front is formed by a pile of Adriatic-verging thrust sheets composed of Mesozoic-Tertiary sedimentary sequences which have undergone orogenic transport in post-Tortonian times. The late Tortonian represents a critical moment in the Apennine mountain building since a sudden increase in the flexure hinge retreat of the subducting Adria lithosphere produced in that time a decoupling between the upper plate (Corsica-Sardinia) and the lower plate with the consequent opening of the Tyrrhenian Basin driven by rollback mechanisms [*Malinverno and Ryan*, 1986; *Patacca and Scandone*, 1989] (see rates of the Adria flexure hinge retreat in work by *Patacca et al.* [1990] and *Patacca and Scandone* [2001]). A long-lasting debate among geologists concerns the tectonic style, thin-skinned or thick-skinned thrust tectonics, of the post-Tortonian Apennine wedge (see discussion in work by *Tozer et al.* [2002] and *Scrocca et al.* [2005]). At the state of the art, we do not know whether slices of crystalline basement have been or not been detached from the subducting lower plate and incorporated in the thrust belt during the of Tyrrhenian opening. The debate about thin-skin or thick-skin tectonics in the post-Tortonian mountain chain has recently weakened because of the success obtained by inversion models postulating basement involvement by reverse-sense reactivation of Mesozoic (mostly Jurassic) extensional faults [e.g., *Tavarnelli*, 1997; *Calamita et al.*, 2003; *Tavarnelli et al.*, 2003, 2004; *Butler et al.*, 2004]. However, it should be stressed that no seismic evidence of syn-rift Mesozoic deposits reactivated by the late Neogene compressional tectonics has been provided until now in the Apennines. The CROP 11 line was expected to shed light on the deep structure of the mountain chain and on the involvement/non-involvement of the crystalline basement in the tectonic shortening. We will see in the next pages that the recognition of a thick pile of Paleozoic-Triassic deposits beneath the upper Triassic dolomites and anhydrites of the Apulia Platform provided an important contribution to decipher the tectonic style of the central Apennines since this sedimentary unit seems to represent the deepest unit of Adria crust involved in the post-Tortonian orogenic transport.

2. Stratigraphic-Structural Lineaments of the Central Apennines and Adriatic Foreland

[6] The CROP 11 line crosses the central Apennines in correspondence to the southern termination of the Northern Apenninic Arc (see Figure 1) in a region in which the trend of the major tectonic structures changes from a NW-SE direction into a N-S direction. In its westernmost portion (see Figure 2) the seismic line runs through the so-called Roman magmatic district [*Serri et al.*, 2001, and references therein], a first-order half-Graben feature trending NW-SE, characterized by a widespread Quaternary volcanism related to the extensional and transtensional faulting of the Apennine Tyrrhenian margin [*Funiciello and Parotto*, 1978; *Faccenna et al.*, 1994]. Positive Bouguer gravity anomalies [*Carrozzo et al.*, 1991] related to the presence of a soft mantle at shallow depths (22–25 km, see "Tyrrhenian Moho" in work by *Locardi and Nicolich* [1988], *Nicolich and Dal Piaz* [1990], *Ponziani et al.* [1998], and *Scarascia et al.* [1998]) represent the most relevant geophysical

Figure 1. Structural sketch of the Italian Peninsula (modified after *Patacca et al.* [1993]) with the location of the CROP 11 seismic line and other CROP profiles that have cut across the Apennine thrust belt (CROP 03 and CROP 04). In the lower left insert, subtle lines indicate the traces of selected refraction seismic profiles providing information on the crustal characteristics of central-southern Italy. Key: 1, pre-Pliocene carbonates and minor volcanites exposed in the foreland regions; 2, isobaths (in km) of the base of the PIio-Pleistocene deposits in the foredeep basins; 3, major subaerial Quaternary volcanoes; 4, buried front of the thrust sheets in the Apennines, Calabrian Arc and Sicily; 5; conventional boundary between the Northern Apenninic Arc and the Southern Apenninic Arc; 6, front of the thrust sheets in the Southern Alps and Dinarides, major internal thrusts in the Apennines, Calabrian Arc, and Sicily; 7, normal faults; 8, strike-slip faults; 9, anticline axis; 10, syncline axis; 11, Wadati-Benioff zone in the Southern Tyrrhenian region (depths in kilometers); 12, Tyrrhenian area floored by oceanic crust and thinned continental crust, with positive Bouguer gravity anomalies exceeding 200 mgals; 13, CROP profiles cutting across the Apennine mountain chain; 14, commercial wells quoted in the text that have reached Triassic or older deposits. Abbreviations: AL1, Alessandra 1; AM1, Amanda 1; AS1, Assunta 1; FU1, Foresta Umbra 1; GA1, Gargano 1; PG2, Perugia 2; PU1, Puglia 1; SD1, San Donato 1.

characteristics of this extensional area. East of the Roman magmatic district, the CROP 11 line crosses a N-S trending fold-and-thrust system made up of Upper Triassic–lower Liassic shallow-water dolomites and limestones and middle Liassic–lower Miocene deeper-water carbonate deposits referred to the Sabina domain (southwestern portion of the Umbria-Marche paleogeographic realm). Moving eastward, toward the Abruzzi region, the line cuts across a N-S trending thrust system known in the current geological literature as the Olevano-Antrodoco Line [*Cipollari and Cosentino*, 1991, and references therein] and finally runs in the Mesozoic-Tertiary deposits of the Western Marsica-Meta Unit until it reaches the Apennine watershed in correspondence to the Fucino Plain. Starting from the Tiber Valley, the entire mountain chain is characterized by negative Bouguer gravity anomalies. The minimum values are reached in correspondence to the Fucino area. Along the trace of the seismic profile, the "Tyrrhenian Moho" (i.e., the tip of the Tyrrhenian soft-mantle wedge) would overthrust the "Adriatic Moho" (i.e., the crust-mantle boundary in the subducting lower plate) roughly in correspondence to the Olevano-Antrodoco Line [*Scarascia et al.*, 1994, 1998; *Cassinis et al.*, 2003]. According to the aforementioned authors, the "Tyrrhenian Moho" would deepen from 22–24 km to 25–26 km moving from the Roman volcanic region to the Olevano-Antrodoco Line. Conversely, the "Adriatic Moho" would rise from 40 km to less than 30 km moving from the Olevano-Antrodoco Line to the Fucino Plain. Note that the depth of the Moho deduced from the DSS experiments is quite poorly constrained in correspondence to the Fucino Plain. A deeper and probably more realistic crust-mantle boundary has been suggested in the same area by *Tiberti and Orlando* [2006] on the base of a 2D gravimetry modelling. East of the orographic divide, the CROP 11 profile cuts across an imbricate fan of thrust sheets referred to the Western Marsica-Meta, Gran Sasso-Genzana, Morrone-Porrara, Queglia and Majella Units. In correspondence to the eastern foot of the Majella Mountain, the seismic line intersects the Molise nappes and finally reaches the Plio-Pleistocene terrigenous deposits of the Adriatic foredeep. In the Vasto area, where the gravimetric map shows weak negative values of the Bouguer anomalies, the crust-mantle boundary lies at a depth of 32 km according to *Scarascia et al.* [1994, 1998] and *Cassinis et al.* [2003].

[7] In the interpreted portion of the CROP 11 line (see Figure 3), the thrust sheets belonging to the Western

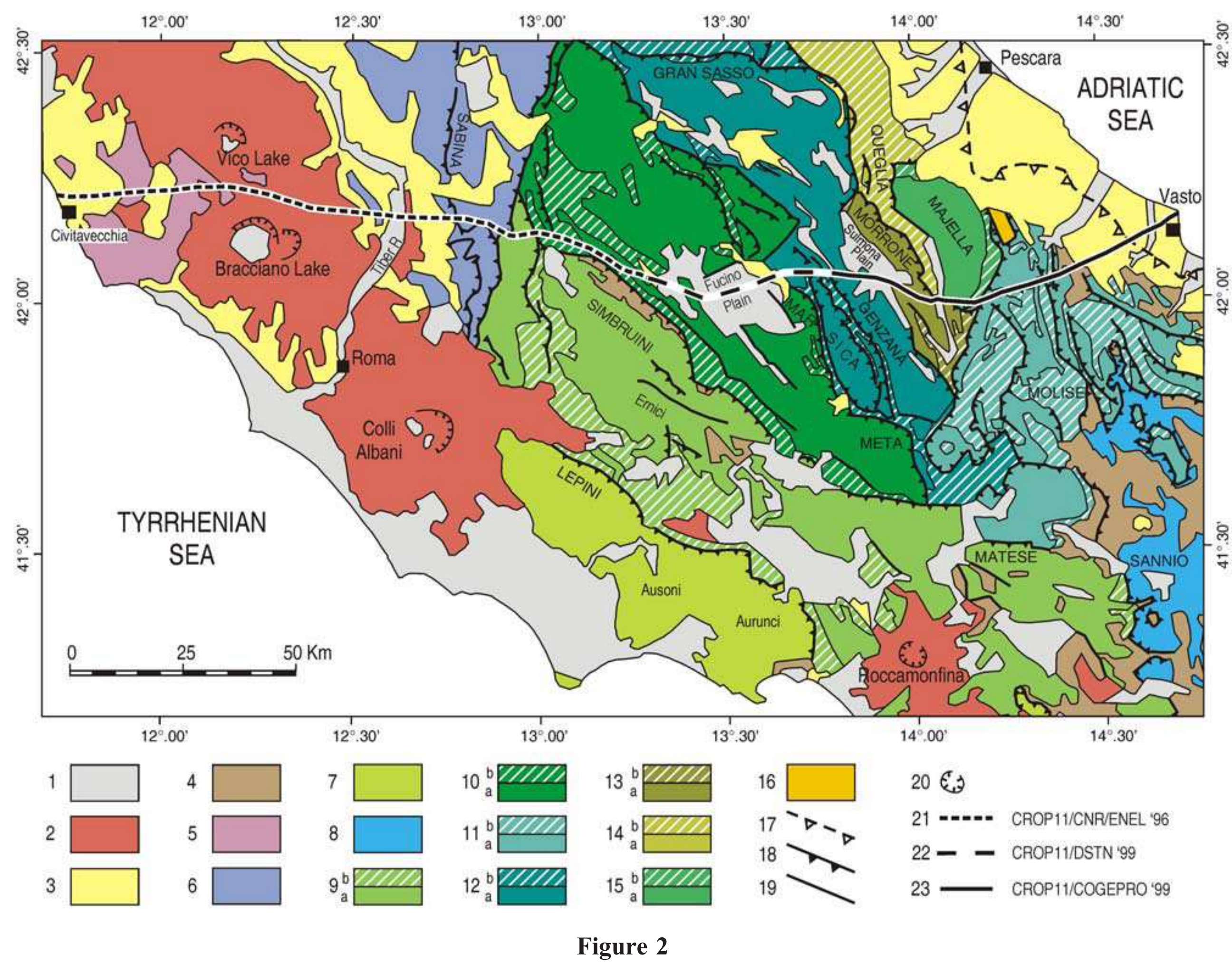


Figure 2

Marsica-Meta, Morrone-Porrara and Majella Units are basically constituted of Upper Triassic–Upper Cretaceous shallow-water carbonates replaced toward the north (and also toward the southeast in the case of the Western Marsica-Meta Unit) by slope and proximal-basin limestones [see *Accordi and Carbone*, 1988]. Both shallow-water and deeper-water carbonates are disconformably overlain by open-ramp carbonate deposits. In the Gran Sasso-Genzana Unit, Upper Triassic–Lower Jurassic *p.p.* shallow-water carbonates are overlain by lower Jurassic *p.p.*-Paleogene slope and proximal-basin limestones followed by open-ramp Miocene carbonate deposits. In the southernmost outcrops of this unit, the shallow-water carbonates reach the early Cretaceous. In all the aforementioned tectonic units, the sequence ends with siliciclastic flysch deposits. The thickness of the single thrust sheets ranges from 2–3 km to 6–7 km. Owing to the up-section trajectory of the base thrust moving from the south toward the north, the Molise nappe deposits crossed by the eastern termination of the CROP 11 profile are represented by a thinner sedimentary sequence (max. 2–3 km) basically made up of Miocene basinal carbonates followed by an uppermost Tortonian–lower Messinian siliciclastic flysch [*Patacca et al.*, 1991].

[8] The progressive shifting of the Apennine foredeep basin toward the east/northeast is indicated by the onset of the siliciclastic flysch deposits the age of which becomes progressively younger moving toward the NE: Tortonian in the Simbruini-Matese Unit, uppermost Tortonian–Messinian in the Molise nappes, Messinian presalinity crisis in the Western Marsica-Meta and Gran Sasso-Genzana Units, Messinian after the salinity crisis and before the Lago-Mare episode in the Morrone-Porrara Unit, base of the Lago-Mare episode in the Queglia Unit and finally lower Pliocene in the Majella Unit [see *Crescenti*, 1971a; *Patacca et al.*, 1990, 1991; *Cipollari and Cosentino*, 1991, 1995, 1997, 1999; *Cipollari et al.*, 1995; *Parotto and Praturlon*, 2004, and references therein]. The time-space migration of the siliciclastic flysch deposits and the contemporaneous opening of the Tyrrhenian basin in a backarc position have been classically related to the rollback of the subducting Adria lithosphere [*Malinverno and Ryan*, 1986; *Royden et al.*, 1987; *Patacca and Scandone*, 1989; *Patacca et al.*, 1990; *Doglioni*, 1991]. The same process also caused the incorporation in the thrust belt of progressively more external foreland segments which underwent orogenic transport toward east and northeast. Along the interpreted portion of the CROP 11 line, tectonic shortening reached the Fucino region in the early Messinian and the most external areas east of Majella (Casoli-Bomba High) in the early Pleistocene. Evidence of a still active compression in the central/northern Apennines with persisting subduction of the Adria lithosphere beneath the mountain chain derives from fault-plane solutions of crustal earthquakes [*Frepoli and Amato*, 1997; *Vannucci et al.*, 2004, and referenced therein] and from the hypocenter distribution of subcrustal earthquakes [*Selvaggi and Amato*, 1992; *Amato et al.*, 1997].

[9] Referring to the eastern half portion of the central Apennines, i.e., to the part of the tectonic wedge created in post-Tortonian times, a thin-skin tectonics has been postulated by some authors [*Bally et al.*, 1986; *Mostardini and*

Figure 2. Structural map of the central Apennines and trace of the CROP 11 seismic line. Key: 1, middle Pleistocene to Holocene continental and subordinate shallow-marine deposits; 2, upper Pliocene–Quaternary volcanites and volcaniclastic deposits; 3, Pliocene–lower Pleistocene continental and marine deposits; 4, undifferentiated Tortonian to uppermost Messinian/lowermost Pliocene thrust-top deposits, uppermost Tortonian–Messinian terrigenous deposits unconformably overlying the Simbruini-Matese Unit grading laterally, north of Matese, into siliciclastic flysch deposits of the Molise sequence; 5, external Ligurian Units: Cretaceous-Paleogene deep basinal deposits; 6, Sabina Units: Upper Triassic–lower Liassic shallow-water carbonates followed by middle Liassic–lower Miocene basinal carbonates; 7, Lepini Unit: Upper Triassic–Upper Cretaceous shallow-platform carbonates followed by lower-middle Miocene deeper-water carbonate deposits; 8, Sannio Unit: Lower Cretaceous–middle Miocene basinal deposits; 9, Simbruini-Matese Unit: (part a) shallow-platform dolomites and limestones (Upper Triassic–Upper Cretaceous) and slope-to-proximal-basin carbonates (Lower Jurassic–Paleogene) disconformably overlain by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Tortonian); 10, Western Marsica-Meta Unit: (part a) shallow-platform dolomites and limestones (Upper Triassic–Upper Cretaceous) and subordinate slope-to-proximal-basin carbonates (Lower Jurassic–Paleogene) disconformably overlain by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 11, Molise Units: (part a) basinal carbonates (Jurassic/Lower Cretaceous to Tortonian), and (part b) siliciclastic flysch deposits (uppermost Tortonian–Messinian); 12, Gran Sasso-Genzana and Montagna dei Fiori Units: (part a) shallow-platform dolomites and limestones (Upper Triassic–Lower Cretaceous) and slope-to-proximal-basin carbonates (Lower Jurassic–Paleogene) overlain, locally in disconformity, by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 13, Morrone-Porrara Unit: (part a) shallow-platform (Jurassic–Upper Cretaceous) and slope-to-proximal-basin carbonates (Jurassic-Paleogene) disconformably overlain by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 14, Queglia Unit: (part a) Upper Cretaceous–Paleogene basinal carbonates followed by Miocene open-ramp carbonate deposits and by Messinian evaporites, and (part b) siliciclastic flysch deposits (Messinian–lower Pliocene); 15, Majella Unit: (part a) shallow-platform to proximal-basin carbonate deposits (Lower Cretaceous–Paleogene) overlain by Miocene open-ramp carbonates and by Messinian evaporites and marls, and (part b) siliciclastic flysch deposits (lower Pliocene); 16, lower Pliocene marly clays of the Casoli Unit; 17, buried front of the Apennine thrust sheets; 18, major thrusts and backthrusts; 19, faults, including normal faults and strike-slip faults; 20, crater/caldera rims; 21, 22, and 23, trace of the Crop 11 seismic line.

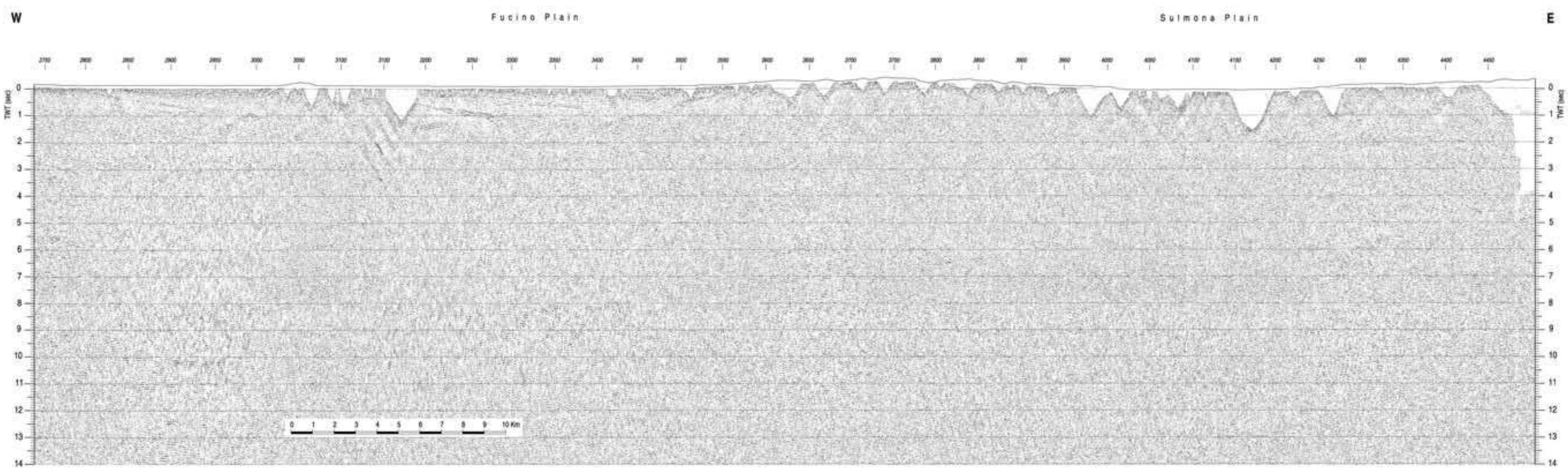
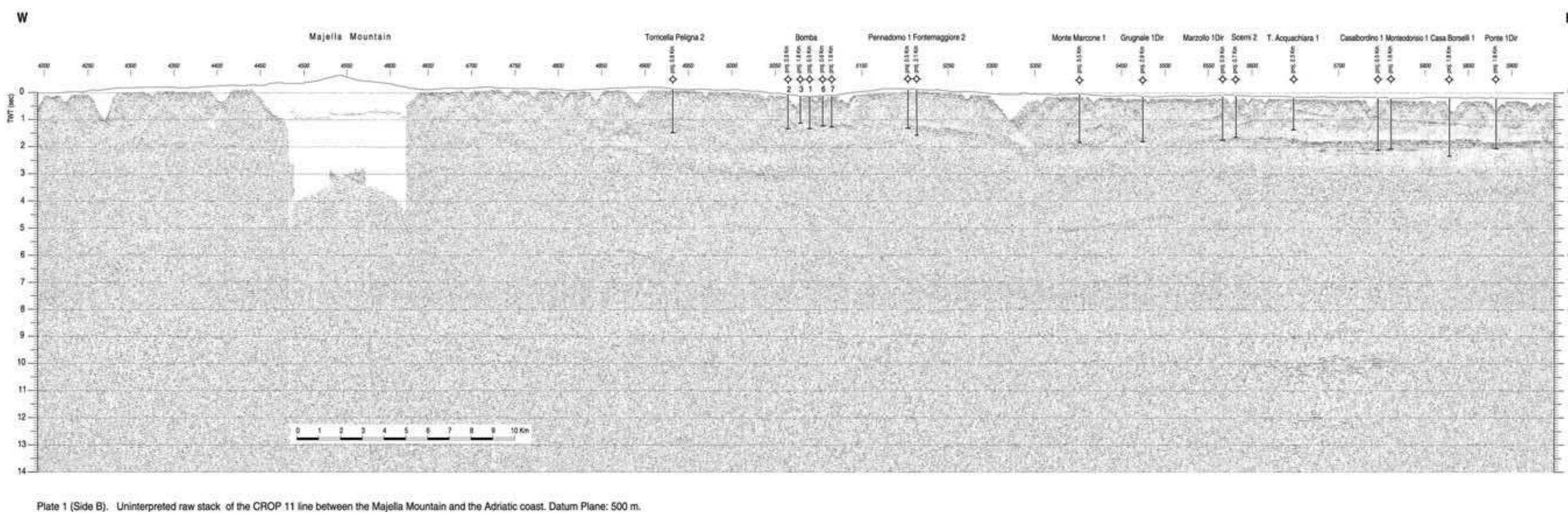
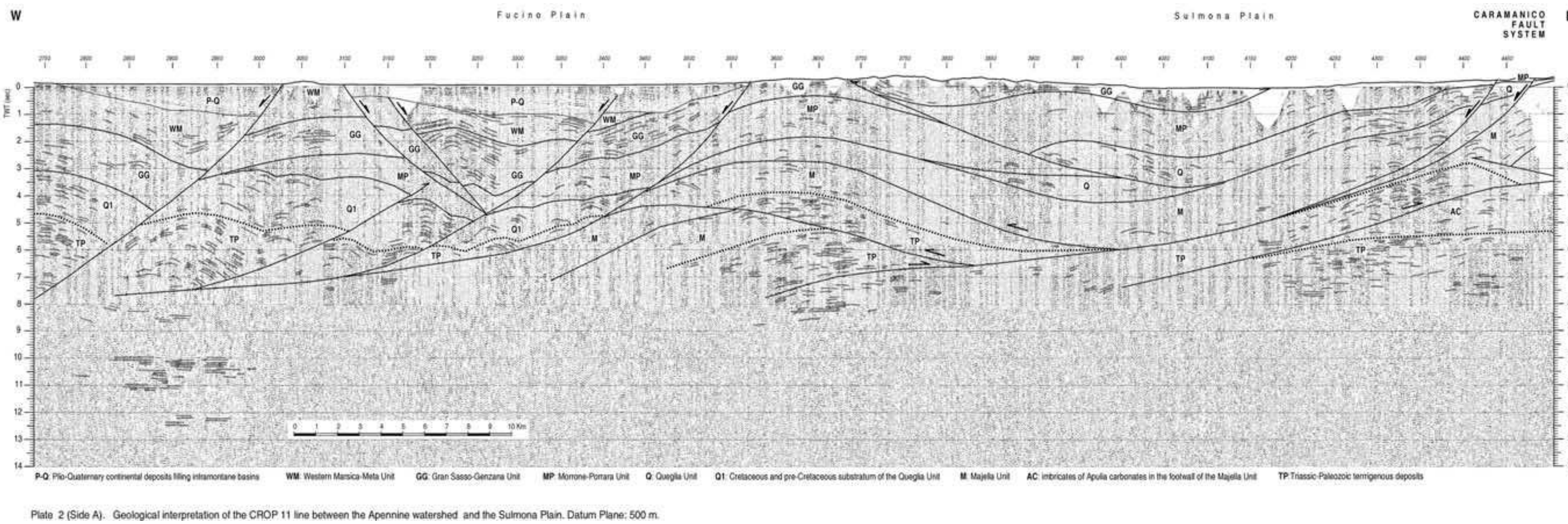


Plate 1 (Side A). Uninterpreted raw stack of the CROP 11 line between the Apennine watershed and the Sulmona Plain. Datum Plane: 500 m.

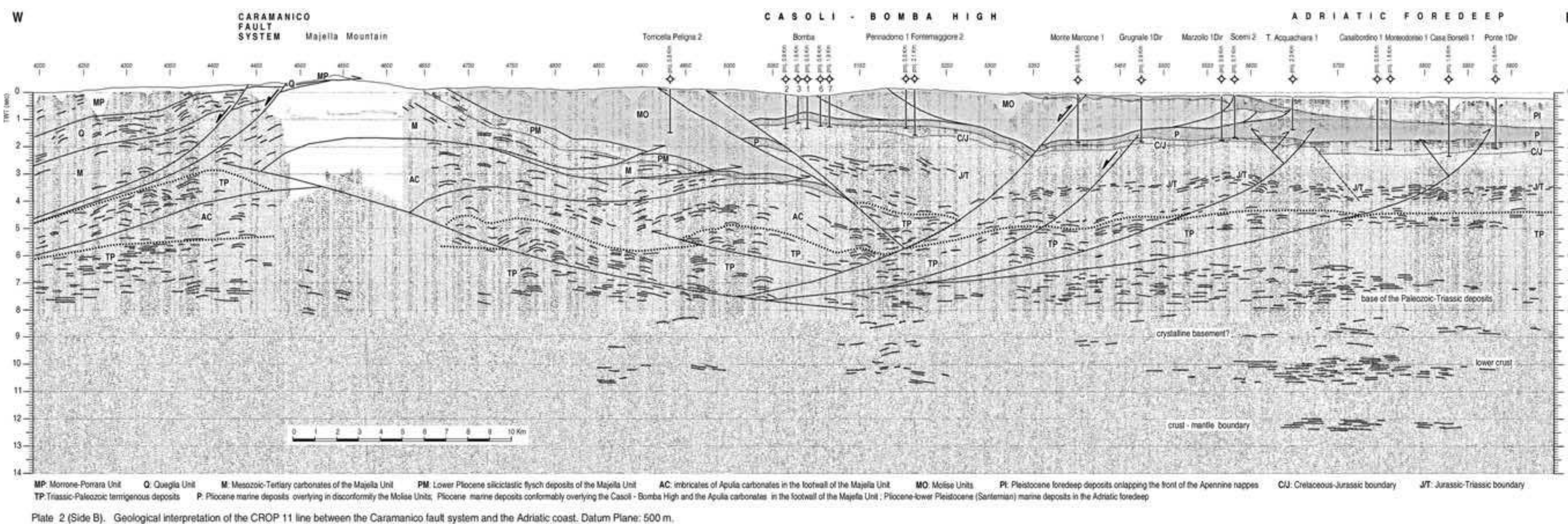
Foldout 1. Uninterpreted raw stack of the CROP 11 line between the Apennine watershed and the Sulmona Plain; datum plane is 500 m.



Foldout 2. Uninterpreted raw stack of the CROP 11 line between the Majella Mountain and the Adriatic coast; datum plane is 500 m.



Foldout 3. Geological interpretation of the CROP 11 line between the Apennine watershed and the Sulmona Plain; datum plane is 500 m.



Foldout 4. Geological interpretation of the CROP 11 line between the Caramanico fault system and the Adriatic coast; datum plane is 500 m.

Merlini, 1986; *Bigi et al.*, 1995] which have interpreted the tectonic style as a consequence of a major detachment in correspondence to upper Triassic evaporites overlying an undeformed crystalline basement. Conversely, a thick-skin deformation implying a rather severe involvement of the crystalline basement in the crustal shortening has been hypothesized by other authors [*Barchi*, 1991; *Lavecchia et al.*, 1994; *Barchi et al.*, 1998; *Coward et al.*, 1999]. Analogous controversies exist on the Southern Apennine deep structure since a quite important contribution of the crystalline basement to the post-Tortonian mountain chain has been postulated by some authors [*Casero et al.*, 1988; *Endignoux et al.*, 1989; *Mazzoli et al.*, 2000; *Menardi Noguera and Rea*, 2000; *Speranza and Chiappini*, 2002] whilst a thin-skin tectonic style implying greater volumes of sedimentary rocks and consequently greater amounts of shortening has been proposed by other authors [*Patacca et al.*, 2000; *Patacca and Scandone*, 2004a; *Scrocca et al.*, 2005]. What is certain is that crystalline rocks detached from a continental basement are documented in the Apennines [see *Vai*, 2001, and references therein] only in tectonic units involved in the orogenic transport before the late Tortonian, i.e., before the onset of the Tyrrhenian extension.

[10] As regards the crystalline basement of the Adriatic foreland, the only direct information derives from the Assunta 1 well near Venice (see location in Figure 1), which penetrated lower Paleozoic acidic plutonites from 4711 m to the final depth 4747. The age of these plutonites (446 ± 18 Ma) testifies to the existence of a pre-Hercynian crystalline crust in the area. According to *Vai* [1994, 2001], a Precambrian (Baikalian-Panafrican) basement had to floor the entire Adriatic region, which in Paleozoic times constituted the foreland of the Hercynian chain. The latter was widely developed in the areas presently occupied by the Southern Alps, the Po Plain and the Apennines. Information on the sedimentary cover of the pre-Cambrian basement derives form a few commercial wells (see location in Figure 1) and only concerns the Permo-Triassic portion of the sequence. In the Northern Adriatic region, the Assunta 1 well penetrated a pile about 3000 m thick of upper Triassic dolomites (Norian-Rhaetian "Dolomia Principale" Fm *Auct.*) directly overlying the aforementioned lower Paleo-

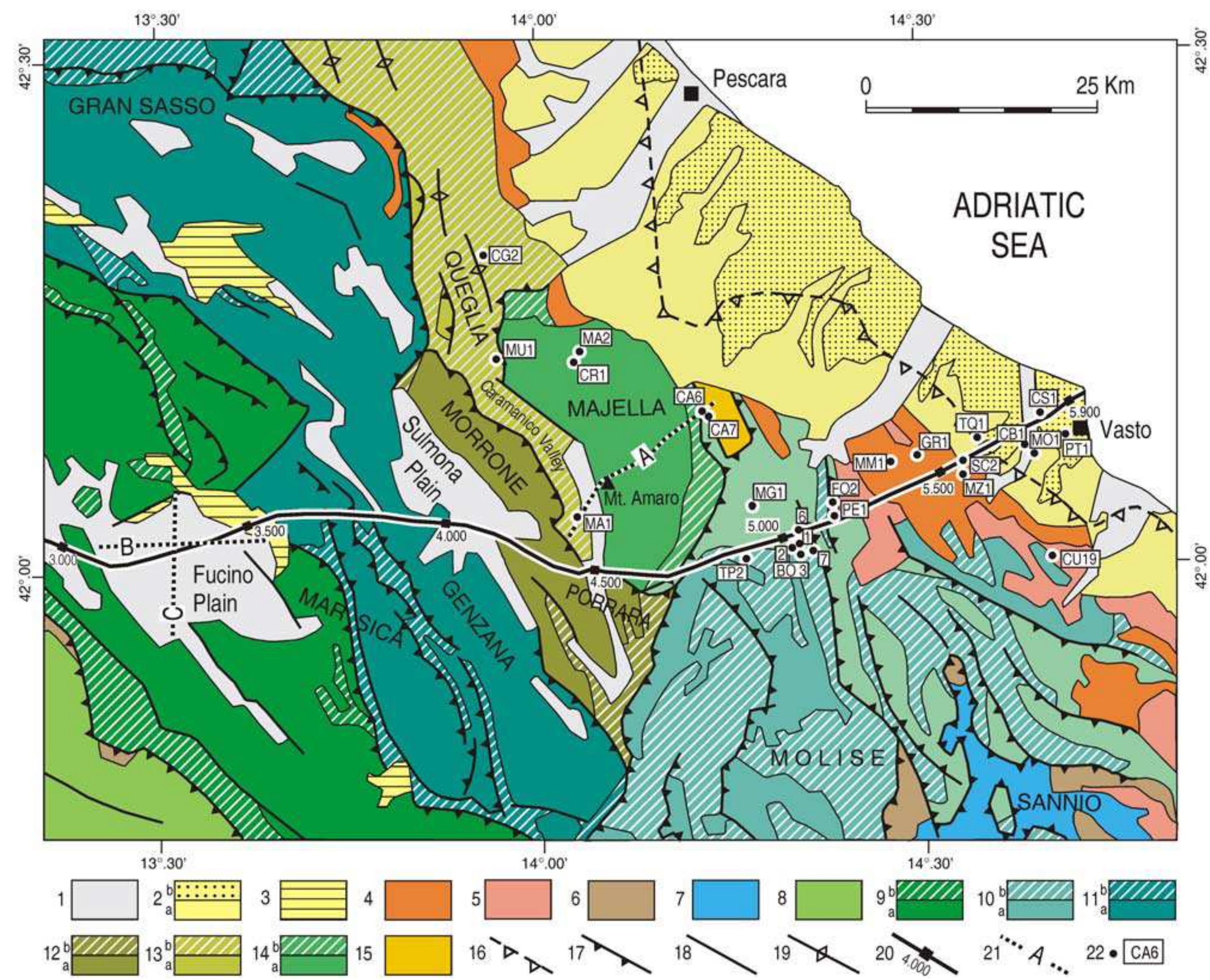


Figure 3

zoic plutonites [*Cati et al.*, 1987]. Not far from Assunta 1, the Amanda 1 well drilled, beneath 1373 m of Norian-Rhaetian dolomites ("Dolomia Principale" Fm), a relatively thick sedimentary sequence represented by Carnian evaporites and dolomites (201 m), upper Ladinian volcanites and volcaniclastites (464 m) and Ladinian–uppermost Anisian dolomites (755 m). The latter directly overlie Permian shallow-water carbonates and coarse-clastic deposits (465 m) with no trace of lower Triassic terms [*Cati et al.*, 1987; *Sartorio and Rozza*, 1991]. Unlike the Northern Adriatic region, the Central-Southern Adriatic area seems to be characterized by the systematic absence of Middle Triassic deposits as shown by commercial wells (Figure 4). For instance, in the Alessandra 1 well more than 1500 m of Upper Triassic dolomites (well-bedded dolomites from 3710 to 4100 and massive dolomites from 4100 to 5225) overlie a rather thick shaly sequence yielding early Triassic palinomorphs, as well as reworked fusulinids. The upper portion of the Lower Triassic deposits (5235–5310 m) is characterized by the occurrence of red and green barren siltstones and dolomitic silty mudstones. Also the sequence explored by Puglia 1 shows no trace of Middle Triassic deposits as the well crossed Upper Triassic bedded dolomites (3535 and 4450 m) and evaporites with subordinate dolomites (Burano Fm, 4450–6112 m) directly overlying Lower Triassic clastic deposits. The latter are represented by red continental siltstones associated with fine-grained sandstones and coarse-clastic carbonates (6112–6243 m), as well as by gray limestones and fine-grained calcareous sandstones indicative of coastal-lagoon environment (6243–6307 m). The lower Triassic deposits are stratigraphically underlain by Upper Permian gray sandstones and dark-red siltstones associated with subordinate clastic carbonates containing fragmented fusulinids (from 6307 to the final depth 7070 m). Getting near the CROP 11 line, the Gargano 1 well penetrated 625 m (1425–2050 m) of Upper Triassic bedded dolomites and a thick sequence (2050–4230 m) of dolomites and anhydrites representing the equivalent of the Burano Fm of Puglia 1. The evaporites overlie red siltstones, dolomitic silty mudstones and coarse-clastic carbonates (4230–4475 m). The latter have been attributed to the Ladinian-Carnian in the well log but this attribution is questionable considering the equivalence in facies and stratigraphic position of these red-stained clastic deposits with the red clastic sediments of Puglia 1 and the Alessandra 1 which have been attributed to the Early Triassic on the base of palynological data. In Gargano 1, the red-colored deposits stratigraphically follow gray sandstones and siltstones alternating with dolomites still referable to the Triassic (4475–4545 m) which in turn overlie gray dolomitic siltstones, white carbonates and dark-gray shales with intercalations of whitish dolomites attributed to the Paleozoic (4545–4853). In addition, some mafic rocks have been recognized in the Gargano 1 well at about 4700 m, but it is not clear whether these rocks are referable to Paleozoic lava flows or to dykes of Tertiary volcanites

Figure 3. Detail of Figure 2 with some additional geological information. The map shows the interpreted segment of the CROP 11 line together with the location of the commercial lines and wells discussed in the text. Key: 1, middle Pleistocene to Holocene continental and subordinate shore deposits; 2, lower Pleistocene deposits: (part a) marine clays and silty clays, and (part b) regressive sands and conglomerates; 3, upper Pliocene–lower Pleistocene continental deposits in Apennine intramontane basins; 4, Pliocene marine deposits; 5, Messinian evaporites and uppermost Messinian/lowermost Pliocene landslide chaotic deposits; 6, uppermost Tortonian–lower Messinian thrust-top deposits; 7, Sannio Unit: Lower Cretaceous–middle Miocene basinal deposits; 8, Simbruini-Matese Unit: shallow-platform dolomites and limestones (Upper Triassic–Upper Cretaceous); 9, Western Marsica-Meta Unit: (part a) shallow-platform dolomites and limestones (Upper Triassic–Upper Cretaceous) and slope-to-proximal-basin carbonates (Lower Jurassic–Paleogene) disconformably overlain by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 10, Molise Units: (part a) basinal carbonates (Jurassic/Lower Cretaceous to Tortonian), and (part b) siliciclastic flysch deposits (uppermost Tortonian–Messinian); 11, Gran Sasso-Genzana and Montagna dei Fiori Units: (part a) shallow-platform dolomites and limestones (Upper Triassic–Lower Cretaceous) and slope-to-proximal-basin carbonates (Lower Jurassic–Paleogene) overlain, locally in disconformity, by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 12, Morrone-Porrara Unit: (part a) shallow-platform (Jurassic–Upper Cretaceous) and slope-to-proximal-basin carbonates (Jurassic-Paleogene) disconformably overlain by Miocene open-ramp carbonate deposits, and (part b) siliciclastic flysch deposits (Messinian); 13, Queglia Unit: (part a) Upper Cretaceous–Paleogene basinal carbonates followed by Miocene open-ramp carbonate deposits and by Messinian evaporites, and (part b) siliciclastic flysch deposits (Messinian–lower Pliocene); 14, Majella Unit: (part a) shallow-platform to proximal-basin carbonate deposits (Lower Cretaceous–Paleogene) overlain by Miocene open-ramp carbonates and by Messinian evaporites and marls, and (part b) siliciclastic flysch deposits (lower Pliocene); 15, lower Pliocene marly clays of the Casoli Unit; 16, buried front of the Apennine thrust sheets; 17, major thrusts and backthrusts; 18, faults, including normal faults and strike-slip faults; 19, anticline axis; 20, interpreted segment of the CROP 11 line with selected CDP; 21, commercial line (A line) crossing the Majella anticline in correspondence to the axial culmination and traces of two other commercial lines (B line and C line) cutting through the Fucino basin; 22, selected wells: BO, Bomba wells (Bomba 1, 2, 3, 6, 7); CA6, Casoli 6; CA7, Casoli 7; CB1, Casalbordino 1; CG2, Cigno 2; CR1, Caramanico 1; CS1, Casa Borselli 1; CU19, Cupello 19; F02, Fontemaggiore 2; GR1, Grugnale 1Dir; MA1, Maiella 1; MA2, Maiella 2; MG1, Morgia 1; MM1, Monte Marcone 1; MO1, Monteodorisio 1; MU1, Musellaro 1; MZ1, Marzollo 1Dir; PE1, Perano 1; PT1, Ponte 1Dir; SC2, Scerni 2; TP2, Torricella Peligna 2; TQ1, Torrente Acquachiara 1.

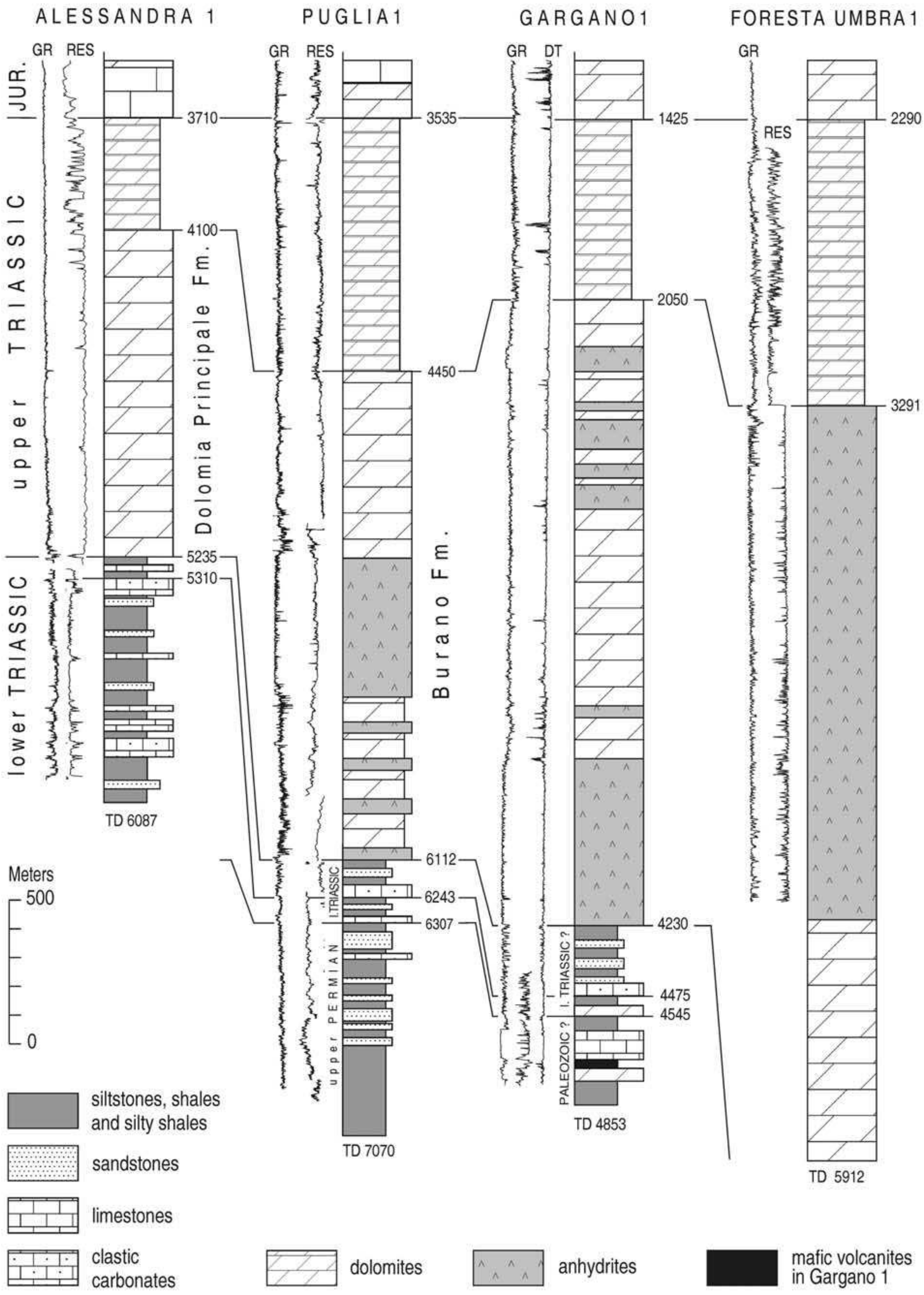

ALESSANDRA 1
PUGLIA 1
GARGANO 1
FORESTA UMBRA 1
GR
RES
DT
JUR.
upper TRIASSIC
lower TRIASSIC
Dolomia Principale Fm.
Burano Fm.
l.TRIASSIC
upper PERMIAN
l. TRIASSIC ?
PALEOZOIC ?
3710
4100
5235
5310
3535
4450
6112
6243
6307
1425
2050
4230
4475
4545
2290
3291
TD 6087
TD 7070
TD 4853
TD 5912
Meters
500
0
siltstones, shales and silty shales
sandstones
limestones
clastic carbonates
dolomites
anhydrites
mafic volcanites in Gargano 1

Figure 4

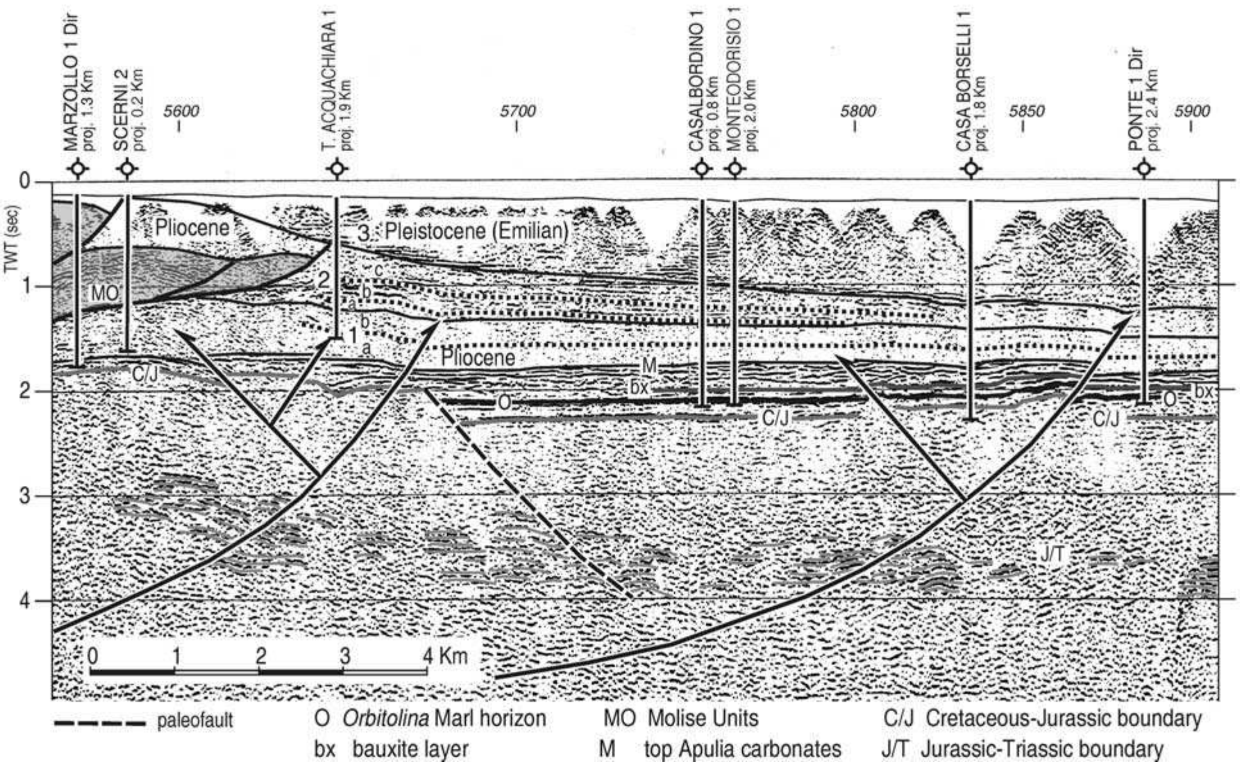


Figure 5. Easternmost portion of the CROP 11 profile showing in some details the seismic signatures in the foreland area at relatively shallow depths. The reflection data highlight the seismic facies configuration of the Apulia carbonates and overlying Plio-Pleistocene foredeep deposits. Well-log expressions of the Mesozoic-Tertiary carbonates and of the overlying Plio-Pleistocene deposits are shown in Figures 6 and 10, respectively. Arabian numbers with associated small letters a, b, and c refer to the intervals illustrated in Figure 10. The datum plane of the seismic line is 400 m above sea level. Rotary table elevations and total depths of the projected wells are indicated in Figure 10.

analogous to those cropping out at Punta delle Pietre Nere about 12 km west of Gargano 1 [*Boni et al.*, 1969]. In this locality, a dyke of Paleogene mafic volcanites [*De Fino et al.*, 1981; *Bigazzi et al.*, 1996] associated with Upper Triassic dark-gray marls [*Di Stefano*, 1895] is exposed, pushed up by a diapir of Triassic evaporites [*Cotecchia and Canitano*, 1955; *Martinis and Pieri*, 1963]. Diapirs of Triassic salts are quite common features in the Adriatic region [*De Alteriis*, 1995]. Not far from Gargano 1, finally, the Foresta Umbra 1 well penetrated Upper Triassic deposits represented by 1000 m of well-bedded dolomites (2290–3291 m), more than 1700 m (3291–5071 m) of anhydrites (Burano Formation from *Martinis and Pieri* [1963]) and about 800 m of dolomites (5071–5912 m) without reaching the Permo-Triassic deposits.

[11] In the following pages, we will describe the geological features recognized in the CROP 11 seismic profile moving along the trace of the line from the east to the west, i.e., from the gently deformed foreland areas reached by the Apennine compression during the Pleistocene toward more and more complex internal sectors of the thrust belt incorporated in the tectonic wedge during Pliocene and Messinian times.

3. Crustal Structure of the Adriatic Foreland in the Region Crossed by the CROP 11 Seismic Line

[12] Geological information on the uppermost portion of the Adriatic crust in the area crossed by the CROP 11 line mostly derives from the extensive petroleum exploration. The investigated sedimentary sequence consists of a pile around 7 km thick of upper Triassic dolomites and anhydrites and of Jurassic–Upper Cretaceous shallow-water

Figure 4. Stratigraphic correlation of some key wells exploring the Triassic and Permian deposits of the Adriatic foreland (well location in Figure 1). The basic stratigraphic information derives from the public composite logs and, as concerns Foresta Umbra 1, from *Martinis and Pieri* [1963]. The wireline-logs evidence the overall serrated cylinder-shaped profile characterizing the Upper Triassic anhydrites. Alessandra 1 and Gargano 1, as well as to some extent Puglia 1, show an abrupt change of the electrofacies in correspondence to the Permo-Triassic clastic deposits.

carbonates (Apulia Platform of the geological literature) stratigraphically overlying the Permo-Triassic continental to shallow-marine clastic deposits described in the previous session. The Jurassic-Cretaceous shallow-marine carbonates are disconformably covered by Miocene open-ramp carbonate deposits (Bolognano Formation) followed by Messinian evaporites (''Gessoso-Solfifera'' Formation). The Miocene deposits, never exceeding a few hundred meters in thickness, are in turn overlain by Plio-Pleistocene siliciclastic flysch deposits up to 1800 m thick. The composite logs of several wells close to the CROP 11 line that have reached the Mesozoic carbonates (Fontemaggiore 2, Grugnale 1Dir, Marzollo 1Dir, Casalbordino 1, Monteodorisio 1, Casa Borselli 1 and Ponte 1Dir; see Figure 5) and the accurate stratigraphic analysis of the Cupello 19 well (see location in Figure 3) carried out by *Dondi et al.* [1966] provide quite detailed information on the Jurassic-Miocene portion of the foreland sequence.

[13] In the CROP 11 profile, as in several commercial lines available in the area, the top of the Apulia Platform is a prominent feature easily identifiable because of the strong acoustic impedance between the well-lithified Mesozoic-Tertiary limestones and the overlying Plio-Pleistocene soft sediments. The Messinian evaporites of the ''Gessoso-Solfifera'' Fm and the Miocene limestones of the Bolognano Fm at the top of the Apulia Platform are physically imaged by a characteristic and fairly continuous couple of strong reflectors that can be followed through the whole profile of Figure 5. Between Ponte 1Dir and Torrente Acquachiara 1, at about 1.8 s TWT, this couple overlies a package of very high amplitude reflectors with subparallel to hummocky configuration identified in several wells (see Figure 6) as the Turonian-Senonian portion of the Cupello Limestone of petroleum geologists (Ponte 1Dir, Casa Borselli 1, Monteodorisio 1 and Casalbordino 1). This portion of the Cupello Limestone is the subsurface equivalent of the Altamura Limestone, a shelf-lagoon carbonate deposit widely exposed in Apulia. In the aforementioned wells, the Turonian-Senonian carbonates lie in disconformity over the Cenomanian *p.p.*-Neocomian portion of the Cupello Limestone made up of restricted-platform carbonates and known in surface sections as the Bari Limestone. In correspondence to the contact between the Altamura Limestone and the Bari Limestone equivalents, a sharp deflection of both SP and resistivity curves evidences a ''terra rossa'' layer associated with karstic breccias. This characteristic key bed, corresponding to the well-known bauxite horizon developed at a regional scale in the peri-Adriatic carbonate platforms, testifies to a prolonged (Cenomanian to early Turonian) episode of subaerial exposure. A second key bed is represented by a layer of green nodular marls rich in *Orbitolina* (*Orbitolina* Marl horizon in Figure 5). In the analyzed wireline logs, this horizon is easily recognizable as it is systematically marked by a strong deflection of the SP (or an increase in the GR values) and a concomitant strong deflection of the resistivity curve.

[14] In the CROP 11 profile (see Figure 5), the bauxite layer divides the Cupello Limestone into a rather well-layered upper unit, coinciding with the Altamura Limestone, and a lower unit characterized by discontinuous reflectors with variable amplitude and frequency, which coincides with the Bari Limestone. Just in the east of Torrente Acquachiara 1, the layered upper Cretaceous portion of the Cupello Limestone terminates abruptly against a paleofault. West of this fault, the Miocene Bolognano and ''Gessoso-Solfifera'' formations lie in disconformity above the lower Cretaceous portion of the Cupello Limestone, as indicated by Grugnale 1Dir, Marzollo 1Dir and Fontemaggiore 1 wells (see Figure 6). Jurassic shallow-water carbonates have been reached in the study area by the Casa Borselli 1 well, as well as by Cupello 19. In the wireline logs, these carbonates are represented by a rather massive unit showing a low degree of serration of the SP curve compared with the overlying Cretaceous limestones (see Casa Borselli 1 in Figure 6). In the CROP 11 profile, the Jurassic carbonates are seismically expressed by a rather massive reflection-free unit with discontinuous zones of weak and disorganized reflections having a thickness of about 1.2 s TWT, which corresponds to a value of 3300–3500 m if we assume for the dense, scarcely fractured platform carbonates of the foreland a velocity range between 5.5 km/s and 5.8 km/s. The calculated value does not contrast with Cupello 19 that penetrated 2446 m of Jurassic carbonates without reaching the Jurassic-Triassic boundary.

[15] In correspondence to the eastern termination of the CROP 11 line, a broadly layered seismic unit 0.4–0.5 s TWT thick recognizable between 3.5 and 4 s separates the massive Jurassic interval from another poorly reflective unit showing only weak and rather chaotic reflections. We think that the broadly layered unit, characterized by discontinuous packages of low-frequency and moderate to high-amplitude parallel reflectors, corresponds to the well-bedded Rhaetian dolomites crossed by the wells Gargano 1 (1425-205), Foresta Umbra 1 (2290-3291) and Puglia 1 (3535-4450), while the seismically disorganized unit should represent the bulk of the Upper Triassic anhydrites.

[16] Below 4.4 s TWT, the massive unit attributed to the Upper Triassic anhydrites is underlain by an irregularly layered seismic interval imaged by discontinuous packages of subtle parallel reflectors with variable amplitude and frequency (see Foldouts 3 and 4). This new unit corresponds to the Permo-Triassic clastic deposits documented by the Gargano 1 and Puglia 1 wells, as well as by Alessandra 1 in the Central Adriatic area. The strong seismic impedance at the top of the layered unit coincides with the abrupt change in the log profiles at the top of the Permo-Triassic deposits outlined by a sudden increase in the GR values and by a concomitant pronounced deflection of the resistivity and Δt values (see Figure 4). A relatively smooth cylinder-shaped profile characterizes the upper Triassic massive dolomites and anhydrites while a strongly ragged signature identifies the underlying clastic deposits. It is important to stress that commercial lines located a few tens of kilometers south of the CROP 11 profile show that the 958 m of Permo-Triassic deposits drilled by Puglia 1 from 6112 m to the final depth 7070 m represent only the upper portion of a layered

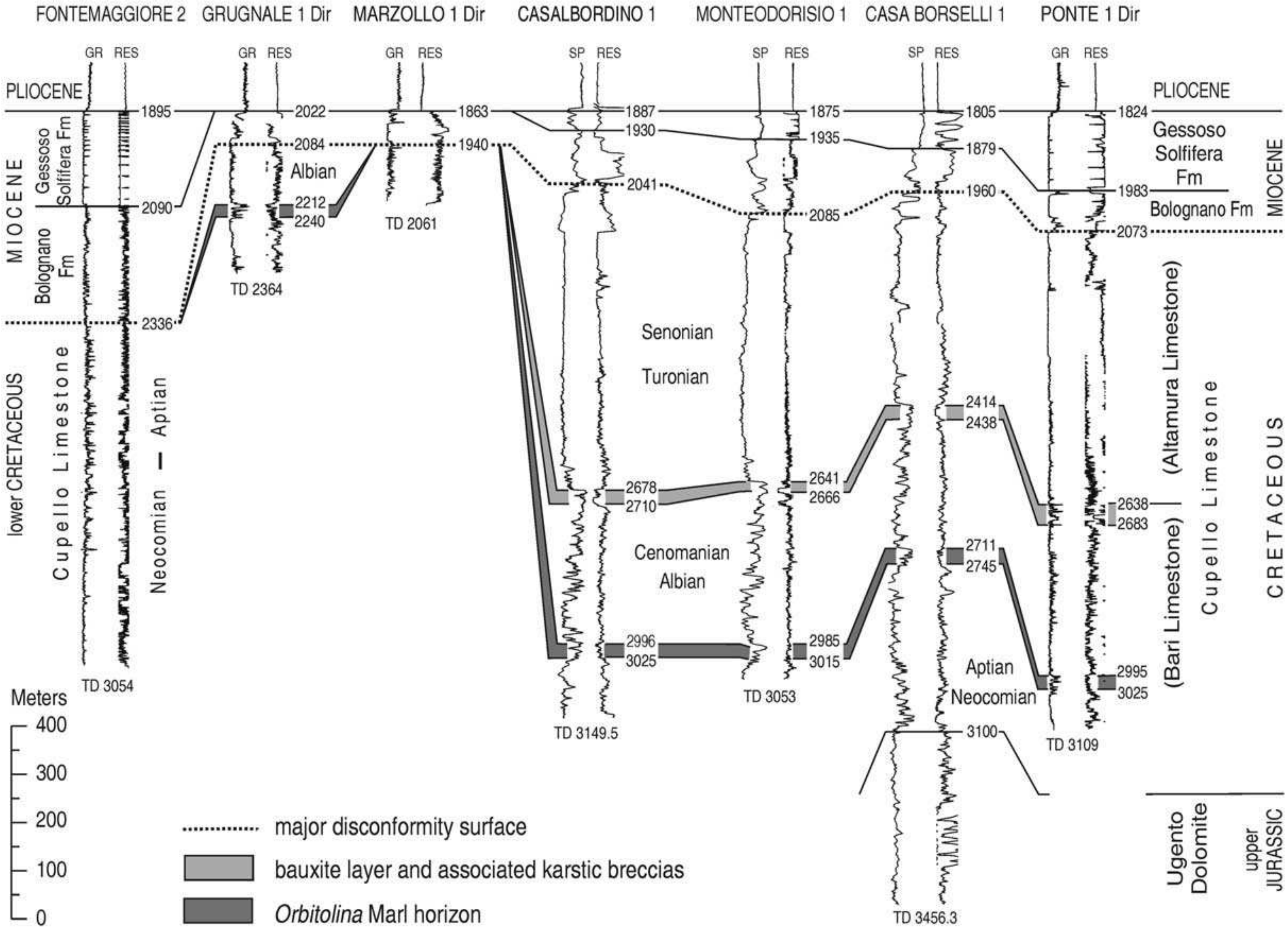


Figure 6. Stratigraphic correlation and well-log signatures of the pre-Pliocene deposits of the Apulia Platform in the easternmost portion of the CROP 11 line (well location in Figure 3). The log correlation evidences in the Fontemaggiore-Grugnale-Marzollo area an important disconformity at the base of the Miocene Bolognano Formation testified by the absence of a significant portion of the Cupello Limestone (the entire upper Cretaceous and a part of the lower Cretaceous). The wireline-log data evidence the wide areal extent of the two Cretaceous key horizons discussed in the text.

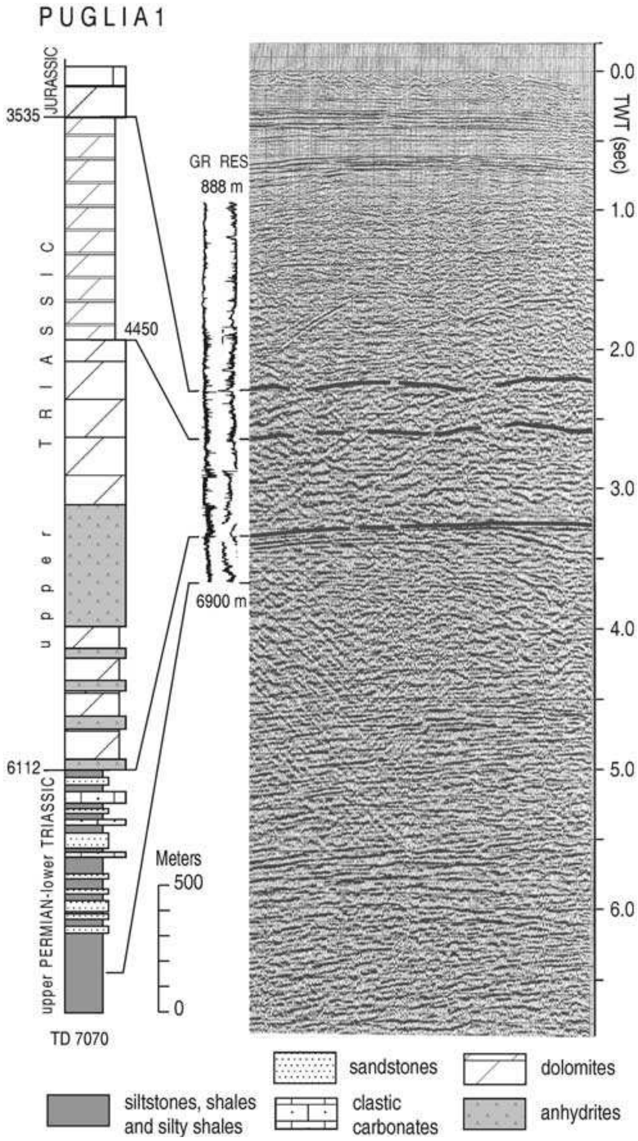


Figure 7. Detail of a commercial line showing the entire Apulia Platform and the thick sedimentary sequence underlying the Upper Triassic dolomites and anhydrites. The Puglia 1 well penetrated only the uppermost portion of this sequence. The gamma ray and resistivity curves of Puglia 1 have been converted from meters into milliseconds in order to allow the correlation between the electrofacies and the seismofacies.

seismic unit that in some cases has been recorded for 3.0 s TWT without reaching the base. 3 s TWT correspond to a thickness not smaller than 7000–7500 m assuming a P-wave velocity not lower than 4.5–5.0 km/s, in agreement with the pronounced Δt curve deflection recognizable in the sonic log of Puglia 1. Higher velocities would obviously imply greater thicknesses. Figure 7 provides a detail of a commercial seismic profile imaging a columnar section with the entire Apulia Platform and with the thick sedimentary sequence underlying the upper Triassic dolomites and anhydrites. The line is located about half way between the CROP 11 line and the Puglia 1 well, in a region in which commercial lines suggest that the Apulia Platform may reach a thickness slightly greater than in Puglia 1.We do not know the downward chronological extent of this thick sedimentary sequence that in the upper portion reaches the Permian and the Early Triassic. A thick carboniferous terrigenous sequence possibly comparable with the Paleozoic cover of the Adriatic-Apulia basement, which exceeds 11,000 m in thickness, has been imaged by NVR experiments in Eastern Europe (EUROPROBE [see *Stovba et al.*, 1996]). In the CROP 11 profile, the layered sequence vanishes below 5 s TWT into a seismically weak zone with highly discontinuous reflections. However, starting from 6.4 s TWT the occurrence of a subhorizontal, rather continuous band of bumpy to gently dipping packages of reflectors suggests the persistence of the sedimentary sequence (likely affected by low-grade metamorphism at that considerable depth) down to 7.8–7.9 s TWT. The total thickness of this sedimentary sequence would thus reach in times a value of 3.4–3.5 s TWT, about 0.5 s greater than the maximum values observed in commercial lines where, in any case, the base of the reflective unit has never been observed.

[17] Between 7.8 and 9.7 s TWT, a massive, rather transparent seismic unit with scattered and fairly weak single reflectors possibly represents a crystalline basement constituting the deepest portion of the upper crust.

[18] Between 9.7 and 12 s TWT, a thick band of dominantly subhorizontal reflectors corresponds, in our opinion, to the lower crust. The upper portion of this unit, between 9.7 and 10.6–10.7 s TWT, shows a distinctively layered seismic fabric evidenced by very strong, continuous subhorizontal reflectors. The lower portion, on the contrary, displays scattered sets of parallel reflectors with variable amplitude and frequency. At 12.0–12.5 s TWT, finally, a narrower band of reflectors indicates the crust-mantle boundary.

[19] Refraction seismic experiments carried out in the late seventies some tens of kilometers north of the Crop 11 line evidenced in the Pescara area a layered continental crust 32 km thick [*Scarascia et al.*, 1994, and references therein; *Cassinis et al.*, 2003]. Four seismic layers were identified above the Moho discontinuity: (1) Layer 1, with velocity values lower than 6 km/s, extending from the surface down to a depth of about 7 km; (2) Layer 2, with increasing velocity values that reach a maximum of 6.7 km/s at a depth of about 12 km; (3) Layer 3, a low-velocity layer extending from about 12 to 22 km with an average velocity of 6.2 km/s; (4) Layer 4, extending from 22 to 32 km with an average velocity of 7.0 km/s, interpreted as a typical lower crust. At the base of this layer, a sudden velocity increase up to 8 km/s evidences the Moho discontinuity.

[20] Figure 8 shows the correspondences between the velocity units recognized in the refraction experiments and the seismic units recognized in the CROP 11 profile. The anhydrite layer recognized in the CROP 11 profile between 3.8 and 4.4 s TWT (i.e., between 7.3 and 9.3 km) should correspond to the lower part of the layer 2 identified in the

Vp: <6.0 Km/sec Thickness of the layer: 7.0 Km Depth of the lower boundary: 7.0 Km	Plio-Pleistocene deposits	Lower boundary: 1.8 sec TWT Δt: 1.7 sec TWT Vp: 2.0 Km/sec Thickness of the unit: 1.7 Km Depth of the lower boundary: 1.7 Km
	Messinian-Jurassic shallow-marine deposits	Lower boundary: 3.4 sec TWT Δt: 1.6 sec TWT Vp: 5.5 Km/sec Thickness of the unit: 4.4 Km Depth of the lower boundary: 6.1 Km
Vp: increasing up to 6.7 Km/sec Thickness of the layer: 5.0 Km Depth of the lower boundary: 12 Km	Upper Triassic dolomites	Lower boundary: 3.8 sec TWT Δt: 0.4 sec TWT Vp: 6.0 Km/sec Thickness of the unit: 1.2 Km Depth of the lower boundary: 7.3 Km
	Upper Triassic anhydrites	Lower boundary: 4.4 sec TWT Δt: 0.6 sec TWT Vp: 6.7 Km/sec Thickness of the unit: 2.0 Km Depth of the lower boundary: 9.3 Km
Vp: 6.2 Km/sec Thickness of the layer: 10 Km Depth of the lower boundary: 22 Km	Sedimentary unit underlying the upper Triassic anhydrites	Lower boundary: 7.8 sec TWT Δt: 3.4 sec TWT Vp: 4.5 Km/sec Thickness of the unit: 7.6 Km Depth of the lower boundary: 16.9 Km
	Crystalline upper crust	Lower boundary: 9.7 sec TWT Δt: 1.9 sec TWT Vp: 6.2 Km/sec Thickness of the unit: 5.9 Km Depth of the lower boundary: 22.8 Km
Vp: 7.0 Km/sec Thickness of the layer: 10 Km Depth of the lower boundary: 32 Km	Layered lower crust	Lower boundary: 12 sec TWT Δt: 2.3 sec TWT Vp: 7.0 Km/sec Thickness of the unit: 8.0 Km Depth of the lower boundary: 30.8 Km

Figure 8. Correlation between the results of deep-seismic-sounding (DSS) refraction experiments in the Pescara area (about 50 km NW of Vasto) and the results of the CROP 11 reflection seismic profile in the Vasto area.

refraction seismic experiments (see easternmost part of the cross section D-D in Figure 5 of *Scarascia et al.* [1994] and cross section 8-8 in Figure 6 of *Cassinis et al.* [2003]). Massive thick anhydrites may account for the maximum velocity values (up to 6.7 km/s) recorded in the lower part of the DSS layer 2. The different depth values attributed to the bottom of the anhydrites in the CROP profile (around 9.3 km according to our calculations) and to the bottom of the layer 2 in the Pescara area (12 km according to *Scarascia et al.* [1994] and *Cassinis et al.* [2003]) is likely related to the relevant increase in the thickness of the Plio-Pleistocene deposits moving from the CROP 11 region to the area investigated by the refraction seismic experiments. The depth of the base-of-Pliocene deposits, in fact, lies at less than 2 km in correspondence to the CROP 11 line and reaches about 5 km in the Pescara region [see *Bigi et al.*, 1991]. The underlying low-velocity layer (indicated by dashed lines in the D-D section of *Scarascia et al.* [1994] and in the 8-8 section of *Cassinis et al.* [2003]) roughly corresponds to the seismically heterogeneous zone between the upper Triassic anhydrites and the well-layered deep crust that in our interpretation is representative of a tick sedimentary unit (possibly affected by low-grade metamorphism) plus a crystalline basement making up the deepest part of the upper crust. The last seismic unit recognized in the CROP 11 line, featured by subparallel high-amplitude reflection fabric and interpreted as a layered lower crust, closely corresponds to the layer 4 of the refraction seismic experiments. The high P-wave velocity (7.0 km/s) characterizing this layer supports our interpretation. The Moho discontinuity at a depth of about 31 km (time depth = 12 s TWT) in correspondence to the Adriatic coast is not far from the Moho discontinuity at 32 km of the refraction experiments.

4. Apennine Nappe Front and the Casoli-Bomba Positive Structure

[21] The region that extends from the eastern foot of the Majella anticline to the front of the Apennine chain is occupied by the Molise nappes, a complex stack of allochthonous sheets made up of well-bedded Mesozoic-Tertiary basinal deposits overlain in angular unconformity by Messinian to upper Pliocene thrust-top deposits (see Figure 3). The Molise nappes, formally established by *Selli* [1962] and stratigraphically defined by *Clermontè* [1977], have been subdivided into several tectonic units by *Patacca et al.* [1991]. The more internal units (Frosolone and Agnone Units) are represented by Upper Jurassic/Lower Cretaceous to Tortonian basinal carbonates containing recurrent and volumetrically important layers of coarse-grained resediments rich in penecontemporaneous shelf materials. These coarse resediments, mainly carbonate debrites, grade laterally northward and eastward into distal calciturbidites intercalated with pelagic deposits. No Mesozoic terms have been documented until now in the more external units (Tufillo and Daunia Units) which are typified by the widespread occurrence of Paleogene red shales absent in the more internal units. These red shales represent the basal level above a detachment surface. In all Molise Units, the Tortonian basinal carbonates are conformably overlain by uppermost Tortonian-Messinian siliciclastic flysch deposits displaying, as the underlying carbonate deposits, a general decrease in the grain size and bedding thickness toward the north and the east.

[22] Along the trace of the CROP 11 profile, the Molise nappes have been cut across by a series of backthrusts responsible for quite complex imbricated structures. Some thrust surfaces are rooted in the buried Apulia carbonates. Other thrusts, on the contrary (e.g., important backthrust reaching the surface between Bomba 1 and Bomba 6 in Foldouts 3 and 4), have no continuation in the carbonate substratum and surely pre-date the growth of the Casoli-Bomba High. The latter represents the most striking tectonic feature in the foreland carbonates. The top of the Casoli-Bomba positive structure is exposed in a small tectonic window at the eastern foot of the Majella anticline (see Figures 2 and 3). In this window, the Molise nappes tectonically overlie a lower Pliocene clayey sequence that

conformably covers Mesozoic-Tertiary carbonates (plus Messinian evaporites) of the Apulia Platform reached by several commercial wells at shallow depths. The CROP 11 seismic profile intersects the Casoli-Bomba structure between the Torricella Peligna 2 and Monte Marcone 1 wells. The top of the Apulia carbonates, outlined by the characteristic strong reflectors of the "Gessoso-Solfifera" and Bolognano Formations, rises from about 2 s TWT in correspondence to the foot of the foreland homocline to a maximum of 1 s TWT in correspondence to the Bomba 1 and Bomba 3 wells. West of this positive structure, the top carbonates abruptly deepens to a depth of about 3.5 s TWT, evidencing in this way a vertical displacement of 2.5 s TWT. Moving westward, in the direction of the Majella Mountain, the top of the carbonates progressively ramps at shallow depths until it emerges in correspondence to the eastern foot of the Majella anticline.

[23] On the basis of a seismic line that crosses the Casoli-Bomba High a few kilometers north of the CROP 11 line in correspondence to the Morgia 1 well (see well location in Figure 3), *Scisciani et al.* [2001] have interpreted the displacement of the Apulia carbonates in correspondence to the western flank of the Casoli-Bomba High as a normal fault active in early Pliocene times, before the transport of the Molise nappes in the area. Figures 9a and 9b shows a mute section of the aforementioned commercial line and the relative seismic interpretation proposed by *Scisciani et al.* [2001]. The CROP 11 line, tied in this area to several wells, suggests a different tectonic configuration (see Foldouts 1–4). The profile, in fact, shows that the western termination of the shallow strong reflector marking the top of the Apulia carbonates in the structural high (reached by Bomba 2 at a depth slightly exceeding 1 s TWT) overlaps a deeper horizon still referable to the top carbonates recognizable between Torricella Peligna 2 and Bomba 2 at 3.0–3.5 s TWT. The geometric relationships between these reflectors suggest that the deeper Apulia carbonates belong to the footwall of NE-dipping reverse fault rather than to the hangingwall of a SW-dipping normal fault, as it would be expected from the interpretation of the Casoli-Bomba High of *Scisciani et al.* [2001]. In addition, a careful examination of the seismic line published by these authors shows that the geometric array of some strong reflectors is comparable with the array observed 5 km southward in the CROP 11 line. Figure 9c provides the alternative interpretation, featured by a backthrust structure in agreement with the reading of the CROP 11 profile.

[24] In the CROP 11 profile, the top of the Apulia carbonates at the rear of the Casoli-Bomba structure lies at a depth of 3.5 s TWT, which is 1.0–1.5 s TWT deeper than the depth expected just considering the gentle regional dip of the foreland homocline depicted by the top of the Apulia carbonates between the eastern termination of the CROP 11 line and the Monte Marcone 1 well (see Foldouts 3 and 4). Therefore, an important westward-dipping normal fault is required west of Monte Marcone 1 in order to justify the displacement of the top-carbonate horizon from about 2 s TWT in correspondence to Monte Marcone 2 to about 3.5 s TWT west of Bomba 2, over a distance of only 10–11 km. Consequently, we have interpreted the Casoli-Bomba High as an inverted structure created by the reactivation of an important normal fault as a reverse fault, with the contemporaneous activation of backthrusts nucleated from a triangle zone. The absence of growth strata that would be expected in the hangingwall block may be justified by subsequent erosional processes, considering that in correspondence to the eastern termination of the structural high the vertical component of the slip related to the shortening roughly equalled the accommodation space created by the extension. High-relief, double-vergence popup-like structures similar to the Casoli-Bomba High and occupying the same structural position close to the front of the allochthonous sheets have been recognized also in the Southern Apennines. The most striking one is the Tempa Rossa oil field in Basilicata [see *D'Andrea et al.*, 1993] recently interpreted as an inversion thrust fold [*Casero*, 2004].

[25] As concerns the time relations between the transport of the allochthonous sheets over the foreland margin and the growth of the Casoli-Bomba High, the CROP 11 line suggests that the structural high formed after and not before the final transport of the Molise nappes in the area as it has been suggested by *Scisciani et al.* [2001]. The major evidence is provided by the bumped geometry of the Molise base thrust that has accommodated the growth of the underlying structural high. Along the trace of the CROP 11 profile, the base thrust of the Molise nappes lies at 700–800 m b.s.l. in correspondence to the Casoli-Bomba culmination and deepens to more than 2000 m b.s.l. in correspondence to the eastern foot of the structure (Monte Marcone 1 well). West of the Casoli-Bomba structure, the base thrust of the Molise nappes must lie at depths largely exceeding 2000 m b.s.l. since Torricella Peligna 2 was stopped at a depth of 1997 m b.s.l. quite far from the deepest reflectors still referable to the allochthonous sheets (see Foldouts 3 and 4). In addition, the overall reflector geometry shows that the lower part of the allochthonous sheets explored by Torricella Peligna 2 deepens again toward the east before being overthrust by the Apulia carbonates of Bomba 2.

[26] No stratigraphic constraints for dating the described tectonic structures are available in the Casoli-Bomba area. However, important pieces of information can be derived from the Plio-Pleistocene autochthonous deposits of the Adriatic foredeep the internal architecture of which appears to have been closely controlled by the kinematic history of the nappe front. As everywhere along the outer margin of the Apennines, the Plio-Pleistocene foredeep deposits can be divided into three intervals (preramp, synramp and postramp intervals in Figures 5 and 10), each interval being characterized by specific stratigraphic signatures imprinted by the active thrust propagation in the mountain chain. Ages and biozone definition of the Plio-Pleistocene deposits in the study area derive from the composite logs of Monteodorisio 1 and Ponte 1Dir. Biostratigraphic data have been obviously integrated with lithology and wireline-log correlations. Figure 11 provides a biostratigraphic scheme of the Pliocene and Pleistocene with the foraminiferal zones quoted in the text.

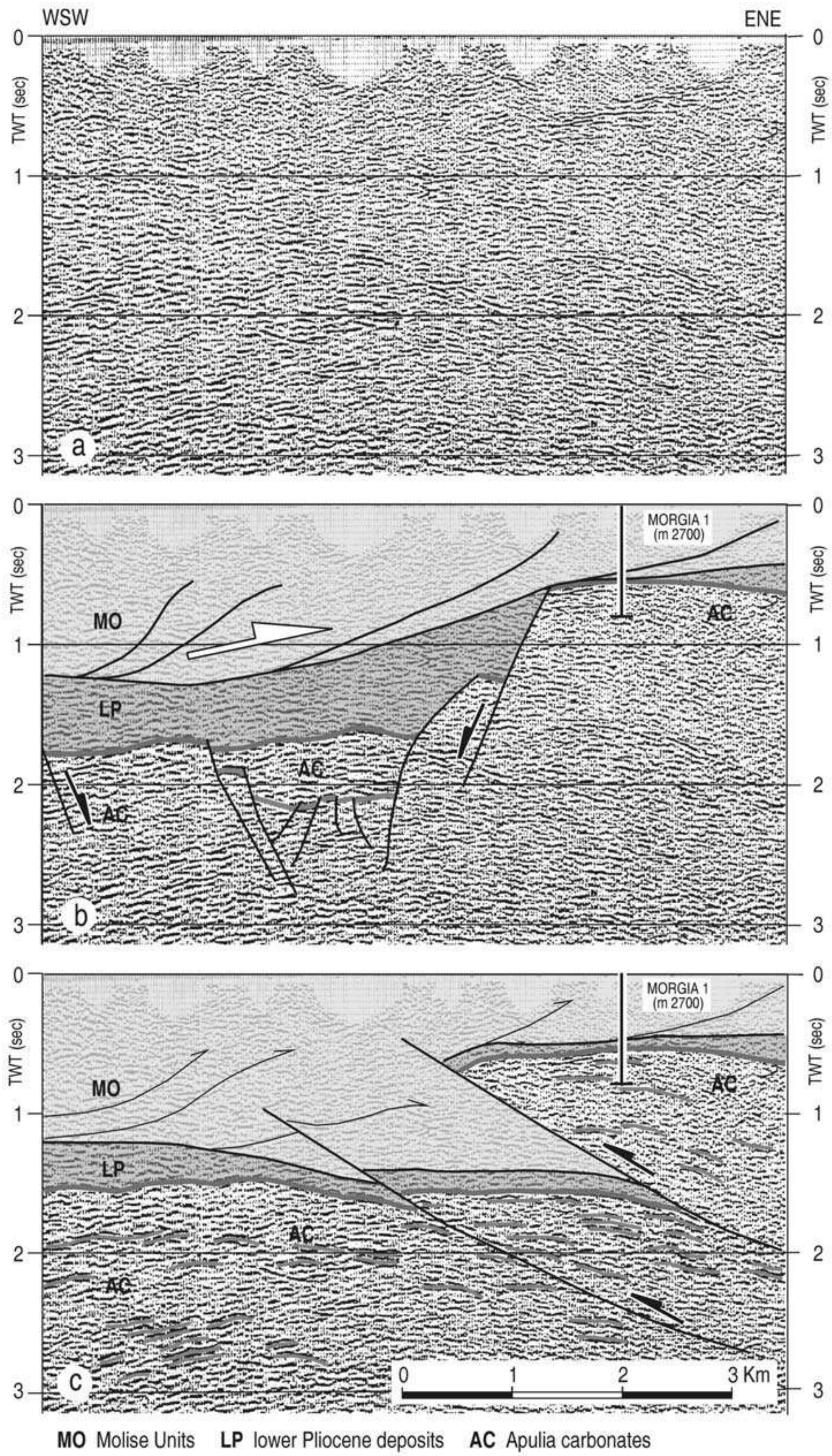


Figure 9. Different structural interpretations of the western flank of the Casoli-Bomba High. (a) Uninterpreted segment of a commercial line parallel to the CROP 11 line located a few kilometers toward the north. (b) Interpretation according to *Scisciani et al.* [2001]. (c) Alternative interpretation proposed in this paper. See in Figure 3 the location of Morgia 1.

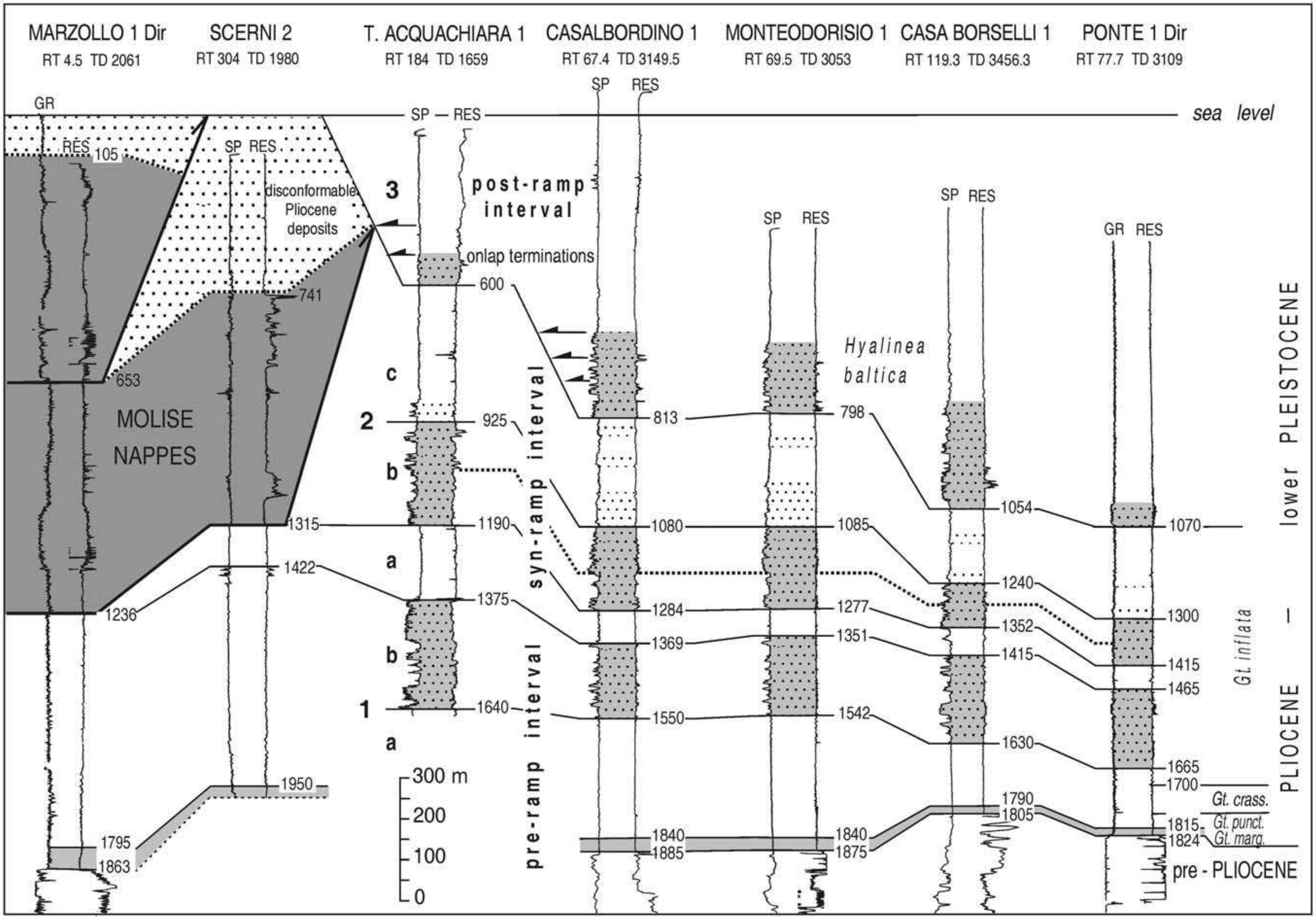


Figure 10. Well-log correlation of the Plio-Pleistocene foredeep deposits crossed by the CROP 11 line. Bold numbers 1, 2, and 3 indicate the preramp, synramp and postramp deposits, respectively. Geometry and mutual relationships of the foredeep deposits have derived from the seismic interpretation. Ages and biozone attributions have derived from Ponte 1Dir as concerns the Pliocene and from Monteodorisio 1 as concerns the Pleistocene.

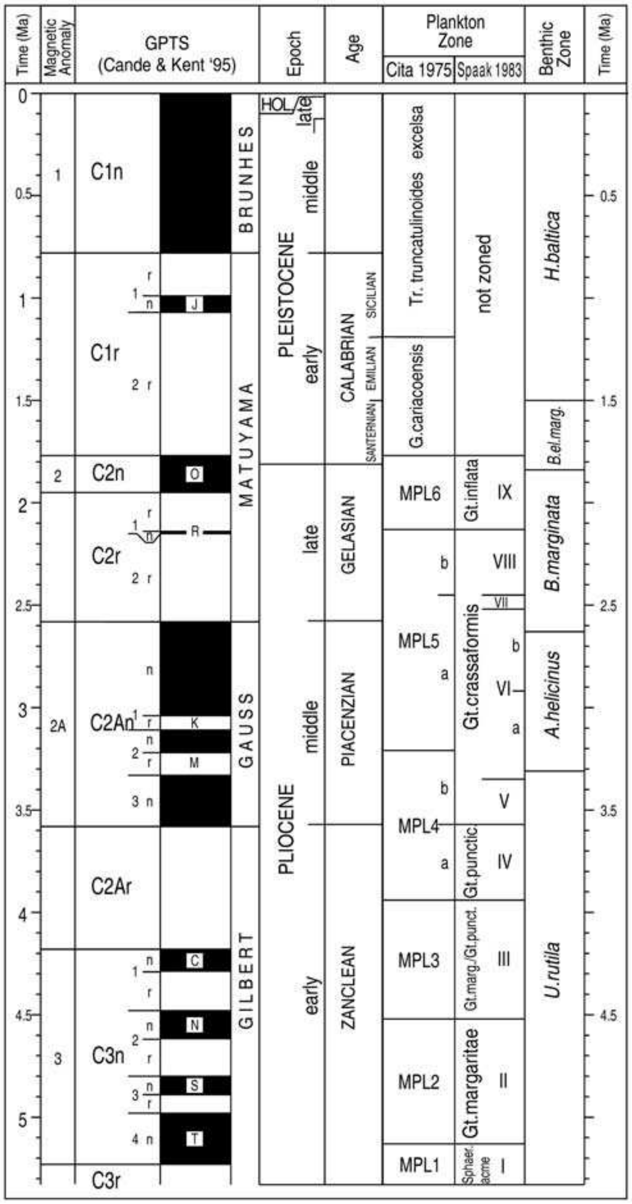


Figure 11. Adopted Plio-Pleistocene timescale (simplified from *Patacca and Scandone* [2004b]), showing the most significant bioevents recalibrated according to the global polarity timescale of *Cande and Kent* [1995]. Plankton zones after *Cita* [1975] and *Spaak* [1983]. Benthic zones after *Colalongo and Sartoni* [1979].

4.1. Preramp Interval (Interval 1 in Figures 5 and 10)

[27] This interval is expressed by a reflection-free seismic facies (1a) upward followed by a faintly layered unit with even parallel, rather weak reflectors (1b). In commercial lines, these bedded deposits are usually marked by stronger and more continuous reflectors. Lithologically, the sequence consists of a basal clayey unit some hundred meters thick (1a) upward followed by a stack of aggrading well-bedded sandstones and shales displaying a broad blocky well-log profile (1b). The basal clayey unit, forming a widespread pelagic sheet on top of the Apulia carbonates, yielded planktonic-foram associations (e.g., Ponte 1Dir) indicative of the *Gt. margaritae* zone (early Pliocene) up to the *Gt. inflata* zone (late Pliocene, see Figure 11). The overlying sandy packages still belong to the late Pliocene (*Gt. inflata* zone).

4.2. Synramp Interval (Interval 2 in Figures 5 and 10)

[28] The synramp interval is represented by a clastic wedge thinning toward the east, landward (westward) truncated upsection by the Apennine frontal ramp. In correspondence to Ponte 1Dir, the synramp deposits thin out into a relatively transparent seismic facies represented by claystones with minor intercalations of very thin-bedded sandstones (see ragged well-log profile of Ponte 1Dir in Figure 10). Well logs and commercial profiles, obviously providing a vertical resolution higher than the resolution obtained from the CROP 11 seismic data, show a quite complex depositional architecture. Three portions may be broadly identified. The thin lower portion (2a) is pictured by a shaly linear log profile and is seismically poorly resolved in the CROP 11 line. The thicker middle portion (2b) is a well distinct seismic unit characterized by rather continuous, even-parallel strong reflectors. The fairly good quality of the log data allows the recognition of two superimposed thinning- and fining-upward sequences of bedded turbidites with a broad bell-shaped well-log profile particularly well evident in Casalbordino 1. The upper portion of the synramp interval (2c) consists of a muddier sedimentary unit seismically featured by a chaotic to reflection-free internal configuration laterally substituted by a package of continuous parallel reflectors with a very gently mounded external profile. The change in the seismic facies reflects a change from slumped massive clays (e.g., Torrente Acquachiara 1) to well-bedded fine-grained sandy turbidites (e.g., Casalbordino 1). According to the biostratigraphic data reported in the composite log of Ponte 1Dir, the entire synramp interval should belong to the late Pliocene. However, the occurrence of *H. baltica* (Emilian, see Figure 11) in the immediately overlying postramp deposits suggests a Santernian age (early Pleistocene before the first occurrence of *H. baltica*) of the synramp muddier deposits distinguished as interval 2c in Figure 10.

4.3. Postramp Interval (Interval 3 in Figures 5 and 10)

[29] This interval is imaged in its lower part by fairly continuous horizontal reflectors corresponding to fine-grained sandy turbidites and mudstones, locally interrupted by concave-up reflections featuring channels that may have been filled with pebbly conglomerates (e.g., Torrente Acquachiara 1 and Casa Borselli 1). Landward (westward), the even-parallel reflectors seal the frontal ramp of the allochthonous sheets with an evident marine onlap termination. The occurrence of *Hyalinea baltica* in Monteodorisio 1 and Ponte 1Dir at the base of the postramp interval fixes the age of deactivation of the frontal ramp around the Santernian-Emilian boundary, i.e., around 1.5 Ma. The upper portion of the lower Pleistocene sequence, not detected by the CROP 11 profile but well exposed in the

area (see Figure 3), is represented by a transgressive-regressive cycle topped by a thin veneer of reddish continental sandstones. The latter laterally evolve, in the Adriatic Sea, into a prograding shelf-margin system seismically imaged by sigmoid reflectors with clear offlapping geometry (see CROP M13, M14 and M15 lines, located in the offshore not far from the CROP 11 line, inwork by *Scrocca et al.* [2003]).

[30] The described Plio-Pleistocene foredeep deposits provide important constraints on the timing of the tectonic evolution of the area east of Majella. Moving over a long thrust flat acting as a conveyor belt for forward nappe transport, the Molise nappes approached their present-day position around the Pliocene-Pleistocene boundary, after the deposition of the *Gt. inflata* turbidites and before the onset of the synramp clastic wedge. Consequently, the Casoli-Bomba structural high, the growth of which bumped the Molise base thrust, did not exist in that time and the corresponding paleogeographic realm had to be part of the foreland homocline. The Majella Unit, on the contrary, had already been incorporated in the Apennine thrust belt when the Molise nappes underwent the last tectonic transport over the foreland margin. This constraint is established by the occurrence of upper Pliocene thrust-top deposits unconformably overlying the northeastern margin of the Majella anticline [*Crescenti*, 1971b]. The Casoli-Bomba positive structure began to grow after the forward transport of the allochthonous sheets, i.e., after the deposition of the upper Pliocene *Gt. inflata* turbidites of the Adriatic foredeep basin. However, the stratigraphic constraints established by the Plio-Pleistocene foredeep deposits do not allow us to establish whether the growth of the Casoli-Bomba High predates (as suggested in our seismic interpretation) or is coeval with the backthrust responsible for the positive structure on top of which the Majella Mountain was passively uplifted. We will return to this subject in the next session after having discussed the deep structure of the Majella massif.

5. Deep Structure of the Majella Massif

[31] A few tens of kilometers far from the Adriatic coast, the Majella Mountain features a box-shaped anticline that describes an arc about 35 km long, convex toward the northeast, and reaches the remarkable elevation of 2793 m a.s.l. (Monte Amaro) in correspondence to the axial culmination. The fold has a gentle axial plunging toward the north and a steeper plunging toward the south (see Figures 2 and 3). Along the eastern margin of the structure, the forelimb of the anticline is tectonically overlain by the Molise nappes that in this area are westward limited by a lateral ramp. At the western margin of Majella, the backlimb of the fold is missing, cut across and downthrown by an important normal fault system known in the geological literature as the Caramanico Fault [*Ghisetti and Vezzani*, 2002]. In correspondence to the axial culmination of the fold, the fault system has produced a cumulative downthrow of the hangingwall block exceeding 3500 m. A narrow tectonic depression parallel to the fault system (Caramanico depression) separates the western edge of the Majella Massif from the Morrone Ridge (see Figure 3).

[32] The sedimentary sequence of the Majella Unit is represented by upper Triassic to upper Miocene carbonates followed by Messinian evaporites and marls conformably overlain by lower Pliocene siliciclastic flysch deposits. The upper Triassic-Jurassic portion of the sequence is known only in the subsurface, explored by the wells Cigno 2, Musellaro 1, Maiella 2 and Caramanico 1 (see location in Figure 3). These wells testify to the drowning of an upper Triassic-lower Jurassic carbonate shelf and to the establishment of a Jurassic *p.p.*-Cretaceous basin in northern Majella. A very well preserved transition between the Cretaceous platform and the adjacent basin is spectacularly exposed in central Majella, with isopic facies distribution following a W-E direction roughly perpendicular to the Pliocene fold axis. The sedimentary sequence and the stratigraphic evolution of Majella are well known owing to the existence of several biostratigraphic and sedimentological studies, in some cases accompanied by detailed field surveys (see, among many others, *Crescenti et al.* [1969], *Donzelli* [1969], *Accarie* [1988], *Vecsei* [1991], and *Vecsei et al.* [1998]).

[33] The CROP 11 line crosses the Majella Massif in correspondence to the southern termination of the anticline, where the Majella Unit disappears beneath the Morrone-Porrara Unit (Figure 3). In this part of the profile there is a gap of information on the shallow structure because the acquisition of seismic data in the region was precluded in the early nineties after the institution of the Majella National Park. However, well organized sets of reflectors east of Majella between the CDP 4700 and 5000 suggest the existence of an important westward-climbing structure in the footwall of Majella that we have interpreted as a blind backthrust nucleated at the rear of the Casoli-Bomba High at a depth exceeding 7 s TWT (see Foldouts 3 and 4). According to this interpretation, the Majella Massif has been passively uplifted on top of the growing backthrust structure. The package of westward dipping reflectors in correspondence to the Caramanico fault system between 3 and 6 s TWT (CDP 4150–4450) has been considered representative of the Paleozoic-Triassic deposits underlying the Mesozoic carbonates that in our interpretation are part of the Majella Unit.

[34] In order to check the proposed tectonic reconstruction and to fill the gap of information of the CROP 11 line at shallow depths, we have analyzed a commercial line (line A in Figure 3) that crosses the Majella anticline. The line extends from the Caramanico depression to the Casoli-Bomba High intersecting the highest peaks of Majella (Monte Amaro and Monte Acquaviva) and is stratigraphically linked to the Maiella 1 well in correspondence to the western termination and to the Casoli 6 and Casoli 7 wells in correspondence to the eastern termination (see Figure 12). The Maiella 1 well, located in the hangingwall of the Caramanico fault, crossed 2160 m of upper Messinian-lower Pliocene siliciclastic flysch deposits of the Queglia Unit and reached Upper Jurassic/Lower Cretaceous shallow-water limestones referable to the Majella Unit at 2160 m

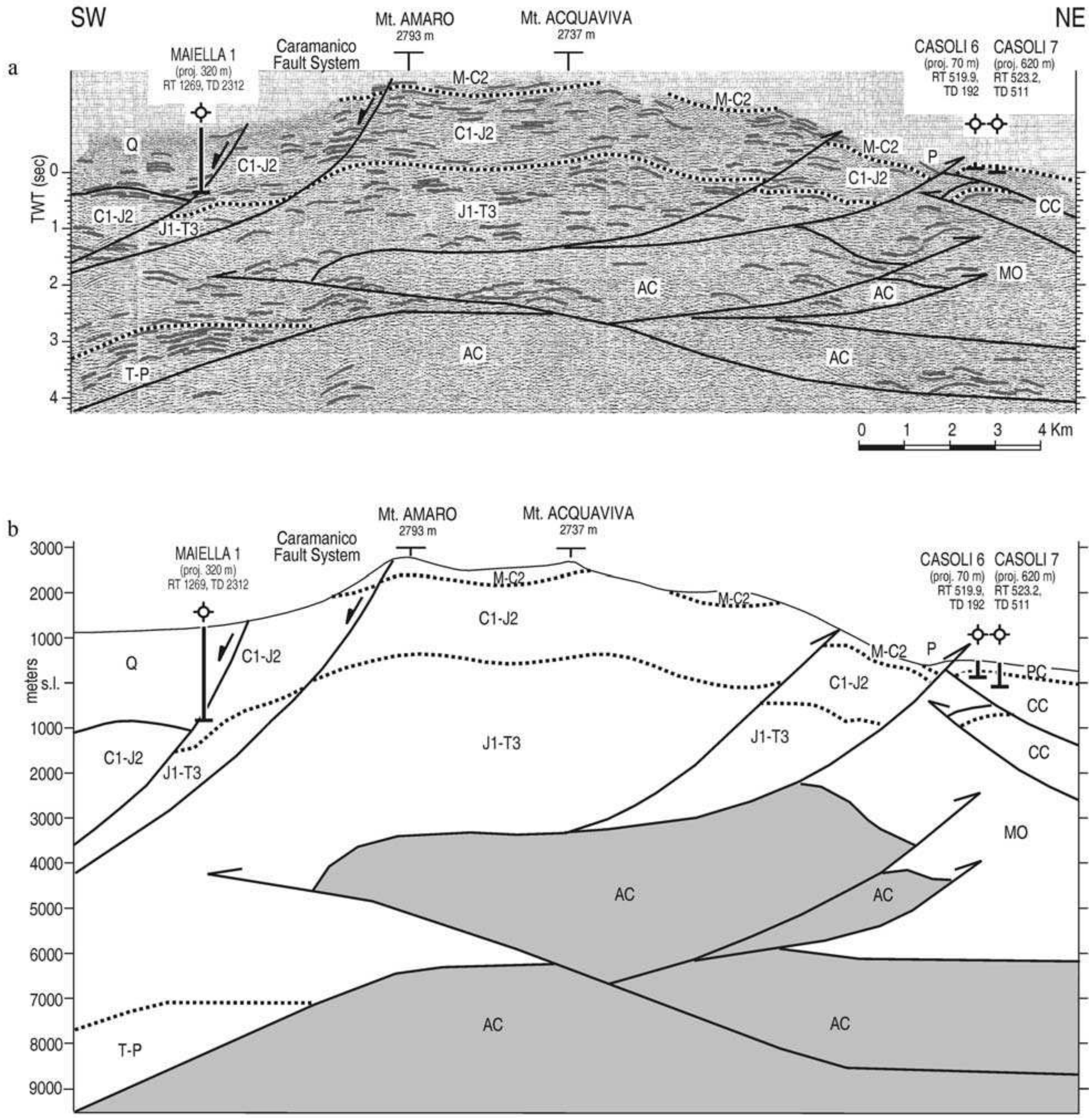


Figure 12. Interpreted commercial line crossing the Majella anticline in correspondence to the (a) axial culmination and (b) corresponding geological section. Datum plane of the seismic profile: 200 m above sea level. Abbreviations: AC, Mesozoic-Tertiary carbonates of the Apulia Platform in the footwall of Majella; CC, Mesozoic-Tertiary carbonates of the Apulia Platform in the Casoli structural high; PC, lower Pliocene marly clays of Casoli; TP, Paleozoic-Triassic deposits of Majella; J_1-T_3, Upper Triassic–Lower Jurassic carbonates of Majella; C_1–J_2, Middle Jurassic–Lower Cretaceous carbonates of Majella (Morrone di Pacentro Fm); M-C_2, Upper Cretaceous–upper Miocene carbonates and Messinian evaporites of Majella; P, lower Pliocene siliciclastic flysch deposits of Majella; Q, upper Messinian–lower Pliocene siliciclastic flysch deposits of the Queglia Unit; MO, Molise nappes.

(890.6 m b.s.l.). In spite of the widespread noise, a couple of well expressed reflectors featuring a rollover anticline in the hangingwall of the fault is evident west of Majella 1 at about 0.3 s TWT (i.e., at a depth of about 800 m b.s.l.). We have referred these reflectors to the "Gessoso-Solfifera" and Bolognano Formations. Considering now that the top of Monte Amaro is constituted of Oligocene limestones and that the thickness of the overlying Bolognano Fm plus "Gessoso-Solfifera" Fm does not exceed 200 m, we obtain for the Caramanico fault system a cumulative downthrow of about 3800 m (2793 m relative to the Monte Amaro elevation area plus 200 m relative to the interval between the Oligocene limestones of Monte Amaro and the top of the Messinian "Gessoso-Solfifera" Fm plus 800 m relative to the depth of the Messinian carbonates and evaporites in the hangingwall of the fault). At the right end of the seismic line, the Casoli 6 and Casoli 7 wells have crossed a short section of lower Pliocene clayey deposits and have reached the Bolognano Fm (plus "Gessoso-Solfifera" Fm in Casoli 7) at 137 and 175 m respectively, on top of the structural high. The emergence of the Majella base thrust in this area is very well constrained by surface geological evidence. In correspondence to the Casoli 6 and Casoli 7 wells, in fact, 45°–50° dipping lower Pliocene siliciclastic flysch deposits of the Majella Unit, stuffed with red-colored olistostromes derived from the Molise nappes, tectonically overlie subhorizontal lower Pliocene marly clays which at shallow depth have resulted to be stratigraphically linked to the carbonates of the Casoli-Bomba High.

[35] The core of the Majella fold has been explored by two wells (the Caramanico 1 and Maiella 2 wells, see Figure 13) located 13–14 km NW of the commercial line A. Both wells, drilled in correspondence to the axis of the anticline, have crossed about 100 m of Miocene open-ramp limestones, 300 m of Paleogene to uppermost Cretaceous deeper-ramp limestones and 900 m of Cretaceous-middle Jurassic basinal limestones before reaching lower Jurassic-upper Triassic shallow-water dolomites and dolomitic limestones. Caramanico 1, deeper than Maiella 2, penetrated a thick pile (about 3800 m) of lower Jurassic-upper Triassic carbonates without reaching the base thrust of the Majella Unit. The occurrence of a thick sequence of upper Triassic dolomites without encountering anhydrites may be attributed to tectonic repetitions within the dolomitic interval or, more probably, to a primary lateral variation of the Upper Triassic facies. Thick dolomite sequences of Late Triassic-Early Jurassic age devoid of evaporites are in fact quite common in other area of the central-southern Apennines (e.g., Simbruini and Picentini Mountains [see *Beneo*, 1936; *Scandone and Sgrosso*, 1963; *Accordi and Carbone*, 1988]).

[36] As concerns the calibration of the commercial line A, the columnar section obtained from Caramanico 1 resulted useful for fixing thickness and facies of the Upper Triassic–Lower Jurassic carbonates but could not be applied to the drilled Middle Jurassic–Upper Cretaceous portion of the sequence which is constituted of basinal deposits. The seismic profile, in fact, crosses the Majella massif just south of the platform margin, in an area in which the Middle Jurassic–Upper Cretaceous deposits are represented by shallow-water carbonates. For this portion of the sequence we have used the composite section of Figure 13 obtained by combining the information on Montagna del Morrone available in the geological literature with original unpublished data on the Monte Amaro-Monte Acquaviva area, together with the Cupello 19 well, the stratigraphic sequence of which should be comparable with the sequence of central and southern Majella. This virtual stratigraphic section slightly exceeds 6000 m (650 m of Upper Cretaceous–Paleogene deposits exposed in the Monte Amaro area, 1900 m of Middle Jurassic–Lower Cretaceous shallow-water carbonates cropping out in the Southern Morrone Ridge and, finally, 3780 m of Upper Triassic–Lower Jurassic dolomites drilled by Caramanico 1. The small difference in thickness between the Middle Jurassic–Upper Cretaceous deposits of the Mt. Morrone–Mt. Amaro composite section and the coeval carbonates of Cupello 19 may be explained considering the generalized higher values of the subsidence in the areas of the Apulia Platform located east and southeast of the Majella domain. Taking into account the average elevation of the shot points of the commercial line in the Monte Amaro–Monte Acquaviva area (around 2750 m a.s.l.), the dolomites at the base of the composite columnar section should lie at a depth slightly exceeding 3500 m b.s.l. (about 6300 m of total thickness minus 2750 m of ground elevation). Considering the elevation of the datum plane in the commercial line (200 m a.s.l.) and attributing to the dense Lower Jurassic–Upper Triassic dolomites a P-wave velocity value of 5.8–6 km/s, the depth 3500 would lie in the seismic profile at about 1.2 s TWT, just above the time depth we have assigned to the Majella base thrust in Figure 12a. It should be stressed that the thickness of the carbonates above the datum plane appears strongly exaggerated in the commercial section because of the very low and unrealistic replacement velocity used in the Monte Amaro–Monte Acquaviva region that averages 3 km/s. Figure 12b is a geological section representing the depth conversion of the interpreted commercial line. The proposed interpretation has been obviously guided by the deep structure interpretation of the CROP 11 profile between the CDP 4350 and 5100.

[37] *Ghisetti and Vezzani* [2002] have described the Caramanico Fault as a Quaternary normal fault post-dating the tectonic shortening in the area. Conversely, *Scisciani et al.* [2001] have considered the Quaternary activity of the fault very limited (about 700 m of downthrow), the bulk of the displacement having been produced during Messinian and early Pliocene times. These authors have interpreted the difference in thickness between the Messinian-lower Pliocene deposits of the footwall block (100–150 m of Messinian evaporites and marls followed by about 500 m of lower

Figure 13. Stratigraphic correlations in the Mesozoic-Tertiary carbonates of northern Majella (Maiella 2 and Caramanico 1 wells), central Majella (Monte Morrone-Monte Amaro composite section) and Apulia (Cupello 19 well). Well location given in Figure 3. The thicknesses of the lithostratigraphic units have been derived from the reinterpreted composite logs of Maiella 2 and Caramanico 1, from *Raffi and Forti* [1959] as concerns the Jurassic carbonates of southern Morrone, from *Dondi et al.* [1966] as concerns Cupello 19, and from original unpublished data as concerns the Majella sequence and the Lower Cretaceous portion of the Morrone di Pacentro Fm in the southern Morrone area.

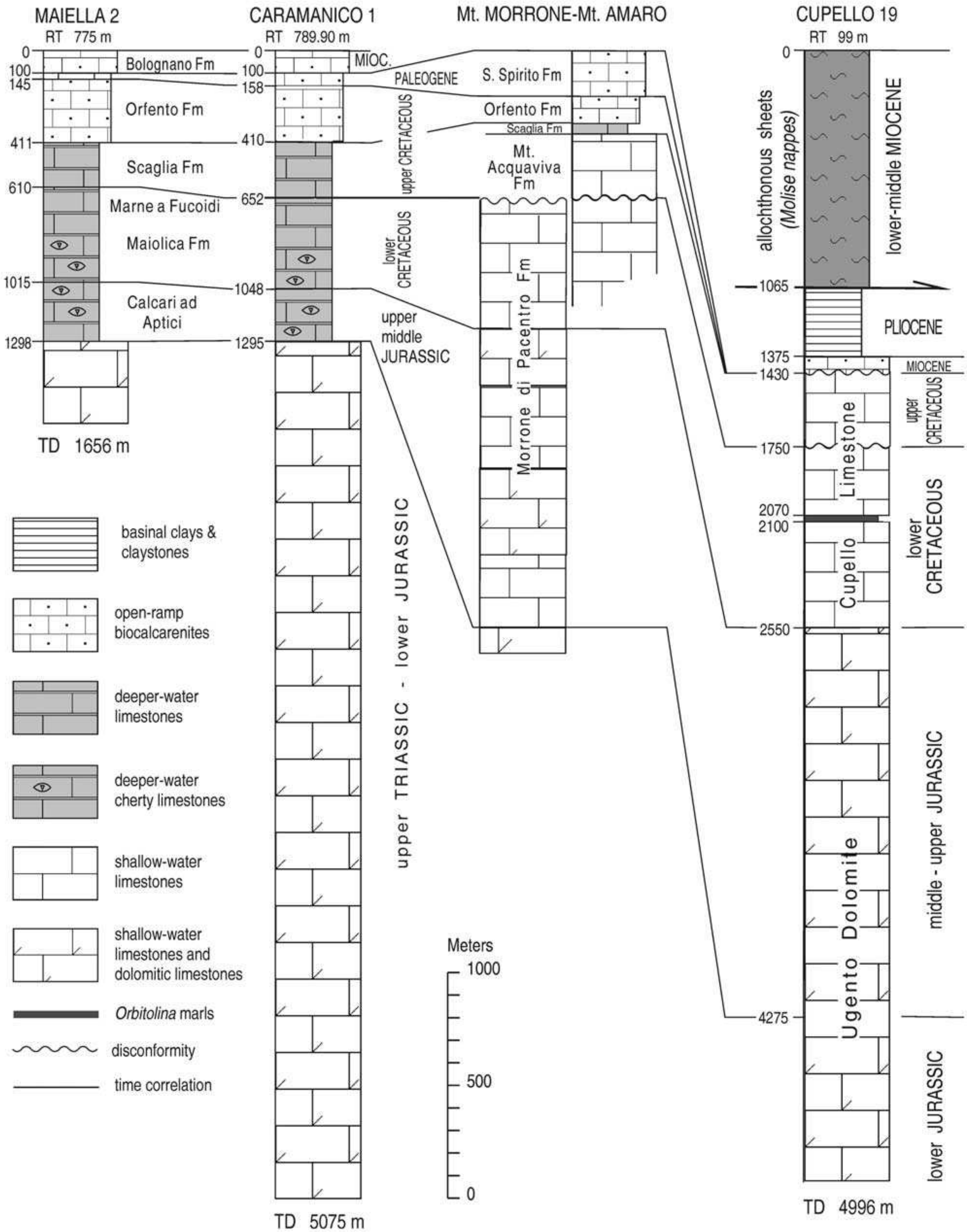

MAIELLA 2
RT 775 m
CARAMANICO 1
RT 789.90 m
Mt. MORRONE-Mt. AMARO
CUPELLO 19
RT 99 m
Bolognano Fm
MIOC.
PALEOGENE
S. Spirito Fm
Orfento Fm
upper CRETACEOUS
Scaglia Fm
Mt. Acquaviva Fm
Marne a Fucoidi
Maiolica Fm
lower CRETACEOUS
Calcari ad Aptici
upper middle JURASSIC
Morrone di Pacentro Fm
TD 1656 m
upper TRIASSIC - lower JURASSIC
TD 5075 m
allochthonous sheets (Molise nappes)
lower-middle MIOCENE
PLIOCENE
MIOCENE
Cupello Limestone
middle - upper JURASSIC
Ugento Dolomite
lower JURASSIC
TD 4996 m
basinal clays & claystones
open-ramp biocalcarenites
deeper-water limestones
deeper-water cherty limestones
shallow-water limestones
shallow-water limestones and dolomitic limestones
Orbitolina marls
disconformity
time correlation
Meters
1000
500
0

Figure 13

Pliocene siliciclastic deposits) and the coeval deposits of the hangingwall block (exceeding 2100 m in the Maiella 1 well) as the evidence for a syntectonic sedimentary wedge grown during the activity of the fault. In reality, the thick section of Messinian–lower Pliocene siliciclastic deposits crossed by Maiella 1 does not belong to the Majella Unit, where the base of the siliciclastic flysch deposits has an early Pliocene age, but to the more internal Queglia Unit where the base of the siliciclastic flysch deposits dates back to the Messinian. Therefore, the Caramanico Fault cannot be interpreted as a growth fault active in Messinian and early Pliocene times since its activation post-dates the tectonic transport of the Queglia Unit over the Majella domain (Zanclean, *Globorotalia margaritae/Gt. puncticulata* concurrent range zone, see time table in Figure 11). The CROP 11 line suggests that the Majella anticline overlies a popup structure in the Mesozoic-Tertiary carbonates of the Apulia Platform related to an important blind backthrust. In such a structural framework, we have interpreted the Caramanico Fault as a gravity-collapse feature developed in the roof of the tectonic edifice at the front of a growing ridge. This fault may have progressively accommodated with a listric geometry the increase in the structural elevation created by the backthrust structure grown in the footwall of the Majella anticline. Our interpretation implies the existence of close relationships between structural elevation and amount of displacement across the fault. We have seen that the cumulative vertical downthrow across the Caramanico fault system averages 3800 m in correspondence to Monte Amaro, i.e., in correspondence to the axial culmination of the anticline. Moving northward in the direction of the Pescara River, the elevation of the Majella Mountain gradually decreases as a consequence of the gentle plunging of the fold axis. Referring to the base of the Bolognano Fm, the elevation decreases from about 2750 m a.s.l. in the Monte Acquaviva area to a few hundreds of meters in correspondence to the Pescara Valley. The gradual decrease in the structural elevation is accompanied by a simultaneous decrease in the fault displacement until zero displacement is reached in correspondence to the Pescara Valley where the Majella Unit disappears beneath the Messinian–lower Pliocene terrigenous deposits of the Queglia Unit [*Patacca et al.*, 1991], the base thrust of this unit being here represented by a long thrust flat gently folded by the northward-plunging Majella anticline.

[38] In the Majella area, no stratigraphic constraint exists for establishing the age of the Caramanico fault activity. Some information on the age of the backthrust developed in the footwall of Majella, and consequently on the age of the gravity collapse at the front of the growing ridge, is provided by the Pliocene-Pleistocene deposits of the Adriatic Apennine margin (see Figures 3 and 10). Uppermost Pliocene thrust-top deposits unconformably overlying Majella (late Gelasian [see *Crescenti*, 1971b]) and sealing the tectonic contact between the Majella and Queglia Units establish an upper chronological boundary for the incorporation of the Majella domain in the Apennine thrust belt (the lower boundary is fixed by the age of the uppermost portion of the siliciclastic flysch deposits of Majella: Zanclean, *Globorotalia margaritae/Gt. puncticulata* concurrent range zone). During the late Pliocene, however, the elevation of Majella had to be very modest since no lithotypes derived from the Majella sequence are present in the coarse-grained layers (pebble conglomerates) of the aforementioned thrust-top deposits. Elevation had still to be modest in the lower part of the early Pleistocene, as testified by the generalized Emilian transgression along the eastern margin of Majella (see transgressive postramp interval of the Plio-Pleistocene deposits of Figure 10) suggesting tectonic subsidence rather than uplift. Finally, in a still undefined moment of the early Pleistocene (late Emilian? Sicilian?) the open-marine conditions east of Majella were suddenly replaced by near-shore conditions so that sands and conglomerates were deposited forming as a whole a shallowing-upward and coarsening-upward prograding system. The occurrence of *Elephas meridionalis* remains in paralic deposits a few kilometers north of Majella [*D'Erasmo*, 1931] confines the regressive event in the early Pleistocene before the extinction of this species and thus before the last magnetic inversion. The upper portion of the regressive sequence, well exposed at about 600 m a.s.l. in correspondence to the northeastern margin of the Majella anticline, is characterized by conglomerates with clasts surely derived from the Mesozoic carbonates of Majella. The sudden, deep erosion of the Majella anticline after the Emilian generalized transgression testifies to an energetic tectonic uplift of the structure within the early Pleistocene. A downthrow of 3800 m across the Caramanico fault system may appear surprisingly high compared with the short time interval in which was completed if we interpret this fault as a normal fault related to a young extensional regime subsequent to the compression in the region. Conversely, if we interpret the Caramanico fault system as a gravity-collapse feature, a displacement of 4 km does not sound strange since it can have been completed in a few hundreds of kyears considering that the tectonic uplift (and consequently the amount of the gravity collapse) represents the vertical component of the active-thrust slip vectors the rate of which in the central-southern Apennines averaged some centimeters per year during the early Pleistocene [*Patacca and Scandone*, 2001, 2004b].

6. Structural Architecture of the Abruzzi Region Between the Majella Massif and the Fucino Region

[39] Between the southwestern margin of the Majella anticline and the Fucino area, the CROP 11 line cuts across a stack of carbonate units constituted of shallow-water-platform and adjacent slope-to-basin deposits [*Accordi and Carbone*, 1988, *D'Andrea et al.*, 1991; *Piacentini*, 2000; *Parotto and Praturlon*, 2004, and references therein]. The seismic resolution of the CROP profile in this part is quite poor, with a few sets of organized reflectors several of which recognizable only at depths exceeding 4 s TWT. In addition, the absence of commercial wells in the area did not allow any link between stratigraphic/tectonic units known on the surface and reflection events identifiable in the subsurface at shallow depths. Consequently, the interpretation of the CROP 11 profile in this segment is rather speculative.

[40] Starting from the Caramanico fault system, the seismic line runs through a stack of thrust sheets referable to the Morrone-Porrara, Gran Sasso-Genzana and Western Marsica Units (see Figure 3). A first problem is represented by the Queglia Unit, not intersected on the surface by the CROP 11 profile but cropping out one kilometer in the north tectonically sandwiched between the Majella and Morrone-Porrara Units. The bulk of the sedimentary sequence making up the Queglia Unit consists of uppermost Messinian–lower Pliocene siliciclastic flysch deposits reaching more than 2500 m in thickness north of the study area [*Casnedi*, 1983; *Patacca et al.*, 1991]. In a few outcrops, these flysch deposits conformably overlie 100–150 m of Upper Cretaceous–upper Miocene carbonates topped by a few meters of Messinian evaporites and marls. In the central Apennines the Queglia Unit forms a thrust sheet that extends uninterruptedly for about 50 km in length and 20–25 km in width. West of Majella, the unit occupies the narrow structural corridor of the Caramanico depression, in the footwall of the Morrone thrust. Moving from the Pescara Valley toward the south, the corridor becomes progressively narrower, until the Queglia Unit disappears beneath the Morrone carbonates. Moving in the same direction, the thickness of the Queglia deposits appears to become progressively smaller. We do not know whether the Queglia Unit is still represented in the subsurface along the trace of the CROP 11 line (as suggested by a strike commercial line running along the Caramanico corridor) or it ends somewhere in the north limited by a lateral/oblique ramp. In such a case, the deposits we have attributed to the Queglia Unit should be part of the Morrone-Porrara Unit. Everywhere the sequence of the Queglia Unit is exposed, the structural architecture is characterized by a tight system of short-wavelength folds, frequently reverse folds, systematically trending N-S also in the areas in which the contact with the overlying tectonic units suddenly changes from a N-S direction (Montagna dei Fiori plus Gran Sasso in the hangingwall) to a NW-SE direction (Morrone-Porrara in the hangingwall). These geometric relationships (see Figure 3) suggest an undisturbed continuation of the Queglia Unit in the footwall of the Gran Sasso and Morrone-Porrara thrust sheets. In our interpretation of the CROP 11 line, we have postulated the persistence of a thin section of Queglia Unit sandwiched between the Morrone-Porrara and the Majella Units and have assumed a distance between the front of the Queglia Unit and its trailing edge not smaller than 25–30 km, which corresponds to the minimum width of the Queglia Unit in the north. The front of the Queglia Unit has been easily traced by projecting on the CROP 11 line the closest outcrop. The position of the trailing edge, on the contrary, is not constrained by any reliable seismic imaging. A volume-balancing approach suggested the termination of the unit east of the Fucino Plain in correspondence to the CDP 3800. Once the position of the Queglia Unit at the rear of Majella was fixed, we have tried to reconstruct the overall structural architecture of the area by projecting to the subsurface the geometric array of the major surface structures, obviously using the few seismic features showing a coherently layered signature.

[41] Along the trace of the CROP 11 line, the Morrone-Porrara carbonates disappear beneath the Gran Sasso-Genzana Unit. The contact is covered by the continental Quaternary deposits of the Sulmona Plain, but it is well exposed at the northern and southern terminations of the intramontane basin (see Figure 3). In the seismic profile, we have tentatively followed the trend of badly defined parallel reflectors which appear to characterize the basinal upper sequence. The vaguely layered seismic fabric attributed to the Gran Sasso-Genzana Unit has been recognized as far as to the western termination of the interpreted profile. The existence of deposits referable to the Gran Sasso-Genzana Unit at shallow depths in this area would account for the occurrence of small and scattered outcrops of Jurassic basinal limestones just north of the Fucino Plain [see *Accordi and Carbone*, 1988], in an area entirely dominated by shallow-marine Mesozoic-Tertiary carbonates surely belonging to the Western Marsica-Meta Unit. West of the Fucino Plain, the seismic facies attributed to the Gran Sasso-Genzana Unit are tectonically sandwiched between the carbonates of the Western Marsica-Meta Unit and a deeper quite massive unit (Q_1 in Foldouts 3 and 4) that has been dubitatively referred to the Upper Triassic–Cretaceous *p.p.* original carbonate substratum from which the upper Cretaceous to lower Pliocene deposits of the Queglia Unit have been detached.

[42] As concerns the deep structure of the area between the Majella anticline and the Fucino Plain, a relevant seismic datum coming from the CROP 11 line is the occurrence of a layered seismic zone well expressed from 4 s TWT to 7–8 s TWT between the CDP 3500 and 3800. This layered zone, pointing to a deep-seated sedimentary sequence, seems to link with the eastward-climbing reflective interval recognizable between 4000 and 4450 attributed to the Paleozoic-Triassic deposits of the Majella Unit. We have interpreted the layered zone as an antiformal imbricated structure of Paleozoic-Triassic terrigenous deposits dubitatively attributed to the Majella Unit. Between the CDP 3550 and 3800, well organized sets of reflectors feature a ramp anticline that appears to have been breached by a foreland-dipping backthrust. The amount of forward transport of the terrigenous deposits in the hangingwall of a hinterland-dipping thrust surface has been balanced by a tectonic doubling of the overlying Mesozoic-Tertiary carbonates caused by a backthrust nucleated from an intracutaneous triangle zone. The younger and deeper backthrust that cuts across the ramp anticline contributed to the growth of the antiformal structure and consequently to the increase in the structural relief east of the Fucino Plain. This interpretation is obviously highly speculative. However, the occurrence at considerable depths of a reflective unit likely representative of a thick sedimentary sequence represents in any case an indisputable fact well documented by the CROP 11 seismic data.

[43] *Calamita et al.* [2004] have recently proposed a structural interpretation of the central Apennines according to which the crystalline basement, severely involved in the compressional deformation, should lie at very shallow

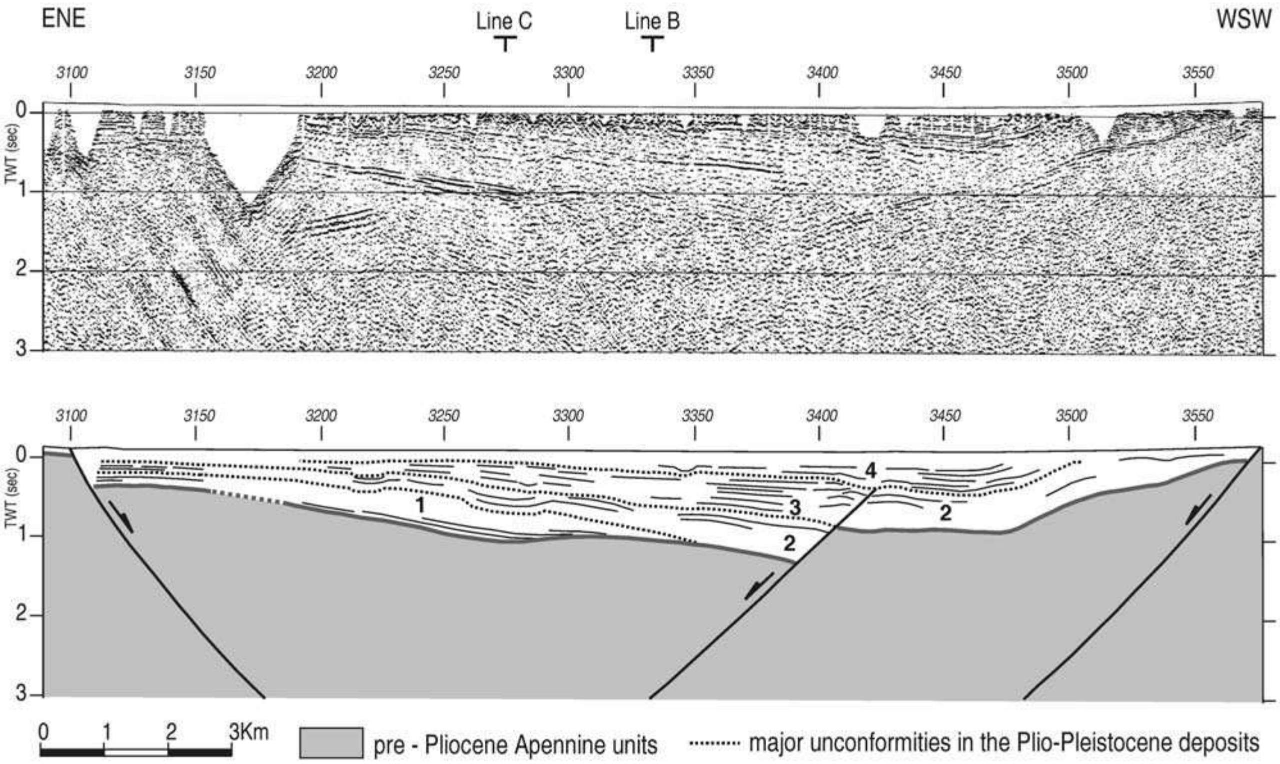


Figure 14. Interpretation of the CROP 11 profile in the Fucino area with the stratal architecture of the Plio-Pleistocene continental deposits filling the intramontane basin. Arabian numbers indicate the identified tectonically controlled seismic units (units 1–4) described in the text.

depths. In a geological section running a few tens of kilometers north of the CROP 11 line, these authors suggest the existence of an important shear zone produced by a lithospheric breach that would reach the surface in correspondence to the N-S trending lateral ramp of Gran Sasso. Because of this breach, the crystalline basement would have raised up to about 5 km below sea level. Projecting this geometric reconstruction on the CROP 11 profile, the crystalline basement should lie at a depth of about 2 s TWT beneath the mountains bordering in the east the Fucino Plain. The CROP 11 seismic data do not support this structural reconstruction since the overall reflection pattern suggests the existence of a sedimentary sequence involved in the Apennine shortening at depths largely exceeding the depth of the supposed crystalline basement.

[44] At the western termination of the interpreted seismic profile, a set of subhorizontal well organized reflectors is evident at a depth of 10.0–10.5 s TWT. We have been for a long time uncertain about the geological meaning of this seismic signal. The layered package, in fact may be identified with the layered seismic unit at the base of the Upper Triassic dolomites and anhydrites (considered representative of a thick sedimentary sequence) or with the layered seismic unit recognized near the eastern termination of the line at about 10 s TWT (considered representative of a crystalline lower crust). We have preferred the first solution, which better agrees with the flexure of the lower plate and the consequent deepening of the sole thrust and with the regional gravimetric minimum that would not be justified by a dense lower crust at relatively shallow depths. The structural reconstruction derived from this interpretation, not reported in Foldouts 3 and 4 because too much speculative, has been drawn in the synthetic Figure 17.

7. Structural Architecture of the Fucino Basin

[45] The Fucino basin is a Pliocene-Quaternary structural depression that hosted the greatest lake of central Italy before its artificial drainage in the second half of the 19th century. In correspondence to this tectonic feature, a short-wavelength local minimum of 15–20 mgals is superimposed on the regional negative field of the Bouguer gravity anomaly that characterizes the central Apennines from the Adriatic coast to the eastern boundary of the Sabina Units [see *Carrozzo et al.*, 1991]. The local gravimetric minimum may be related to the quite thick column of low-density Plio-Pleistocene continental deposits filling the structural depression. The sedimentary features and the tectonic evolution of the Fucino basin have been extensively investigated by several authors [see *Galadini and Messina*, 1994; *Bosi et al.*, 1995; *Cavinato et al.*, 2002, and references therein] who have related the origin of the basin to an extensional tectonics responsible for the generation of a half-Graben structure bounded by normal faults.

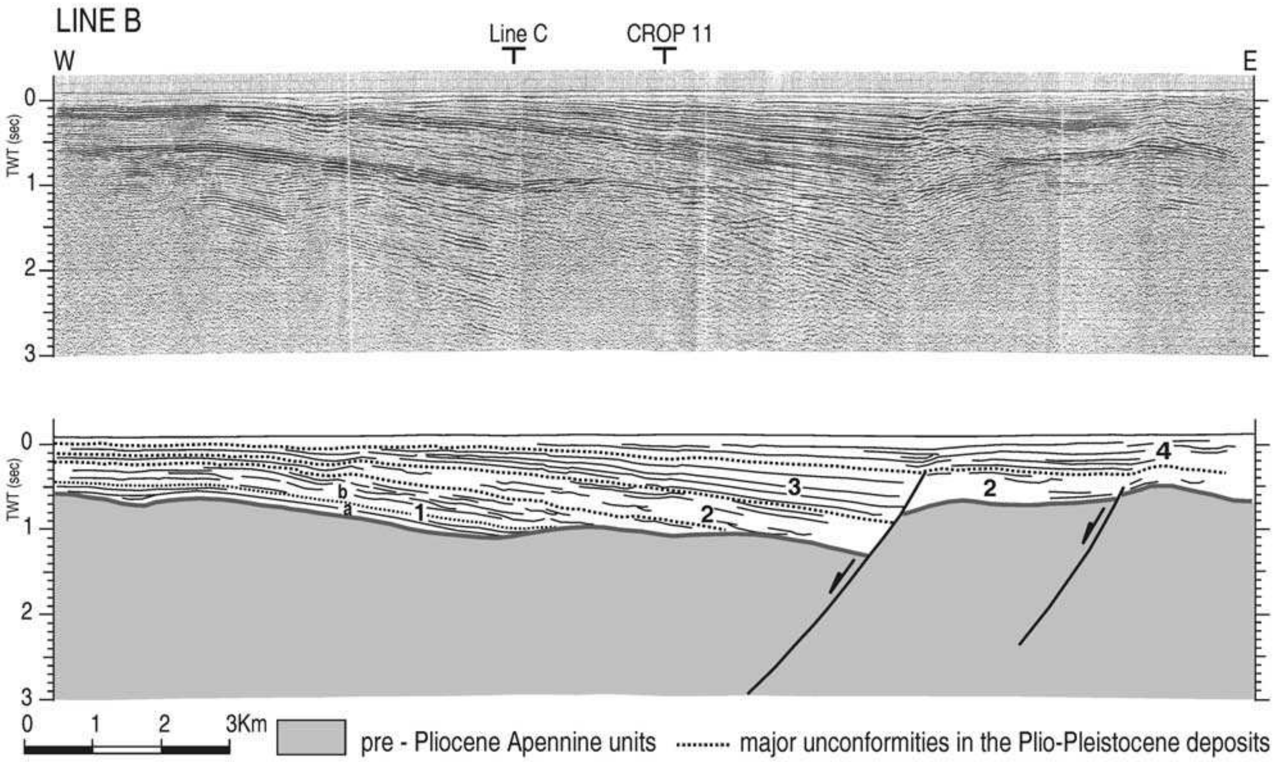


Figure 15. Commercial line (B line in Figure 3) showing the internal architecture of the Plio-Pleistocene continental deposits of the Fucino basin along a W-E oriented profile. The direction of the profile roughly coincides with the direction of the CROP 11 line in the area. Arabian numbers indicate the tectonically controlled seismic units distinguished in the CROP 11 profile.

[46] In correspondence to the Fucino Plain, the relatively good seismic resolution of the CROP 11 profile at shallow depths allows the recognition of four tectonically controlled sedimentary units displaying an upward decrease in the dip of the boundary surfaces. The lower unit (unit 1 in Figure 14), displays a broad lens-shaped external geometry with a strong angular unconformity at the base and is internally featured by high-frequency strong parallel reflectors followed by an ill-defined seismic facies. The second unit (unit 2 in Figure 14) is a wider lens-shaped sedimentary body testifying to an important expansion of the basin toward the east. This unit, dissected by retrocessive westward-dipping normal faults, is characterized by low-frequency and low-amplitude concave-up reflections associated with vaguely mounded seismic forms suggesting a channelized system with longitudinal sediment dispersal. The overlying third unit (unit 3 in Figure 14) is represented by a more confined wedge-shaped seismic unit characterized by rather continuous eastward-divergent reflectors. This unit, evidencing a transversal sediment supply, is eastward delimited by a west-dipping normal fault responsible for a progressive synsedimentary tilting of the depositional surfaces in the hangingwall block. The persistent eastward divergence of the reflectors in the overlying unit 4 suggests an unchanged direction of the sediment supply. The western updip margin of the units 1–4, characterized by high-frequency parallel strong reflectors indicative of a more starved sedimentation, is abruptly truncated by an east-dipping normal fault.

[47] The overall geometry of the recognized seismic units and their mutual relationships, together with the time-space migration of the active faults, point to a basin evolution with source of sediment and extent of the filling changing through time, more complex than we would expect in the case of a simple half-Graben structure. In order to better understand the tectonic structure and the kinematic evolution of the Fucino basin, we picked the key horizons recognized in the CROP profile on a grid of commercial lines altogether exceeding 130 km in length. The results of this investigation are exemplified by two seismic profiles intersecting each other at about 90° (see traces in Figure 3) that adequately describe the structural framework and the time-space migration of the active Plio-Pleistocene faults in the area. The W-E directed commercial line (B line in Figure 3) crosses the CROP 11 line at a very low angle and obviously shows a seismic reflection pattern and an overall basin-fill architecture similar to those depicted by the CROP profile (see Figure 15). The commercial line, in fact, shows two superimposed broad channelized systems with longitudinal sediment dispersal (units 1 and 2) upward followed by two wedge-shaped units (units 3 and 4) characterized by transversal sediment supply. It should be noted that the B line allows a better recognition of the

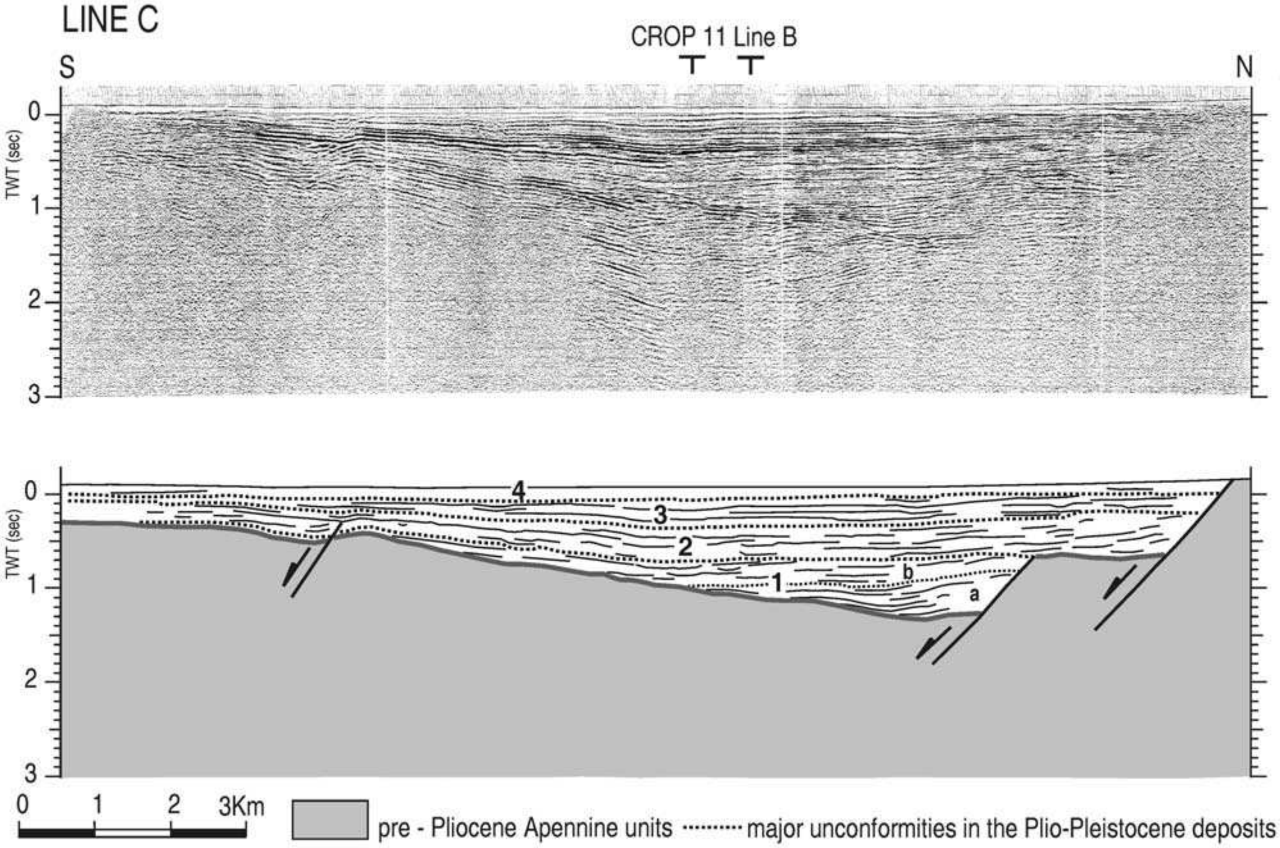


Figure 16. Commercial line (C line in Figure 3) showing the internal architecture of the Plio-Pleistocene continental deposits of the Fucino basin along a S-N oriented profile. This profile intersects the profile of Figure 15 at an angle of about 90°. Arabian numbers indicate the tectonically controlled seismic units distinguished in the CROP 11 profile.

longitudinal sediment dispersal in the units 1 and 2. The unit 1 is characterized by two evident seismic facies. The lower facies is expressed by high-frequency and high-amplitude basal reflectors (1a in Figure 15) showing unequivocal onlap terminations. This facies, possibly representative of lake-floor deposits, is upward followed by low-amplitude concave-up reflectors (1b in Figure 15) indicative of a prograding alluvial system with axial drainage. Concave-up reflectors featuring a channelized system with longitudinal sediment supply are evident also in the unit 2. As in the CROP 11 line, the units 3 and 4 depict an asymmetric basin with the eastern steep margin controlled by west-dipping synsedimentary faults and the western margin featured by a depositional ramp gently dipping toward the east. The overall wedge-shaped geometry is internally defined by an aggrading package of superimposed eastward divergent reflectors related to the progressive tilting of the depositional surfaces.

[48] The S-N oriented seismic line (C line in Figure 3) is crucial for understanding the external form and the internal architecture of the units 1 and 2 (see Figure 16). Both units are featured by a wedge-shaped sedimentary body that thins toward the south indicating a sediment accumulation controlled by south-dipping backstepping normal faults. Intersecting the N-S and E-W lines, it is possible to see that the continuous northward divergent reflectors of the unit 1 in the C line (1a in Figure 16) correspond to the basal strong parallel reflectors of the unit 1 in the B line (1a in Figure 15) interpreted as lake-floor deposits. In Figure 16, a quite isopachous aggrading sequence of discontinuous subparallel reflectors (corresponding to the channelized alluvial sediments 1b of Figure 15) blankets the previous fandelta/lacustrine deposits onlapping the hangingwall slope. The seismic interpretation of the commercial line C suggests that the units 1 and 2 were accumulated in a fault-controlled basin where in an early stage the high rate of subsidence related to the tectonic activity outpaced sedimentation, so that a pronounced fault scarp was created at the margin of the basin. Subsequently, the sedimentation rate outpaced subsidence, as testified by the package of subparallel reflectors that have smoothed the remnant topography.

[49] The CROP 11 line shows that the Fucino basin is located in correspondence to a sort of gentle synform limited westward and eastward by structural highs. In the

interpretation proposed in Foldouts 3 and 4, we suggest that the westward-dipping fault system bordering in the east the Fucino Plain and controlling the deposition of the units 3 and 4 represents, as in the case of the Caramanico fault system, a gravity-collapse feature accommodating the increase in the structural relief produced by a growing contractional ridge. We have accommodated the listric geometry of these faults on the inactive thrust flat at the base of the Paleozoic-Triassic deposits of the Queglia substratum, The eastward-dipping faults delimiting in the west the Fucino Plain have been interpreted as antithetic features of the westward-dipping master fault. The W-E oriented and southward-dipping normal faults controlling the deposition of the units 1 and 2 might represent gravitational collapses too related to the occurrence of previously active lateral/oblique ramps. If our interpretation is correct, the existence of the Fucino basin, as well as the existence of other important intramontane basins in the central Apennines, is not necessarily related to a generalized change from a compressional tectonic regime to an extensional one, as commonly reported in the current geological literature. The recent fault activity and the associated seismicity [*Galadini and Galli*, 1999; *Galadini and Messina*, 2004, and references therein] can be seen as expressions of normal faulting by gravity collapse driven by tectonic uplift during crustal shortening and not during extension. The recent uplift in the Fucino area could be explained by admitting a temporary out-of-sequence migration of the active thrusts from the Majella area toward the present Apennine watershed. True extensional areas, in which the compressional regime has been definitively substituted by an extensional one because of the forward migration of the backarc-arc system, are located farther in the west, between the eastern boundary of the Sabina Units and the Tiber Valley, in the half portion of the CROP 11 line that has not been interpreted as yet. In these areas, characterized by the occurrence of middle-late Pleistocene volcanic manifestations indicative of widespread extensional processes [*Cavinato et al.*, 1994a; *Stoppa and Woolley*, 1997; *Lavecchia and Boncio*, 2000], we would expect to observe the transition between the flexured Moho of the subducting lower plate and the shallower Moho of the backarc region, as deep seismic profiles have shown in other regions of the world characterized by similar tectonic structure and comparable kinematic evolution (e.g., Carpathians and Pannonian Basin [see *Tomek et al.*, 1987; *Tomek*, 1988]).

8. Summary of Results and Concluding Remarks

[50] The analyzed segment of the CROP 11 seismic profile extends from the Apennine watershed to the Adriatic coast cutting across a pile of thrust sheets referred to five major tectonic units: the Western Marsica-Meta, Gran Sasso-Genzana, Morrone-Porrara, Queglia and Majella Units. East of the Majella anticline, the profile runs in the Molise nappes and finally, in the proximity of the coast, in the autochthonous Pliocene-Pleistocene deposits of the foredeep basin. Figure 17 shows a roughly balanced geological section derived from the depth conversion of Foldouts 3 and 4, together with a synthetic representation of the interpreted time section. We are conscious that different interpretations were possible, in particular between the Sulmona Plain and the Fucino Plain where the signal at shallow depths is quite poor and the geological constraints are very weak. In these areas we have made full use the regional geological knowledge, obviously paying close attention to the geometry of the reflectors where they were present, but interpretation remains highly speculative. Because of the increasing complexity of the tectonic structures moving from the foreland region toward the hinterland areas, we have chosen to summarize the results starting from the slightly deformed Adriatic coastal region.

[51] In correspondence to the eastern termination of the CROP 11 seismic profile, a pile of Mesozoic-Tertiary carbonates 6–7 km thick (Apulia Platform of the geological literature) overlies a well layered reflective unit the uppermost portion of which, reached by a few exploratory wells, has resulted to be constituted of Permo-Triassic terrigenous deposits with subordinate intercalations of clastic carbonates. In agreement with commercial lines available in the area, the CROP profile shows that the seismic record of the layered sedimentary sequence underlying the upper Triassic dolomites and anhydrites exceeds 3 s TWT, corresponding to a thickness not smaller that 7000–7500 m if we assume P-wave velocity values not lower than 4.5–5.0 km/s. This sequence, possibly affected by low-grade metamorphism in its lower part, is supposed to represent the Paleozoic-Triassic sedimentary cover of a pre-Cambrian (Baikalian-Panafrican) continental crust. A possible crystalline basement is imaged by a massive, rather transparent unit recognizable between 7.8 and 9.7 s TWT. A layered lower crust is evident between 9.7 and 10.7 s TWT. Reflectors referable to the Moho discontinuity have been recognized at 12.0–12.5 s TWT. The total thickness of the crust calculated in the foreland area averages 31 km.

[52] Moving toward the west, the first important tectonic feature is represented by the Casoli-Bomba High, a popup structure interpreted as an inverted structure limited westward by a system of backthrusts and eastward by a high-angle reverse fault reactivating a lower Pleistocene west-dipping normal fault. The Casoli-Bomba High, previously interpreted as the footwall of a westward-dipping Pliocene normal fault pre-dating the arrival of the Molise nappes in the region, began to grow in the early Pleistocene after the tectonic transport of the allochthonous sheets on the upper Pliocene *Gt. inflata* turbidites of the foredeep basin.

[53] West of the Casoli-Bomba High, the Majella Mountain is the most prominent physiographic feature in the study region. We have interpreted the Majella Mountain as a Pliocene ramp anticline passively uplifted during the early Pleistocene by a positive structure of Apulia carbonates developed in the hangingwall of a blind backthrust. The west-dipping normal-fault system downthrowing the backlimb of the Majella fold with a maximum vertical displacement of about 3800 m in correspondence to the axial

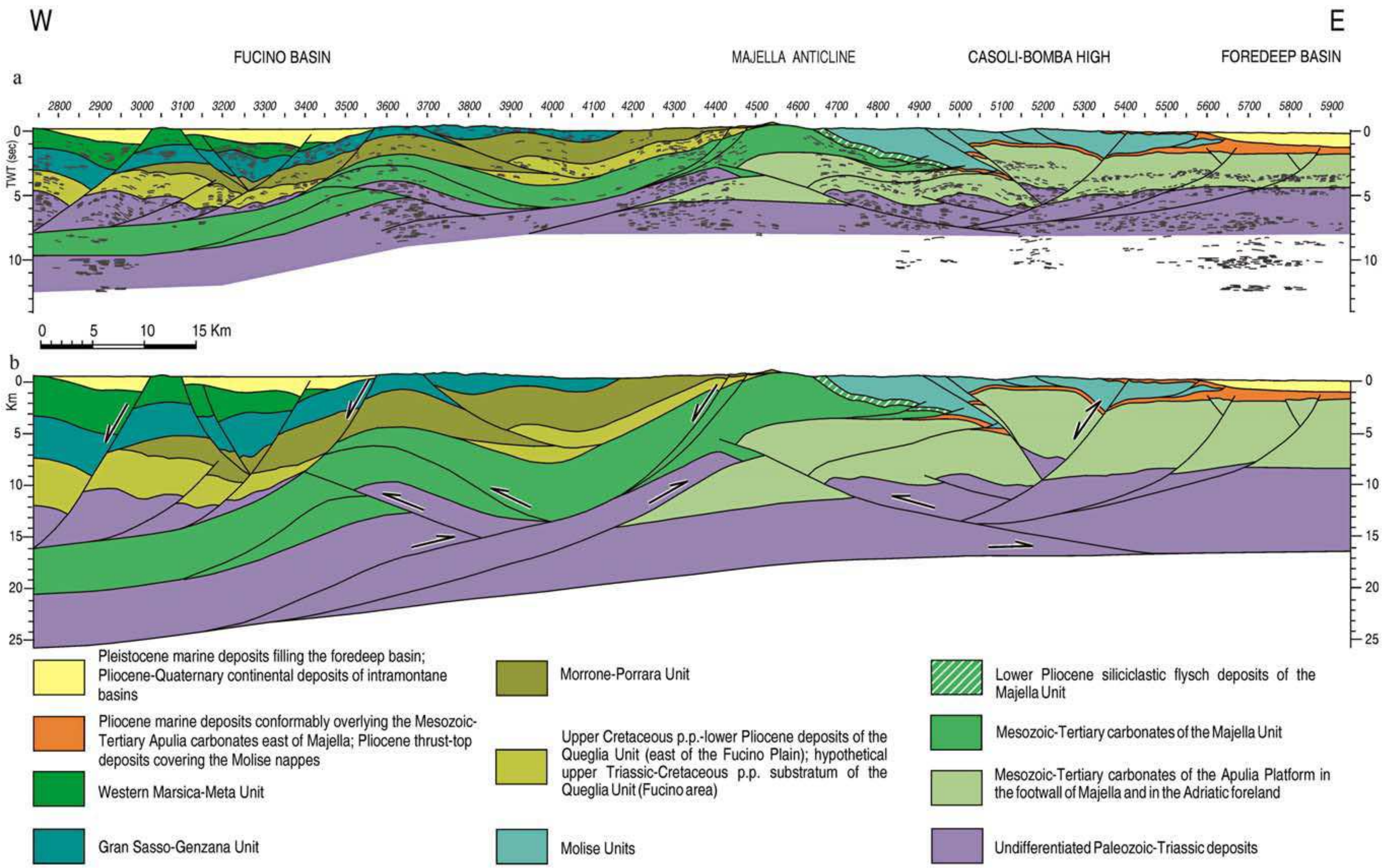


Figure 17. Simplified structural interpretation of the CROP 11 line. (a) Time section. (b) Depth-converted section. At the western termination of the seismic profile, we have reported in both sections the interpretation according which the deepest seismic reflectors are representative of the Paleozoic-Triassic sedimentary sequence underlying the Upper Triassic dolomites and evaporites of the Apulia Platform (see discussion in the text).

culmination, has been interpreted as a gravity-collapse accommodation at the front of the backthrust. This interpretation, which implies a causal relation between structural elevation and fault displacement, can explain the progressive downthrow decrease from 3800 m to 0 m over a distance of only 25 km moving from the axial culmination toward the north, in the direction of the downhill fold plunge.

[54] Between the Caramanico depression and the Fucino region, the absence of well-derived stratigraphic constraints and the poor seismic resolution of the CROP 11 profile at shallow-medium depths prevented a fully reliable structural interpretation. The most relevant seismic feature is represented by a thick reflective unit, well evident east of the Fucino Plain, which has been attributed to the Paleozoic-Triassic deposits forming locally a quite complex imbricated structure. In the proposed interpretation, the bulk of the forward displacement of the Paleozoic-Triassic deposits on top of a hinterland-dipping thrust surface has been compensated by a tectonic doubling of the Mesozoic-Tertiary carbonates related to a backthrust nucleated from an intracutaneous triangle zone. A subsequent deeper backthrust contributed to the increase in the structural relief and consequently to the activation of deep-seated gravity-collapse normal faults along the eastern border of the Fucino Plain. According to our interpretation, the opening of the Fucino basin, as well as the opening of other intramontane basins of the central Apennines, was not related to a change of the tectonic regime from a generalized compressional stress field to a generalized extensional field, as usually reported in the geological literature. Opening was likely produced by gravity-collapse normal faults driven by tectonic uplift caused by crustal shortening. We also believe that the seismic activity associated with the younger, NW-SE trending faults bordering the Fucino basin in the east represents a consequence of the out-of-sequence migration of the active thrusts from the Majella area toward the Apennine watershed.

[55] Recent geological works hypothesize in the central Apennines the occurrence of a lithospheric breach causing a remarkable uplift of the basement. The CROP 11 seismic data do not support such a hypothesis since the layered seismic unit attributed to the Paleozoic-Triassic sedimentary sequence is present, and very well recognizable, at depths largely exceeding the depth at which a massive crystalline basement had been postulated. The belief that the crystalline basement has been incorporated in the post-Tortonian Apennine wedge basically derives from a geophysical modeling of the so-called "magnetic basement" in Italy and surrounding offshore areas proposed in the eighties by *Bolis et al.* [1981], *Arisi Rota and Fichera* [1985] and *Cassano et al.* [1986], and recently re-presented in the same form by *Cassano et al.* [2001]. According to these authors, the "magnetic basement" is the deepest level evidenced by magnetometry, below which no sedimentary rock should exist. In the Apennine mountain chain and in the Padan-Adriatic foreland, the top of the "magnetic basement" has been identified with the base of the Alpine sedimentary cover on top of a Hercynian or pre-Hercynian crystalline basement. Contour maps of the "magnetic basement" with ridges and grooves indicating structural highs and structural depressions of the basement were acritically adopted as geometric constraints for constructing and balancing deep geological sections. The CROP 11 line demonstrates the inconsistency of such an assumption. In correspondence to the Vasto area, for example, the top of the "magnetic basement" should lie at a depth of 8–9 km [*Cassano et al.*, 1986]. The seismic profile shows that this depth roughly corresponds to the base of the upper Triassic evaporites, i.e., to the top of the Paleozoic-Triassic deposits. Someone might suppose that these clastic deposits represent the source of the magnetic anomaly because of a high content in detrital magnetic minerals and could be consequently tempted to identify the top of the "magnetic basement" with the top of the Paleozoic-Triassic sedimentary sequence. This identification would agree with the "magnetic basement" in the Pescara area, where it lies at a depth of about 12 km coinciding with the base of the Upper Triassic anhydrites. In the Gargano 1 area, however, where the top of the "magnetic basement" was expected at about 8 km [*Cassano et al.*, 1986], the top of the Paleozoic-Triassic deposits lies at a depth shallower than 4500 m. In the Puglia 1 area, in addition, the contour map predicts the "magnetic basement" at a depth of 12000–13000 m whilst the Permo-Triassic deposits have been encountered at 5568 m below sea level. We think that the "magnetic basement" of the current geophysical literature is an artifact deriving from different anomaly sources and thus including different geological objects. We also believe that the aforementioned contour maps of the "magnetic basement" have no clear geological meaning and cannot be used in any case for reconstructing the geometry of the sedimentary-cover/crystalline-basement boundary.

[56] In conclusion, the CROP 11 seismic data do not provide evidence for the involvement of a crystalline basement in the post-Tortonian crustal shortening, though do not exclude the occurrence of reverse-sense reactivations of Paleozoic normal faults. As already observed in the line CROP 04-Southern Apennines [*Mazzotti et al.*, 2000; *Patacca et al.*, 2000; *Patacca and Scandone*, 2004a], the layered seismic unit underlying the upper Triassic dolomites and anhydrites of the Apulia Platform, considered representative of the Paleozoic-Triassic sedimentary cover of the Adriatic pre-Cambrian crystalline basement, appears to be the deepest level involved in the compressional deformation. These data suggest for the post-Tortonian compressional deformation an unusual thin-skin tectonic style according to which a very thick sedimentary sequence, possibly affected by low-grade metamorphism in its lower part, has been detached from the original substratum and has been incorporated in the tectonic wedge.

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References

Accarie, H. (1988), Dynamique sédimentaire et structurale au passage plate-forme/bassin. Les faciès carbonatés crétacés et tertiaires du Massif de la Maiella (Abruzzes, Italie), *Mem. Sci. Terre*, *5*, 162 pp.

Accordi, G., and F. Carbone (Eds.) (1988), Lithofacies map of Latium-Abruzzi and neighbouring areas, scale 1:500,000, *Quad. Ric. Sci.*, *114*(5), 223 pp.

Amato, A., C. Chiarabba, and G. Selvaggi (1997), Crustal and deep seismicity in Italy (30 years after), *Ann. Geofis.*, *40*, 981–993.

Arisi Rota, F., and R. Fichera (1985), Magnetic interpretation connected to ''geo-magnetic provinces'': The Italian case history, paper presented at 47th Meeting, Eur. Assoc. of Explor. Geophys., Budapest.

Bally, A. W., L. Burbi, C. Cooper, and R. Ghelardoni (1986), Balanced sections and seismic reflection profiles across the central Apennines, *Mem. Soc. Geol. Ital.*, *35*, 257–310.

Barchi, M. N. (1991), Integration of a seismic profile with surface and subsurface geology in a cross-section through the Umbria-Marche Apennines, *Boll. Soc. Geol. Ital.*, *110*, 469–479.

Barchi, M. R., G. Minelli, and G. Pialli (1998), The CROP 03 profile: A synthesis of results on deep structures of the Northern Apennines, *Mem. Soc. Geol. Ital.*, *52*, 383–400.

Beneo, E. (1936), La formazione mesozoica di Filettino e Collepardo (Monti Simbruini ed Ernici), *Boll. R. Uff. Geol. Ital.*, *61*, 1–8.

Bigazzi, G., M. A. Laurenzi, C. Principe, and D. Brocchini (1996), New geochronological data on igneous rocks and evaporites of the Pietre Nere Point (Gargano Peninsula, Southern Italy), *Boll. Soc. Geol. Ital.*, *115*, 439–448.

Bigi, G., A. Castellarin, M. Coli, G. V. dal Piaz, R. Sartori, P. Scandone, and G. B. Vai (1991), Structural model of Italy, scale 1:500,000, *Quad Ric. Sci.*, *114*(3), 1–7.

Bigi, S., F. Calamita, and W. Paltrinieri (1995), Modi e tempi della strutturazione della catena centro-appeninica abruzzese dal Gran Sasso alla costa adriatica, *Stud. Geol. Camerti, Spec.*, Vol. *2*, 77–85.

BIRPS and ECORS (1986), Deep seismic reflection profiling between England, Ireland and France (SWAT), *J. Geol. Soc.*, *143*, 45–52.

Blundell, D. J. (1988), A proposal for a coordinated programme of deep seismic reflection profiles across Europe, *Ann. Soc. Geol. Belg.*, *111*, 243–256.

Blundell, D. J., and C. Wright (1989), Deep seismic reflection studies, *Newsl.*, *3*, 34 pp., Working Group 3 (Intra-Plate Phenomena), Inter-Union Comm. on the Lithosphere, Basel, Switzerland.

Bois, C., M. Cazes, A. Hirn, A. Mascle, P. Matte, L. Montadert, and B. Pinet (1988), Contribution of deep seismic profiling to the knowledge of the lower crust in France and neighbouring areas, *Tectonophysics*, *145*, 253–275.

Bolis, G., V. Cappelli, and M. Marinelli (1981), Aeromagnetic data of the Italian area: instrumental to a better comprehension of the basement main characteristics in Italy, paper presented at 43rd Meeting, Eur. Assoc. of Explor. Geophys., Venice.

Boni, A., R. Casnedi, E. Centamore, P. Colantoni, G. Cremonini, C. Elmi, A. Monesi, R. Selli, and M. Valletta (1969), Servizio Geologico d'Italia, Note illustrative della Carta Geologica d'Italia, *Foglio 155 San Severo*, 1:100.000, Poligr. and Cartevalori, Ercolano, Italy.

Bosi, C., F. Galadini, and P. Messina (1995), Stratigrafia plio-pleistocenica della conca del Fucino, *Quaternario*, *8*, 83–94.

Brown, L., M. Barazangi, S. Kaufman, and J. Oliver (1986), The first decade of COCORP: 1974–1984, in *Reflection Seismology: A Global Perspective*, *Geodyn. Ser.*, vol. 13, edited by L. Brown and M. Barazangi, pp. 107–120, AGU, Washington, D. C.

Butler, R. W. H., et al. (2004), Applying thick-skinned tectonic model to the Apennine thrust belt of Italy—Limitations and implications, in *Thrust Tectonics and Hydrocarbon Systems*, edited by K. R. McClay, *AAPG Mem.*, *82*, 647–667.

Calamita, F., W. Paltrinieri, M. Pelorosso, V. Scisciani, and E. Tavarnelli (2003), Inherited Mesozoic architecture of the Adria continental paleomargin in the Neogene central Apennines orogenic system, Italy, *Boll. Soc. Geol. Ital.*, *122*, 307–318.

Calamita, F., M. G. Viandante, and K. Hegarty (2004), Pliocene-Quaternary burial/exhumation paths of the central Apennines (Italy): Implications for the definition of the deep structure of the belt, *Boll. Soc. Geol. Ital.*, *123*, 503–512.

Cande, S. C., and D. V. Kent (1995), Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*(B4), 6093–6095.

Carrozzo, M. T., D. Luzio, C. Margiotta, and T. Quarta (1991), Gravity map, scale 1:500,000, *Quad. Ric. Sci.*, *114*(3), 591–593.

Casero, P. (2004), Structural setting of petroleum exploration plays in Italy, in *Geology of Italy*, edited by U. Crescenti et al., pp. 189–199,*Ital. Geol. Soc.*, Florence, Italy.

Casero, P., F. Roure, L. Endignoux, I. Moretti, C. Muller, L. Sage, and R. Vially (1988), Neogene geodynamic evolution of southern Apennines, *Mem. Soc. Geol. Ital.*, *41*, 109–120.

Casnedi, R. (1983), Hydrocarbon-bearing submarine fan system of Cellino Formation, central Italy, *Bull. Am. Assoc. Pet. Geol.*, *67*, 359–370.

Cassano, E., R. Fichera, and F. Arisi Rota (1986), Aeromagnetic survey of Italy: A few interpretative results, Dir. Serv. Cent. per l'Esplorazione-Studi e Metodologie Geofis., 13 pp., San Donato Milanese, Italy.

Cassano, E., L. Anelli, V. Cappelli, and P. La Torre (2001), Magnetic and gravity analysis of Italy, in *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and I. P. Martini, pp. 53–64, Kluwer Acad., Norwell, Mass.

Cassinis, R., S. Scarascia, and A. Lozej (2003), The deep crustal structure of Italy and surrounding areas from seismic refraction data, *Boll. Soc. Geol. Ital.*, *122*, 365–376.

Cati, A., D. Sartorio, and S. Venturini (1987), Carbonate platforms in the subsurface of the northern Adriatic area, *Mem. Soc. Geol. Ital.*, *40*, 295–308.

Cavinato, G. P., D. Cosentino, D. De Rita, R. Funiciello, and M. Parotto (1994a), Tectonic-sedimentary evolution of intraapenninic basins and correlation with the volcano-tectonic activity in central Italy, *Mem. Descr. Carta Geol. Ital.*, *49*, 63–76.

Cavinato, G. P., D. Cosentino, R. Funiciello, M. Parotto, F. Salvini, and M. Tozzi (1994b), Constraints and new problems for geodynamical modelling of central Italy (CROP 11 Civitavecchia-Vasto deep seismic line), *Boll. Geofis. Teor. Appl.*, *36*, 158–174.

Cavinato, G. P., C. Carusi, M. Dall'Asta, E. Miccadei, and T. Piacentini (2002), Sedimentary and tectonic evolution of Plio-Pleistocene alluvial and lacustrine deposits of Fucino Basin (central Italy), *Sediment. Geol.*, *148*, 29–59.

Cipollari, P., and D. Cosentino (1991), La linea Olevano-Antrodoco: Contributo della biostratigrafia alla sua caratterizzazione cinematica, in *Studi Preliminari all'acquisizione Dati del Profilo CROP 11 Civitavecchia-Vasto*, edited by M. Tozzi, G. P. Cavinato, and M. Parotto, *Stud. Geol. Camerti Spec. Vol.*, *1991/2*, 143–149.

Cipollari, P., and D. Cosentino (1995), Miocene unconformities in the central Apennines: Geodynamic significance and sedimentary basin evolution, *Tectonophysics*, *252*, 375–389.

Cipollari, P., and D. Cosentino (1997), Il sistema Tirreno-Appennino: segmentazione litosferica e propagazione del fronte compressivo, *Stud. Geol. Camerti, Spec. Vol.*, *1997/2*, 125–134.

Cipollari, P., and D. Cosentino (1999), Cronostratigrafia dei depositi neogenici del settore ernico-simbruino, Appennino centrale, *Boll. Soc. Geol. Ital.*, *118*, 439–459.

Cipollari, P., D. Cosentino, and M. Parotto (1995), Modello cinematico-strutturale dell'Italia centrale, *Stud. Geol. Camerti, Spec. Vol.*, *1995/2*, 135–143.

Cita, M. B. (1975), Planktonic foraminiferal biozonation of the mediterranean Pliocene deep sea record: A revision, *Riv. Ital. Paleontol. Stratigr.*, *81*, 527–544.

Clermonté, J. (1977), La bordure abruzzaise sud-orientale et le haut Molise: histoire sédimentaire et tectonique comparée, *Riv. Ital. Paleontol. Stratigr.*, *83*, 21–102.

Colalongo, M. L., and S. Sartoni (1979), Schema biostratigrafico per il Pliocene e il basso Pleistocene in Italia, *Note Prelim. alla Carta Neotettonica d'Italia 251*, pp. 645–654, CNR Progetto Finalizzato Geodin., Rome.

Cotecchia, V., and A. Canitano (1955), Sull'affioramento delle ''Pietre Nere'' al Lago di Lesina, *Boll. Soc. Geol. Ital.*, *73*, 3–18.

Coward, M. P., M. De Donatis, S. Mazzoli, W. Patrinieri, and F. C. Wezel (1999), Frontal part of the northern Apennines fold and thrust belt in Romagna-Marche area (Italy): Shallow and deep structural styles, *Tectonics*, *18*(3), 559–574.

Crescenti, U. (1971a), Sul limite Mio-Pliocene in Italia, *Geol. Rom.*, *10*, 1–21.

Crescenti, U. (1971b), Osservazioni sul Pliocene degli Abruzzi settentrionali: la trasgressione del Pliocene medio e superiore, *Boll. Soc. Geol. Ital.*, *90*, 3–21.

Crescenti, U., A. Crostella, G. Donzelli, and G. Raffi (1969), Stratigrafia della serie calcarea dal Lias al Miocene nella regione marchigiano-abruzzese. Parte II. Litostratigrafia, Biostratigrafia, Paleogeografia, *Mem. Soc. Geol. Ital.*, *8*, 343–420.

D'Andrea, M., E. Miccadei, and A. Praturlon (1991), Rapporti tra il margine orientale della piattaforma laziale-abruzzese ed il margine occidentale della piattaforma Morrone-Pizzalto-Rotella, in *Studi Preliminari All'acquisizione Dati del Profilo CROP 11 Civitavecchia-Vasto*, edited by M. Tozzi, G. P. Cavinato, and M. Parotto, *Stud. Geol. Camerti, Spec. Vol.*, *1991/2*, 389–395.

D'Andrea, S., R. Pasi, G. Bertozzi, and P. Dattilo (1993), Geological model, advanced methods help unlock oil in Italy's Apennines, *Oil Gas J.*, *91*, 53–57.

De Alteriis, G. (1995), Different foreland basins in Italy: Examples from the central and southern Adriatic Sea, *Tectonophysics*, *252*, 349–373.

De Fino, M., L. La Volpe, and G. Piccarreta (1981), Geochemistry and petrogenesis of the Paleocene platform magmatism at Punta delle Pietre Nere (Southeastern Italy), *N. Jb. Miner. Abh.*, *142*, 161–177.

D'Erasmo, G. (1931), L'Elephas meridionalis nell'Abruzzo e nella Lucania, *Atti R. Accad. Sci. Fis. Mat. Napoli, Ser. 2a*, *18*, 1–25.

Di Stefano, G. (1895), Lo scisto marnoso a ''Myophoria vestita'' della Punta delle Pietre Nere in provincia di Foggia, *Boll. Com. Geol. Ital.*, *26*, 4–51.

Doglioni, C. (1991), A proposal of kinematic modeling for W-dipping subductions—Possible applications to the Tyrrhenian-Apennines system, *Terra Nova*, *3*, 42.

Dondi, L., I. Papetti, and D. Tedeschi (1966), Contributo alle conoscenze del Mesozoico del sottosuolo abruzzese, *Geol. Rom.*, *5*, 69–98.

Donzelli, G. (1969), Studio geologico della Maiella, edited by U. Crescenti, report, 49 pp., Univ. degli Stud. G. D'Annunzio, Chieti, Italy.

Endignoux, L., I. Moretti, and F. Roure (1989), Forward modeling of the southern Apennines, *Tectonics*, *8*(5), 1095–1104.

Faccenna, C., R. Funiciello, and M. Mattei (1994), Late Pleistocene N-S shear zones along the Latium Tyrrhenian margin: Structural characters and volcano-

logical implications, *Boll. Geofis. Teor. Appl.*, *36*, 507–523.
Frepoli, A., and A. Amato (1997), Contemporaneous extension and compression in the northern Apennines from earthquake fault plane solutions, *Geophys. J. Int.*, *125*, 879–891.
Funiciello, R., and M. Parotto (1978), Il substrato sedimentario nell'area dei Colli Albani: considerazioni geodinamiche e paleogeografiche sul margine tirrenico dell'Appennino centrale, *Geol. Rom.*, *17*, 233–287.
Galadini, F., and P. Galli (1999), The Holocene paleoearthquakes on the 1915 Avezzano earthquake faults (central Italy): Implications for active tectonics in central ltaly, *Tectonophysics*, *308*, 143–170.
Galadini, F., and P. Messina (1994), Plio-Quaternary tectonics of the Fucino basin and surrounding areas (central Italy), *G. Geol., Ser. 3a*, *56*(2), 73–99.
Galadini, F., and P. Messina (2004), Early-Middle Pleistocene eastward migration of the Abruzzi Apennine (central Italy) extensional domain, *J. Geodyn.*, *37*, 57–81.
Ghisetti, F., and L. Vezzani (2002), Normal faulting, extension and uplift in the outer thrust belt of the central Apennines (Italy): Role of the Caramanico fault, *Basin Res.*, *14*, 225–236.
Hauser, E. C., and J. E. Oliver (1987), A new era in understanding the continental basement: The impact of seismic reflection profiling, in *Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System*, *Geodyn. Ser.*, vol. 16, edited by K. Fuchs and C. Froidevaux, pp. 1–32, AGU, Washington, D. C
Lavecchia, G., and P. Boncio (2000), Tectonic setting of the carbonatite-melilite association of Italy, *Min. Mag.*, *64*(4), 583–592.
Lavecchia, G., E. Brozzetti, M. Barchi, M. Menichetti, and J. V. A. Keller (1994), Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress field, *Geol. Soc. Am. Bull.*, *106*, 1107–1120.
Locardi, E., and R. Nicolich (1988), Geodinamica del Tirreno e dell'Appennino centro-meridionale: la nuova carta della Moho, *Mem. Soc. Geol. Ital.*, *41*, 121–140.
Malinverno, A., and W. B. F. Ryan (1986), Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of the arc migration driven by sinking of the lithosphere, *Tectonics*, *5*(2), 227–245.
Martinis, B., and M. Pieri (1963), Alcune notizie sulla formazione evaporitica del Triassico superiore nell'Italia centrale e meridionale, *Mem. Soc. Geol. Ital.*, *4*, 649–678.
Matthews, D. H. (1988), Deep seismic investigations in the UK: BIRPS 1981–1987, *Ann. Soc. Geol. Belg.*, *111*, 311–395.
Matthews, D. H., and the BIRPS Group (1990), Progress in BIRPS Deep Seismic Profiling around the British Isles, *Tectonophysics*, *173*, 387–396.
Mazzoli, S., S. Corrado, M. De Donatis, D. Scrocca, R. W. H. Butler, D. Di Bucci, G. Naso, C. Nicolai, and V. Zucconi (2000), Time and space variability of "thin-skinned" and "thick-skinned" thrust tectonics in the Apennines (Italy), *Rend. Fis. Acc. Lincei*, *11*, 5–39.
Mazzotti, A., E. Stucchi, G. L. Fradelizio, L. Zanzi, and P. Scandone (2000), Seismic exploration in complex terrains: A processing experience in the Southern Apennines, *Geophysics*, *65*(5), 1402–1417.
Meissner, R., and R. K. Bortfeld (Eds.) (1990), *The DEKORP Atlas (80 Seismic Sections)*, Springer, Berlin.
Meissner, R., and W. Rabbel (1999), Nature of crustal reflectivity along the DEKORP profiles in Germany in comparison with reflection patterns from different tectonic units worldwide: A review, *Pure Appl. Geophys.*, *156*(1/2), 7–28.
Meissner, R., , L. Brown, H. J. Duerbaum, W. Franke, K. Fuchs, and F. Seifert (Eds.) (1991), *Continental Lithosphere: Deep Seismic Reflections*, *Geodyn. Ser.*, vol. 22, 450 pp., AGU, Washington, D. C.
Menardi Noguera, A., and D. Rea (2000), Deep structure of the Campanian-Lucanian Arc (southern Apennine, ltaly), *Tectonophysics*, *32*, 239–265.
Mostardini, E., and S. Merlini (1986), Appennino centro-meridionale. Sezioni geologiche e proposta di modello strutturale, *Mem. Soc. Geol. Ital.*, *35*, 177–202.
Nicolich, R., and G. V. Dal Piaz (1990), Moho isobaths, in *Progetto Finalizzato Geodinamica: Structural Model of Italy*, edited by G. Bigi et al., *Quad. de La Ric. Sci. 114*(3), scale 1:500,000, Cons. Naz. delle Ric., Rome.
Parotto, M., and A. Praturlon (2004), The Southern Apennine Arc, in *Geology of Italy*, edited by U. Crescenti et al., pp. 33–58, Ital. Geol. Soc., Florence, Italy.
Parotto, M., F. Salvini, and M. Tozzi (1996), Geologia di superficie e geometrie profonde nell'Italia centrale: per un profilo di revisione CROP11 da Civitavecchia a Vasto, *Mem. Soc. Geol. Ital.*, *51*, 63–70.
Parotto, M., G. P. Cavinato, E. Miccadei, and M. Tozzi (2003), Line CROP 11: Central Apennines, in *CROP Atlas: Deep Seismic Reflection Profiles of the Italian Crust*, edited by D. Scrocca et al., *Mem. Descr. Carta Geol. Ital.*, *62*, 145–154.
Patacca, E., and P. Scandone (1989), Post-Tortonian mountain building in the Apennines: The role of the passive sinking of a relic lithospheric slab, in *The Lithosphere in Italy*, edited by A. Boriani et al., *Atti Conv. Lincei*, *80*, 157–176.
Patacca, E., and P. Scandone (2001), Late thrust propagation and sedimentary response in the thrust belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene), in *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and I. P. Martini, pp. 401–440, Kluwer Acad., Norwell, Mass.
Patacca, E., and P. Scandone (2004a), A geological transect across the Southern Apennines along the seismic line CROP 04, *Field Trip Guide Book P20*, 25 pp., *32nd Intern. Geol. Congr., APAT-Ital.*Agency for the Environ. Prot. and Tech. Serv., Rome.
Patacca, E., and P. Scandone (2004b), The Plio-Pleistocene thrust belt-foredeep system in the Southern Apennines and Sicily (Italy), in *Geology of Italy*, edited by U. Crescenti et al., pp. 93–129, *Ital. Geol. Soc.*, Florence, Italy.
Patacca, E., R. Sartori, and P. Scandone (1990), Tyrrhenian basin and Apenninic arc: Kinematic relations since Late Tortonian times, *Mem. Soc. Geol. Ital.*, *45*, 425–451.
Patacca, E., P. Scandone, M. Bellatalla, N. Perilli, and U. Santini (1991), La zona di giunzione tra l'arco appenninico settentrionale e l'arco appenninico meridionale nell'Abruzzo e nel Molise, in *Studi Preliminari all'acquisizione Dati del Profilo CROP 11 Civitavecchia-Vasto*, edited by M. Tozzi, G. P. Cavinato, and M. Parotto, *Stud. Geol. Camerti, Spec. Vol.*, *1991/2*, 417–441.
Patacca, E., R. Sartori, and P. Scandone (1993), Tyrrhenian basin and Apennines: Kinematic evolution and related dynamic constraints, in *Recent Evolution and Seismicity of the Mediterranean Region*, edited by E. Boschi, E. Mantovani, and A. Morelli, pp. 161–171, Kluwer Acad., Norwell, Mass.
Patacca, E., P. Scandone, and M. Tozzi (2000), Il Profilo CROP-04, *Protecta*, *10–12*, 49–52.
Pfiffner, A. O., P. Lehner, P. Heitzmann, S. Mueller, and A. Stek (Eds.) (1997), *Deep Structure of the Swiss Alps: Results of NRP 20*, 380 pp., Birkhäuser, Basel, Switzerland.
Piacentini, T. (2000), Evoluzione neogenico-quaternaria dell'area tra la Marsica nordorientale e la regione Peligna (Abruzzo): analisi paleogeografica e caratterizzazione strutturale. Diss. Finale, Dottorato di Ricerca in Geodin., 277 pp., Univ. degli Studi di Roma 3, Rome.
Ponziani, F., R. De Franco, and G. Biella (1998), Geophysical reinterpretation of 1974 and 1978 DSS experiments along CROP 03 profile, *Boll. Soc. Geol. Ital.*, *52*, 193–203.
Raffi, G., and A. Forti (1959), Micropaleontological and stratigraphical investigations in "Montagna del Morrone" (Abruzzi, Italy), *Rev. Micropaleontol.*, *2*, 8–20.
Roure, F., P. Heitzmann, and R. Polino (1990), Deep structure of the Alps, *Mem. Soc. Geol. Fr.*, *156*, 350.
Royden, L. H., E. Patacca, and P. Scandone (1987), Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution, *Geology*, *15*, 714–717.
Sartorio, D., and R. Rozza (1991), The Permian of Amanda I bis well (Northern Adriatic Sea), *G. Geol.*, *53*, 187–196.
Scandone, P., and I. Sgrosso (1963), Il Mesozoico nel gruppo montuoso dell'Acellica (M. Picentini-Salerno), *Mem. Soc. Geol. Ital.*, *4*, 1–8.
Scarascia, S., A. Lozej, and R. Cassinis (1994), Crustal structures of the Ligurian, Tyrrhenian and lonian seas and adjacent onshore areas interpreted from wide angle seismic profiles, *Boll. Geofis. Teor. Appl.*, *36*, 5–19.
Scarascia, S., R. Cassinis, and F. Federici (1998), Gravity modelling of deep structures in the northern-central Apennines, *Mem. Soc. Geol. Ital.*, *52*, 231–246.
Scisciani, V., F. Calamita, S. Bigi, C. De Girolamo, and W. Paitrinieri (2001), The influence of syn-orogenic normal faults on Pliocene thrust system development: the Maiella structure (central Apennines, Italy), *Mem Soc. Geol. Ital.*, *55*, 193–204.
Scrocca, D., C. Doglioni, F. Innocenti, P. Manetti, A. Mazzotti, L. Bertelli, L. Burbi, and S. D'Offizi (Eds.) (2003), CROP Atlas: Deep Seismic Reflection Profiles of the Italian Crust, *Mem. Descr. Carta Geol. Ital.*, *62*, 194 pp.
Scrocca, D., E. Carminati, and C. Doglioni (2005), Deep structure of the Southern Apennines, Italy: Thin-skinned or thick-skinned?, *Tectonics*, *24*, TC3005, doi:10.1029/2004TC001634.
Selli, R. (1962), Il Paleogene nel quadro della geologia dell'Italia Meridionale, *Mem. Soc. Geol. Ital.*, *3*, 733–789.
Selvaggi, G., and A. Amato (1992), Subcrustal earthquakes in the northern Apennines (Italy): Evidence for a still active subduction?, *Geophys. Res. Lett.*, *19*, 2127–2130.
Serri, G., F. Innocenti, and P. Manetti (2001), Magmatism from Mesozoic to Present: Petrogenesis, time-space distribution and geodynamic implications, in *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and I. P. Martini, pp. 77–103, Kluwer Acad., Norwell, Mass.
Spaak, P. (1983), Accuracy in correlation and ecological aspects of the planktonic foraminiferal zonation of the mediterranean Pliocene, *Utrecht Micropaleontol. Bull.*, *28*, 158 pp.
Speranza, F., and M. Chiappini (2002), Thick-skinned tectonics in the external Apennines (Italy): New evidence from magnetic anomaly analyses, *J. Geophys. Res.*, *107*(B11), 2290, doi:10.1029/2000JB000027.
Stoppa, F., and A. R. Woolley (1997), The Italian carbonatites: Field occurrence, petrology and regional significance, *Mineral. Petrol.*, *59*, 43–67.
Stovba, S., R. A. Stephenson, and M. Kivshik (1996), Structural features and evolution of the Dniepr-Donets Basin, Ukraine, from regional reflection profiles, *Tectonophysics*, *268*, 127–147.
Tavarnelli, E. (1997), Structural evolution of a foreland fold-and-thrust belt: The Umbria-Marche Apennines, Italy, *J. Struct. Geol.*, *19*, 523–534.
Tavarnelli, E., F. Calamita, and W. Paltrinieri (2003), Inversion tectonics in Italy, *Boll. Soc. Geol. Ital.*, *122*, 220–222.
Tavarnelli, E., R. W. H. Butler, F. A. Decandia, F. Calamita, M. Grasso, W. Alvarez, and P. Renda (2004), Implications of fault reactivation and structural inheritance in the Cenozoic tectonic evolution of Italy, in *Geology of Italy*, edited by U. Crescenti et al., pp. 209–222, *Ital. Geol. Soc.*, Florence, Italy.

Tiberti, M. M., and L. Orlando (2006), 2D gravity modeling along the CROP11 seismic profile, *Boll. Geofis. Teor. Appl.*, *47*, 447–454.

Tomek, C. (1988), Geophysical investigation of the Alpine-Carpathian arc, in *History of the Northern Margin of Tethys*, edited by A. Nairn, *Mem. Soc. Geol. Fr.*, *154*, 167–199.

Tomek, C., L. Dvorakova, J. Ibrmayer, R. Jiricek, and T. Korab (1987), Crustal profiles of active continental collisional belt: Czecho-Slovak deep seismic reflection profiling in the Western Carpathians, *Geophys. J. R. Astron. Soc.*, *89*, 383–388.

Tozer, R. S. J., R. W. H. Butler, and S. Corrado (2002), Comparing Thin- and Thick-Skinned thrust tectonic models of the central Apennines, Italy, in *Continental Collision and the Tectono-Sedimentary Evolution of Forelands*, *Stephan Mueller Spec. Publ. Ser.*, vol. 1, pp. 181–194, *Eur. Geosci. Union*, Strasbourg, France.

Vai, G. B. (1994), Crustal evolution and basement elements in the Italian area: Paleogeography and characterization, *Boll. Geofis. Teor. Appl.*, *36*, 411–434.

Vai, G. B. (2001), Basement and early (pre-Alpine) history, in *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and I. P. Martini, pp. 121–150, Kluwer Acad., Norwell, Mass.

Vannucci, G., S. Pondrelli, A. Argnani, A. Morelli, P. Gasperini, and E. Boschi (2004), An atlas of Mediterranean seismicity, *Ann. Geophys.*, *47*(1), 247–306, suppl.

Vecsei, A. (1991), Aggradation und Progradation eines Karbonatplattform-Randes: Kreide bis Mittleres Tertiar der Montagna della Maiella, Abruzzen. *Mitt. Geol. Inst. Eidg. Tech. Hochsch. Univ. Zurich*, *294*, 169 pp.

Vecsei, A., D. Sanders, D. Bernoulli, G. P. Eberli, and J. S. Pignatti (1998), Cretaceous to Miocene sequence stratigraphy and evolution of the Maiella carbonate platform margin, Italy, in *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*, *Spec. Publ. Soc. Econ. Paleontol. Mineral.*, *60*, 53–74.

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