Boll.Soc.Geol.It. (*Ital.J.Geosci.*), Spec. Issue No. 7 (2007), pp. 241-256, 12 figs., CROP-04 (ed. by A. Mazzotti, E. Patacca and P. Scandone)

Constraints on the interpretation of the CROP-04 seismic line derived from Plio-Pleistocene foredeep and thrust-sheet-top deposits (Southern Apennines, Italy)

E. PATACCA (*) & P. SCANDONE (*)

ABSTRACT

The structural architecture of the Southern Apennines is schematically described by a buried duplex system of shallow-water Mesozoic-Tertiary carbonates (Inner Apulia Platform of petroleum geologists) overlain by a thick pile of NE-verging rootless nappes. Nappe stacking took place mainly during Miocene times. Subsequently, in the early Pliocene, the entire pile of nappes was tectonically transported over the south-western margin of the Apulia Platform. During middle-late Pliocene and early Pleistocene times, finally, the portion of Apulia Platform presently represented in the buried duplex system underwent compressional deformation. The available seismic profiles do not allow an univocal interpretation of the Apennine deep structure, so that strong disagreements exist among geologists about the amount of internal shortening in the Apulia-carbonate duplex system and about the degree of involvement of the crystalline basement in the roots of the mountain chain. An argument used by the supporters of the thick-skin tectonic interpretation in order to discard thin-skin deformation is that the absence of an important basement involvement in the Southern Apennines would require unrealistic amounts of shortening. The present paper illustrates a series of geological features that prove a minimum shortening of about 90 kilometers within the Apulia carbonates during middle-late Pliocene and early Pleistocene times. Such an evidence obviously removes the principal bias against tectonic interpretations of the CROP-04 deep seismic profile implying thin-skin structural restorations.

KEY WORDS: *Italy, Southern Apennines, Plio-Pleistocene shortening, buried Apulia carbonates, thin-skin tectonics.*

RIASSUNTO

Vincoli all'interpretazione della linea sismica CROP-04 derivanti dai depositi plio-pleistocenici dell'avanfossa e della catena appenninica.

La struttura interna dell'Appennino meridionale è rappresentata da un sistema duplex costituito da carbonati mesozoico-terziari seguiti in disconformità da depositi terrigeni pliocenici (Piattaforma Apula Interna della letteratura geologica) e da una potente pila di coltri che ricoprono il duplex sepolto. L'età di costruzione delle falde è essenzialmente miocenica. L'età del trasporto della pila di falde sul margine sud-occidentale della Piattaforma Apula va dal Pliocene medio al Pleistocene inferiore.

I profili sismici che attraversano l'Appennino meridionale non permettono un'interpretazione univoca della struttura profonda della catena. Vi è pertanto in letteratura un profondo disaccordo sullo stile deformativo, in particolare sul coinvolgimento o meno di un basamento cristallino nella tettonica compressiva e sull'entità del raccorciamento all'interno del sistema duplex. Uno dei principali punti di forza a favore dei sostenitori di uno stile di tipo *thick-skin tectonics* è costituito dalla considerazione che l'assenza di coinvolgimento del basamento cristallino richiederebbe considerevoli raccorciamenti nei carbonati apuli a partire dal Pliocene inferiore/medio. In assenza di tali raccorciamenti sarebbe impossibile bilanciare con geometrie realistiche sezioni geologiche che attraversano la catena. In questo lavoro vengono documentate evidenze geologiche che provano un raccorciamento minimo dei carbonati apuli di circa 90 chilometri tra il Pliocene inferiore e il Pleistocene inferiore. Queste evidenze rimuovono tutte le possibili obiezioni di principio ad interpretazioni della linea CROP-04 in termini di *thin-skin tectonics*.

TERMINI CHIAVE: *Italia, Appennino meridionale, accorciamento plio-quaternario, carbonati apuli sepolti, tettonica pellicolare.*

1. INTRODUCTION

Between the southern Abruzzi-Alto Molise region and northern Calabria, a duplex system basically made up of shallow-water Mesozoic-Tertiary carbonates («Inner Apulia Platform» of petroleum geologists, see MOSTARDINI & MERLINI, 1986) forms the backbone of the Apennine mountain chain under a thick pile of NE-verging rootless nappes (MOSTARDINI & MERLINI, 1986; CELLO *et alii*, 1987; CASERO *et alii*, 1988, 1991; PATACCA & SCANDONE, 1989, 2001; PATACCA *et alii*, 1992; ROURE *et alii*, 1991; MATTAVELLI *et alii*, 1993; ROURE & SASSI, 1995; LA BELLA *et alii,* 1996; LENTINI *et alii*, 1996, 2002; MONACO *et alii*, 1998; CELLO & MAZZOLI, 1999; MENARDI NOGUERA & REA, 2000). The roof thrust of the duplex system joins the sole thrust of the tectonic wedge about 30 kilometers behind the nappe front, at maximum depths exceeding 6000 meters, in correspondence to the foot of a thrust-and-fold regional cascade (CASERO *et alii*, 1991; ROURE *et alii*, 1991). The Apulia-carbonate duplex system, representing the main target of oil research in the whole Southern Apennines, has been extensively explored and carefully mapped (see NICOLAI & GAMBINI, *Structural architecture of the Adria platform-and-basin system* in this volume). Along the axis of the mountain chain, the top of the carbonates lies at depths ranging from 1500 to more than 6000 metres below sea level. On the surface, Mesozoic-Tertiary carbonates referable to the Apulia-carbonate duplex system are exposed only in the Monte Alpi tectonic window in southern Basilicata (see PATACCA & SCANDONE, *Geology of the Southern Apennines* in this volume and references therein). Along the trace of the CROP-04 profile, the top of the duplex system rises from depths exceeding 6 kilometers in correspondence to the leading edge to about 3 kilometers in the axial zone and then deepens again towards the Tyrrhenian coast to depths exceeding 6 kilometers.

As concerns the timing of the tectonic deformation, extensive nappe stacking took place mainly in Miocene times. Subsequently, during the early Pliocene, the entire pile of nappes was transported over the inner (south-western) margin of the Apulia Platform that had been affected by flexure-hinge retreat but not yet reached by

(*) Dipartimento di Scienze della Terra dell'Università di Pisa. Via Santa Maria, 53. 56100 Pisa, Italy - patacca@dst.unipi.it - scandone@dst.unipi.it

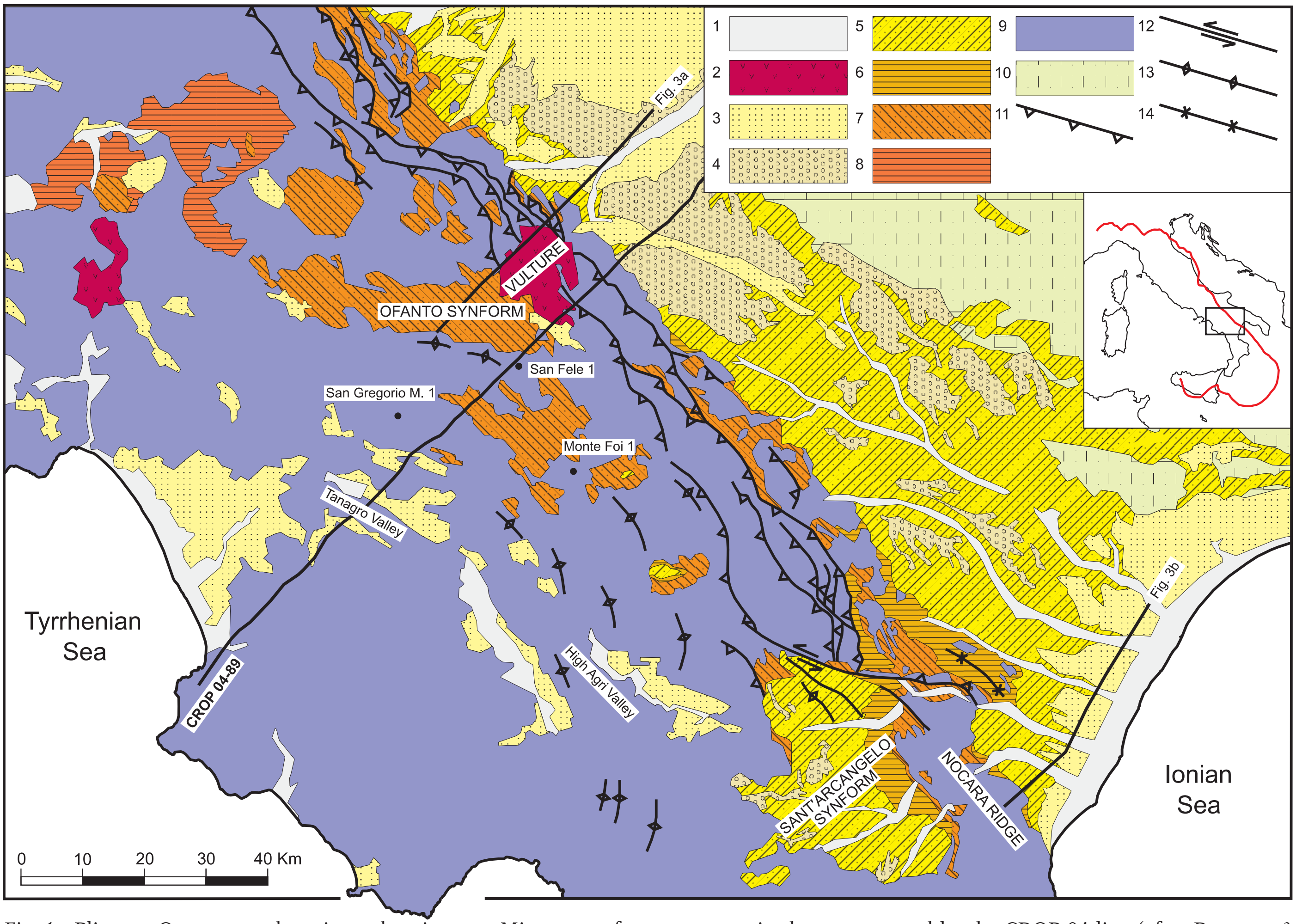

Fig. 1 - Pliocene-Quaternary deposits and major post-Miocene surface structures in the area crossed by the CROP-04 line (after PATACCA & SCANDONE, 2001 with slight modifications). The map also shows the trace of the CROP-04 seismic line and the location of the wells discussed in the text. 1) Alluvial and subordinate shore deposits (Holocene); 2) Volcanites and volcaniclastic deposits (late-middle Pleistocene); 3) Terraced continental and shallow-marine deposits (late-middle Pleistocene); 4) Continental to shallow-marine deposits accumulated in a short time interval following the last (lower Pleistocene) flexure-hinge retreat of Apulia and preceding the generalized middle Pleistocene uplift of the Apennines (Serra Corneta and Irsina conglomerates, middle Pleistocene around 0.65 Ma; Monte Marano sandstones, middle Pleistocene, 0.65-0.66 Ma); 5) Marine and subordinate continental sedimentary units deposited on top of the allochthonous sheets, in the foredeep basin and on the foreland ramp after the last displacement of the Apennine nappes towards the Apulia foreland (middle-early Pleistocene, 0.66-1.50 Ma); 6) Marine sedimentary units deposited on top of the Apennine nappes during their last displacement towards the Apulia foreland (early Pleistocene, 1.50-1.83 Ma); 7) Marine to continental sedimentary units deposited on top of the allochthonous sheets during a time interval characterized by imbrication and telescopic shortening of the Apennine nappes (late Pliocene, 1.83-3.30 Ma), preceded and followed by major events of forward nappe displacement; 8) Marine sedimentary units deposited on top of the Apennine nappes during their displacement towards the Apulia foreland in early-late Pliocene times (early-late Pliocene, 3.30-3.70 Ma); 9) Apennine nappes and thrust-sheet-top deposits older than 3.70 Ma; 10) Mesozoic carbonates of the Apulia foreland; 11) Plio-Pleistocene thrusts; 12) Strike-slip faults; 13) Anticline axis; 14) Syncline axis.

– Depositi plio-pleistocenici e principali strutture di superficie post-mioceniche nell'area attraversata dal profilo CROP-04 (da PATACCA & SCANDONE, 2001 con lievi modifiche). La carta mostra anche la traccia del profilo CROP-04 e l'ubicazione dei pozzi discussi nel testo. 1) Depositi alluviali e subordinatamente di spiaggia (Olocene); 2) Vulcaniti e depositi vulcanoclastici (Pleistocene medio e superiore); 3) Depositi terrazzati continentali e subordinatamente di mare basso (Pleistocene medio e superiore); 4) Depositi continentali e marini accumulati nel breve intervallo temporale successivo all'ultimo arretramento dell'asse di flessura della placca Apula nell'area (parte altissima del Pleistocene inferiore) e precedente il sollevamento generalizzato dell'Appennino nel Pleistocene medio (Conglomerato di Irsina e Conglomerato della Serra Corneta, Pleistocene medio intorno a 0.65 Ma; Sabbie di Monte Marano (Pleistocene medio, 0.65-0.66 Ma); 5) Unità sedimentarie marine e subordinatamente continentali depositate sulla catena, nel bacino di avanfossa e nelle aree di avampaese dopo l'ultimo trasporto delle coltri alloctone verso l'avampaese pugliese (Pleistocene inferiore e medio, 0.66-1.50 Ma); 6) Unità sedimentarie marine depositate sul dorso delle coltri alloctone durante il loro ultimo trasporto verso l'avampaese pugliese (Pleistocene inferiore, 1.50-1.83 Ma); 7) Unità sedimentarie marine e continentali deposte sul dorso delle coltri alloctone in un intervallo temporale caratterizzato da embriciamento e accorciamento telescopico delle coltri appenniniche (Pliocene superiore, 1.83-3.30 Ma), preceduto e seguito da importanti momenti di trasporto orogenico verso l'avampaese; 8) Unità sedimentarie marine deposte sul dorso delle coltri appenniniche durante il loro trasporto verso l'avampaese pugliese nel corso del Pliocene (Pliocene inferiore e superiore, 3.30-3.70 Ma); 9) Coltri appenniniche e depositi discordanti più antichi di 3.70 Ma; 10) Carbonati mesozoici dell'avampaese pugliese; 11) Faglie inverse e sovrascorrimenti plio-pleistocenici; 12) Faglie trascorrenti; 13) Asse di anticlinale; 14) Asse di sinclinale.

compressional deformation. In the middle-late Pliocene, finally, also the Apulia Platform underwent shortening processes that produced duplexing in the deep-seated carbonates and forward displacement of the overlying allochthonous sheets. Duplex breaching alternating with forward nappe transport caused re-imbrication of the allochthonous sheets and generation of antiformal stacks in the roof units of the Apennine system (PATACCA & SCANDONE, 2001). Around the boundary between the early and the middle Pleistocene, flexure-hinge retreat in

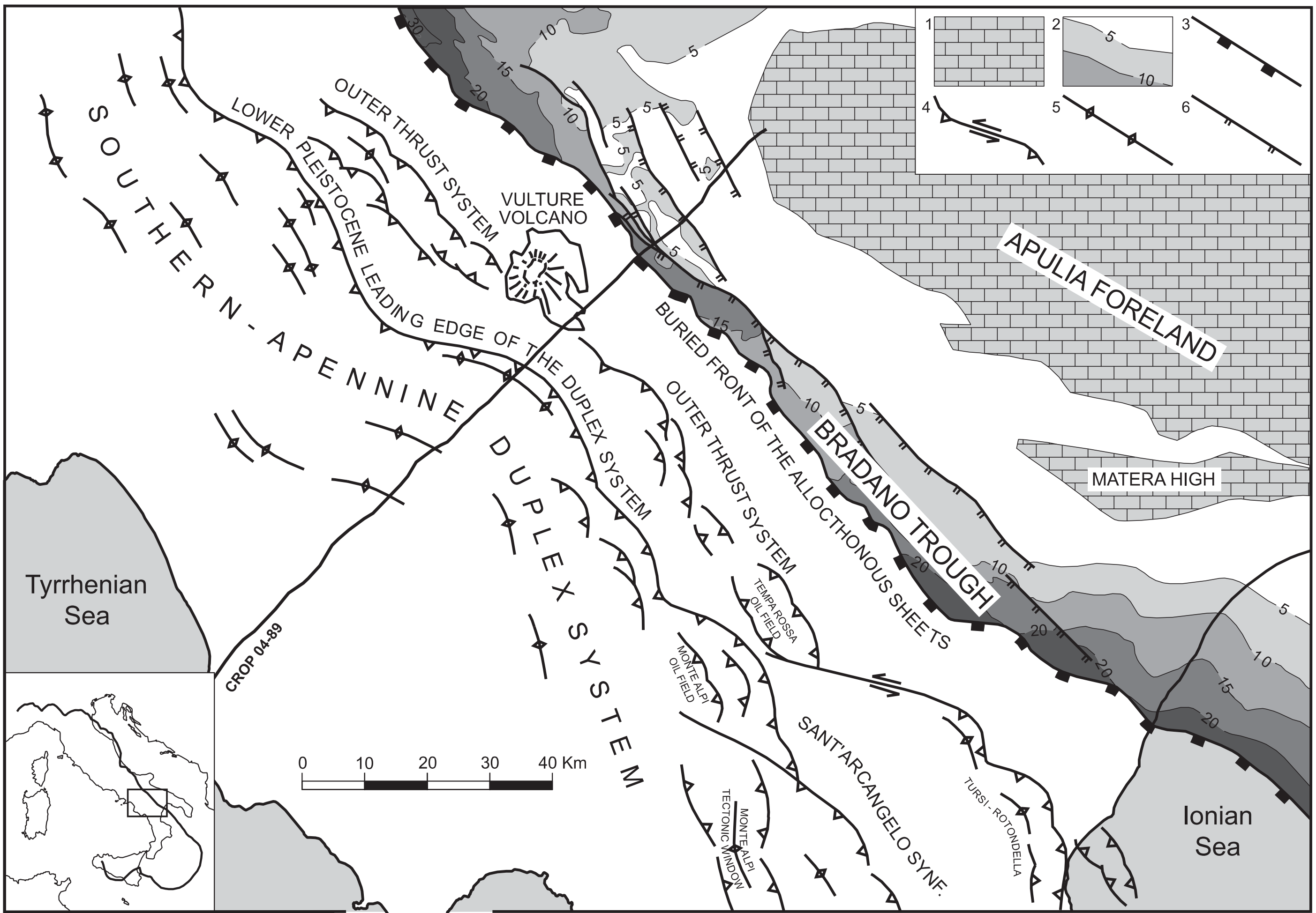

Fig. 2 - Simplified structural map showing the major subsurface tectonic features in the area crossed by the CROP-04 line (after PATACCA & SCANDONE, 2001 with slight modifications). 1) Autochthonous Mesozoic carbonates of the Apulia foreland; 2) Base of the Plio-Pleistocene deposits in the foredeep basin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

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

the Adriatic plate suddenly ceased, together with shortening in the mountain chain, and the entire southern Apennine region began to undergo generalized uplift processes (CINQUE *et alii*, 1993; HIPPOLYTE *et alii*, 1994a).

The amount of shortening of the Apulia carbonates and the degree of involvement of the crystalline basement in the duplex system are matter of debate. According to some authors (e.g. CASERO *et alii*, 1988; ROURE *et alii*, 1991; MAZZOLI *et alii*, 2000, 2001; MENARDI NOGUERA & REA, 2000), a deformed crystalline basement forming a sort of backstop of the tectonic wedge must be expected at relatively shallow depths; according to other authors, on the contrary, the tectonic wedge is entirely composed of sedimentary rocks and is floored by a flat sole thrust gently dipping towards the south-west on top of an undeformed crystalline basement (see among others MOSTARDINI & MERLINI, 1986; DOGLIONI *et alii*, 1996; MAZZOTTI *et alii*, 2000; PATACCA *et alii*, 2000; PATACCA & SCANDONE, 1989, 2001). An argument used by the supporters of a thick-skinned tectonic wedge in order to discard thin-skin deformation is that the absence of an important basement involvement would require in the Southern Apennines unrealistic amounts of shortening (see ENDIGNOUX *et alii*, 1989). The present paper illustrates a series of geological features that prove a minimum shortening of about 90 kilometers within the Apulia Platform during middle-late Pliocene and early Pleistocene times. Such an evidence obviously removes the principal bias against tectonic interpretations of the CROP-04 deep seismic profile suggesting for the Southern Apennines a thin-skin structural style.

Fig. 1 shows the first-order Plio-Pleistocene surface features in the study area with the trace of the CROP-04 seismic line and the location of the wells discussed in the paper. The major subsurface features in the same area are indicated in the structural sketch of fig. 2. Fig. 3 provides Two simplified geological sections, one in the area crossed by the CROP-04 profile and one in an area located at about 90 kilometers towards the south, provide an image of the thrust belt-foredeep system in the South-

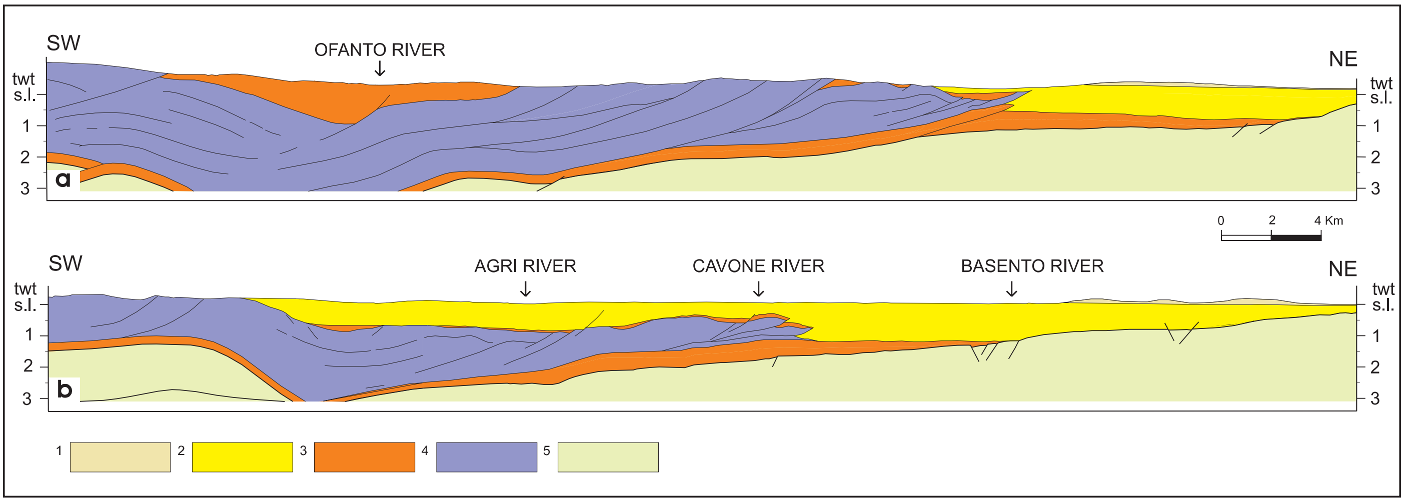

Fig. 3 - Simplified cross-sections across the front of the allochthonous sheets showing the geometric relationships between the Apennine nappes, the Apulia carbonates and the Plio-Pleistocene foredeep/thrust-sheet-top deposits in the study region. (Modified after PATACCA & SCANDONE, 2001). 1) Middle Pleistocene-upper Pleistocene deposits; 2) Pleistocene sedimentary units deposited during and after the last transport of the Apennine nappes towards the Apulia foreland; 3) Pliocene deposits pre-dating the last forward transport of the Apennine nappes; 4) Apennine nappes; 5) Apulia carbonates.
– Sezione schematica attraverso il fronte dell'alloctono mostrante le relazioni geometriche tra le coltri appenniniche, i carbonati apuli e i depositi plio-pleistocenici dell'avanfossa e della catena (modificato da PATACCA & SCANDONE, 2001).

ern Apennines (fig. 3, see location in fig. 1). These profiles give a general idea about the geometric relationships between the allochthonous sheets, the Apulia carbonates and the Plio-Pleistocene foredeep/thrust-sheet-top deposits in the whole study region. Fig. 4, finally, shows the Plio-Pleistocene time table used for stratigraphic correlations and kinematic reconstructions.

2. THE PLIO-PLEISTOCENE FOREDEEP AND THRUST-SHEET-TOP DEPOSITS IN THE SOUTHERN APENNINES

The autochthonous Mesozoic-Tertiary carbonates of the Apulia foreland are widely exposed in the Gargano, Murge and Salento areas. Between these areas and the leading edge of the buried duplex system, the flexured Apulia carbonates gently dip towards the Apennines giving origin to a depression that exceeds 4000 meters in depth. This depression, the southern portion of which is known in the geological literature as the Bradano Trough, represents the youngest foredeep basin of the Southern Apennines, active in late Pliocene and early Pleistocene times. Only the upper portion of the foredeep deposits crops out, exposed along the front of the mountain chain (Sub-Apenninic Clay, Monte Marano Sandstone and Irsina Conglomerate of the geological literature). However, the entire sedimentary succession has been reconstructed in the subsurface tanks to the extensive petroleum exploration in the area. The ages attributed to the foredeep deposits have mostly derived from CRESCENTI (1975) and BALDUZZI *et alii* (1982a, b), with integrations based on the stratigraphic information contained in the composite logs of commercial boreholes and on surface investigations carried out on the Sub-Apenninic Clay unit. The thrust-sheet-top deposits, widely exposed in natural sections along the outer (north-eastern) margin of the Apennines and in major structural depressions of the mountain belt (firstly the Ofanto and Sant'Arcangelo synforms) have been object of investigation by several authors (see PATACCA & SCANDONE, 2001 and references therein).

The Plio-Pleistocene thrust-sheet-top and foredeep deposits object of this paper have been referred to two depositional sequences both controlled by tectonic processes active in the mountain chain ($P_{1\text{-}2}$ and $Q_{1\text{-}2}$ thrust-related depositional sequences). The meaning of thrust-related depositional sequence in the Southern Apennines and the definition of the relative systems tracts, including the characteristic stratigraphic signatures, are provided in PATACCA & SCANDONE (2001). In this paper, we only wish to remark that in a thrust belt having a duplex configuration a thrust-related depositional sequence represents the sedimentary record of a tectonic cycle that starts with an important forward displacement of the roof units over a long thrust flat and ends with a forward propagation of the leading edge of the duplex system and the incorporation in the tectonic wedge of new horses detached from the foreland plate.

2.1. $P_{1\text{-}2}$ FOREDEEP AND FORELAND DEPOSITS

The Plio-Pleistocene deposits the exposed along the Adriatic slope of the Apennines and in the Bradano Trough in the region crossed by the CROP-04 seismic line, referred to $P_{1\text{-}2}$ and $Q_{1\text{-}2}$ sequences, are shown in the geological map of fig. 5 (see fig. 1 for location). The principal characteristics of these deposits on surface and in the subsurface have been schematized in the chronostratigraphic diagram of fig. 6 that includes both thrust-sheet-top and foredeep deposits. Two turbidite units have been distinguished in the foredeep basin. The lower unit consists of a package of thin-bedded sandstones and mudstones, interpreted as lobe-fringe deposits, laterally grading into mudstones with *Globorotalia gr. crassaformis*

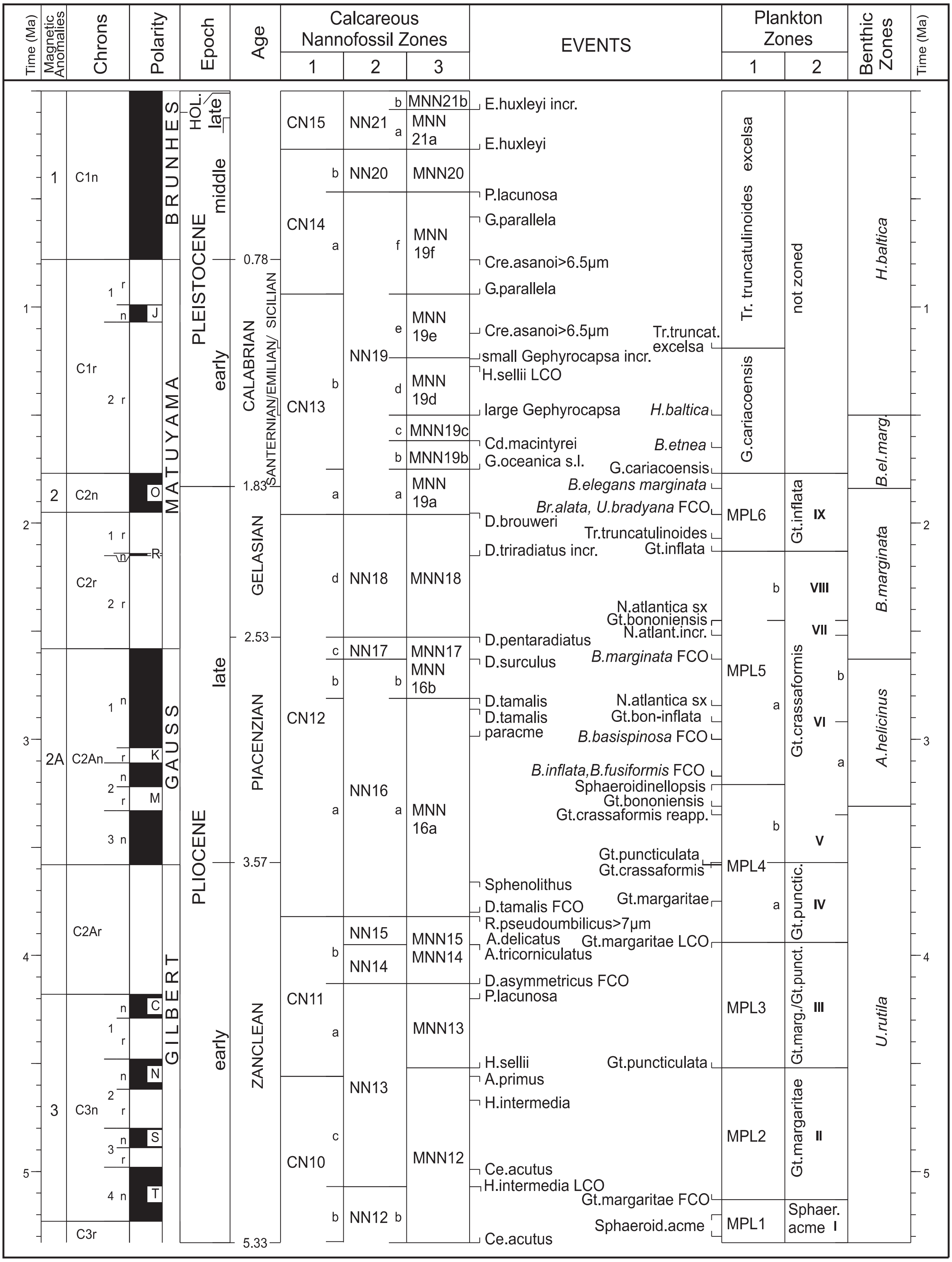

Fig. 4 - Plio-Pleistocene stratigraphic scheme (after PATACCA & SCANDONE, 2001 with slight modifications) showing the most significant bio-events of the Mediterranean region re-calibrated according to the global polarity time scale of CANDE & KENT, 1995. Calcareous Nannofossil Zones after OKADA & BUKRY, 1980 (1), MARTINI, 1971 (2) and RIO *et alii*, 1990 (3). Plankton zones after CITA, 1975 (1) and SPAAK, 1983 (2). Benthic Zones after COLALONGO & SARTONI, 1979.

– Schema stratigrafico del Plio-Pleistocene (da PATACCA & SCANDONE, 2001con lievi modifiche) con i più importanti bioeventi della regione mediterranea ricalibrati secondo la scala di CANDE & KENT, 1995. Zone a nannofossili calcarei da OKADA & BUKRY, 1980 (1), MARTINI, 1971 (2) e RIO et alii, *1990 (3). Zone a foraminifero planctonici da CITA, 1975 (1) e SPAAK, 1983 (2). Zone a foraminiferi bentonici da COLALONGO & SARTONI, 1979.*

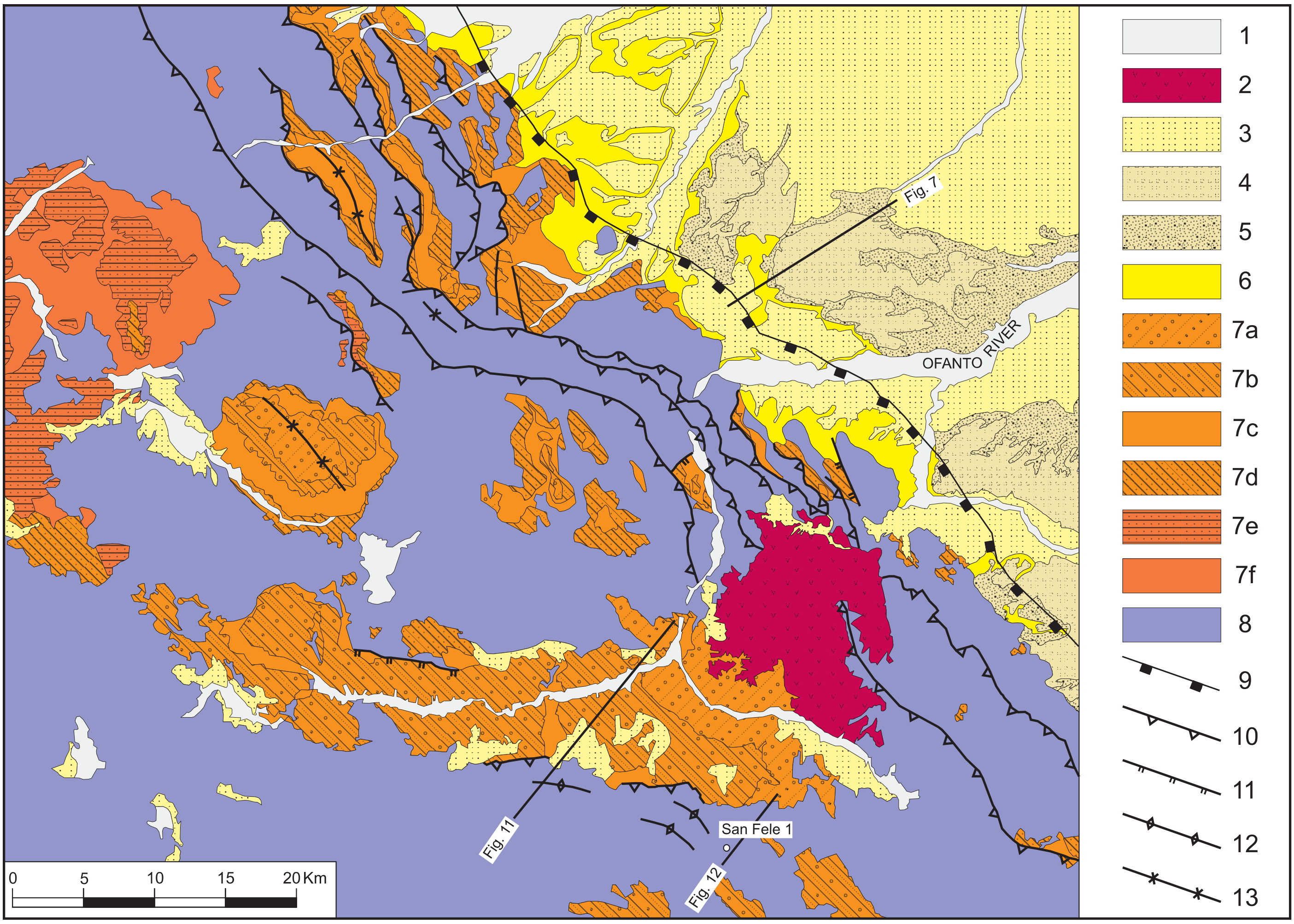

Fig. 5 - Geological map of the Ofanto region showing the Plio-Pleistocene deposits and the major tectonic features in the area crossed by the CROP-04 line (after PATACCA & SCANDONE, 2001 with slight modifications). 1) Alluvial deposits (Holocene); 2) Volcanites and volcaniclastic deposits (middle Pleistocene); 3) Terraced continental deposits (upper-middle Pleistocene); 4) Prograding fluvio-deltaic deposits (Irsina Conglomerate, middle Pleistocene); 5) Shallow-marine deposits (Monte Marano Sandstone, middle Pleistocene); 6) Q_{1-2} depositional sequence: shelf mudstones (Sub-Apenninic Clay, middle Pleistocene-lower Pleistocene); 7) P_{1-2} depositional sequence: 7a) prograding fan-delta conglomerates and conglomeratic sandstones (upper Pliocene); 7b) fan-delta deposits and shallow-marine sandstones (upper Pliocene); 7c) prodelta to open-shelf mudstones (upper Pliocene); 7d) fan-delta conglomerates and (outer margin of the Apennines) shallow-marine bioclastic sandstones and siliciclastic calcarenites (upper Pliocene); 7e) shallow-marine sandstones (upper Pliocene); 7f) open-shelf mudstones (upper-lower Pliocene); 8) Apennine nappes and thrust-sheet-top deposits older than 3.70 Ma; 9) Buried front of the Apennine nappes; 10) Plio-Pleistocene thrusts; 11) Normal faults; 12) Anticline axis; 13) Syncline axis.

– Carta geologica della regione dell'Ofanto con i depositi plio-pleistocenici e con le principali strutture tettoniche nell'area attraversata dalla linea CROP-04 (da PATACCA & SCANDONE, 2001 con lievi modifiche). 1) Depositi alluviali (olocene); 2) Vulcaniti e depositi vulcanoclastici (Pleistocene medio); 3) Depositi continentali terrazzati; 4) Depositi fluvio-deltaici progradanti (Conglomerato di Irsina, Pleistocene medio); 5) Depositi di mare basso (Sabbie di Monte Marano, Pleistocene medio); 6) Depositi fangosi di piattaforma aperta della sequenza deposizionale Q_{1-2} (Argille sub-Appenniniche, Pleistocene inferiore e parte basale del Pleistocene medio); 7) Sequenza deposizionale P_{1-2}: 7a) conglomerati e sabbie conglomeratiche progradanti di fandelta (Pliocene superiore); 7b) depositi di fandelta e arenarie di mare basso (Pliocene superiore); 7c) depositi di prodelta e peliti di piattaforma aperta (Pliocene superiore); 7d) conglomerati di fandelta e (margine esterno dell'Appennino) arenarie bioclastiche e calcareniti silicoclastiche di mare basso (Pliocene superiore); 7e) arenarie di mare basso (Pliocene superiore); 7f) peliti di piattaforma aperta (Pliocene inferiore e superiore); 8) Coltri appenniniche e depositi discordanti più vecchi di 3.70 Ma; 9) Fronte sepolto delle coltri appenniniche; 10) Faglie inverse e sovrascorrimenti plio-pleistocenici; 11) Faglie normali; 12) Asse di anticlinale; 13) Asse di sinclinale.

(3.30-2.13 Ma interval in fig. 6). In seismic lines, these fine-grained siliciclastic deposits are characterized by highly continuous parallel reflectors with low frequency and moderate amplitude (3.30-2.13 Ma interval in fig. 7). A calcarenite key bed, well recognizable in wireline logs and in seismic profiles where it is expressed by a strong and continuous flat reflector (e.g. left side of fig. 7 just below the 2.13 Ma reflector), allowed reliable subsurface correlations in the whole study area. The 3.30-2.13 Ma low-density turbidites stratigraphically overlie a continuous veneer of condensed hemipelagic deposits characterized by the presence of *Globorotalia puncticulata* and *Uvigerina rutila* (3.70-3.30 Ma interval in fig. 7). The upper unit (2.13-1.83 Ma interval) is represented by a stack of turbidites characterized by a higher sand/mud ratio that yielded common *Globorotalia inflata*. These turbidites (*Gt. inflata* turbidites) form as a whole a clastic wedge of aggrading to prograding basin-floor sand lobes. In seismic profiles they are characterized by rather continuous flat reflectors that may be laterally replaced, toward the north-east, by sets of weaker reflectors with a gently-prograding mounded configuration evidenced by

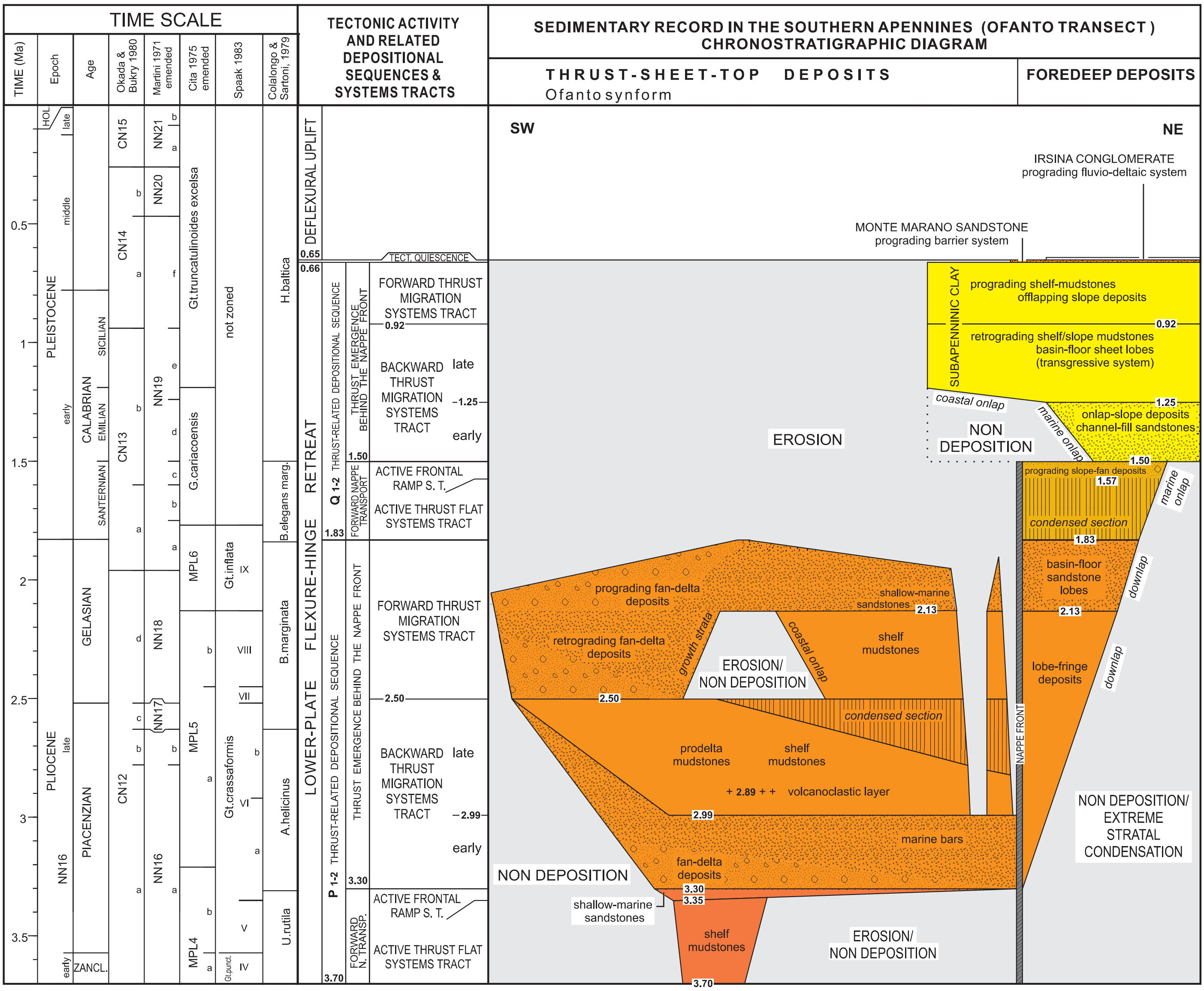

Fig. 6 - Chronostratigraphic diagram showing the principal characteristics of the Plio-Pleistocene thrust-sheet-top, foredeep and foreland deposits in the area crossed by the CROP-04 seismic line (modified after PATACCA & SCANDONE, 2001).
– Diagramma cronostratigrafico mostrante le principali caratteristiche dei depositi plio-pleistocenici della catena, del bacino di avanfossa e dell'avampaese nell'area attraversata dal profilo CROP-04 (modificato da PATACCA & SCANDONE, 2001).

subtle bi-directional downlap terminations. Toward the foreland, an active flexure-hinge retreat in the 2.13-1.83 Ma interval is testified by the presence of south-westward tilted reflectors truncated by the overlying clastic wedge.

The map of fig. 8 is a detail of another area located about 90 kilometers south of the CROP-04 line (Sant'Arcangelo synform and Bradano Trough east of the Nocara Ridge, see location in fig. 1) where the P_{1-2} and Q_{1-2} sequences are well preserved and well exposed. The characteristics of the Plio-Pleistocene deposits in this area are shown in the chronostratigraphic diagram of fig. 9 that integrates the information of fig. 6 in the part concerning the Q_{1-2} thrust-sheet-top deposits not represented in the northern transect. In the foredeep basin, the P_{1-2} siliciclastic deposits display the same characteristics as the coeval sandy deposits of the Ofanto region, with the only difference represented by the fact that the *Gt. inflata* turbidites of the southern transect overlie condensed foraminiferal limestones and marls (3.70-2.13 Ma interval in fig. 10) partly coeval with the more internal *Gt. crassaformis* turbidites described in the northern transect. These condensed foraminiferal limestones and marls form in the southern area a continuous thin layer draping the Apulia carbonates.

At the rear of the nappe front, the allochthonous sheets overlie the described foredeep deposits by means of a long thrust flat. In some seismic profiles crossing the tip of the Apennine nappes in Southern Basilicata, we have followed the reflectors corresponding to the *Gt. inflata* turbidites of the P_{1-2} sequence at the base of the allochthonous sheets as far as the north-eastern foot of the Nocara Ridge, 12-15 kilometers behind the nappe front (see PATACCA & SCANDONE, 2001). Moving towards the axis of the mountain chain, between the Nocara Ridge and the south-western margin of the Sant'Arcangelo depression, drilling data show that the *Gt. crassaformis/Gt. inflata* turbidites are absent and the allochthonous sheets tectonically overlie older turbidite

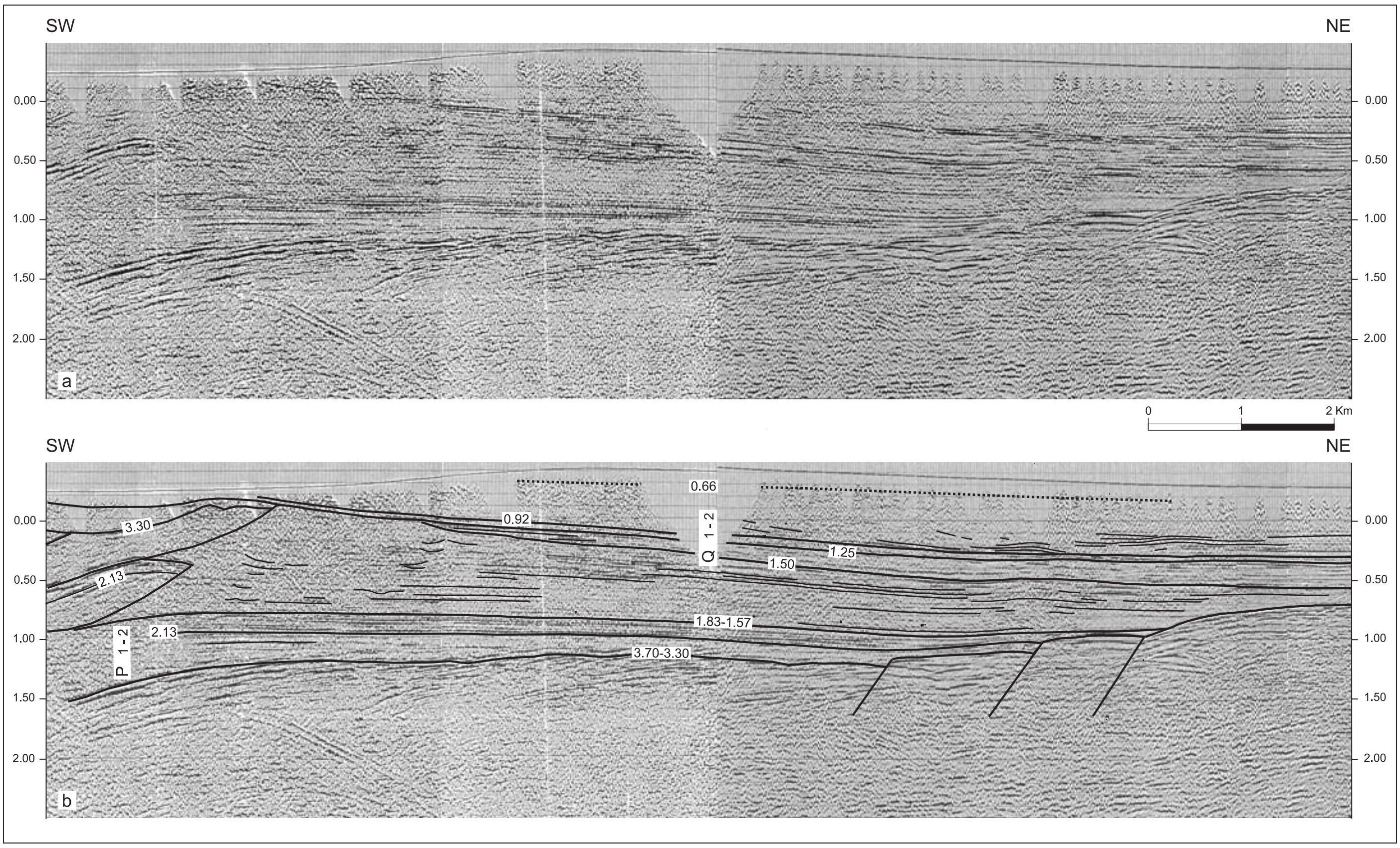

Fig. 7 - Uninterpreted (*a*) and interpreted *b*) seismic profile across the front of the Apennine nappes showing some details of the foredeep configuration in the area crossed by the CROP-04 line. The ages of the surfaces bounding the sequences and the relative systems tracts are the same as in the chronostratigraphic diagram of fig. 6. The top of the Apulia carbonates, usually marked by a couple of high-amplitude/low-frequency reflectors, is highlighted in this profile by the presence of a continuous layer of Pliocene condensed deposits (3.70-3.30 Ma interval). Above these reflective deposits, three major intervals are easily recognizable: 3.30-1.83 Ma interval, deposited before the arrival of the allochthonous sheets in the area; 1.57-1.50 Ma interval, deposited during the growth of the frontal ramp of the allochthonous sheets; interval overlying the 1.50 Ma surface, suturing the frontal ramp and thus post-dating the forward nappe transport. The 1.83-1.57 Ma interval is represented by a condensed muddy section, well recognizable in the whole foredeep basin, deposited during the forward transport of the allochthonous sheets over a long thrust flat. Note the slice of Pliocene foredeep deposits incorporated in the tectonic wedge about 1 Km behind the nappe front.

– Profilo sismico non interpretato (a) *ed interpretato* (b) *attraverso il fronte della catena mostrante alcuni dettagli della configurazione del bacino di avanfossa nell'area attraversata dal profilo CROP-04. Le età delle superfici che limitano le sequenze e i relativi tratti di sistema sono le stesse del diagramma cronostratigrafico di fig. 6. La sommità dei carbonati apuli, generalmente marcata da una coppietta di riflettori ad alta ampiezza e bassa frequenza, è sottolineata in questo profilo da un livello continuo di depositi Pliocenici condensati (intervallo 3.70-3.30 Ma). Sopra a questi depositi riflettivi sono riconoscibili tre intervalli principali: l'intervallo 3.30-1.83 Ma, depositato prima dell'arrivo delle coltri alloctone nell'area, l'intervallo 1.57-1.50, depositato durante la crescita della rampa frontale dell'alloctono, e l'intervallo soprastante la superficie 1.50 Ma che sutura la rampa frontale ed è quindi più giovane dell'ultimo trasporto delle coltri appenniniche verso l'avampaese. L'intervallo 1.83-1.57 Ma è rappresentato da una sezione condensata di sedimenti fangosi, ben riconoscibile nell'intero bacino di avanfossa, deposta durante l'ultimo trasporto dell'alloctono su un lungo thrust flat. Sotto il margine esterno della catena, un chilometro circa a tergo del fronte, è visibile un embrice di depositi pliocenici di avanfossa incorporati nel cuneo tettonico.*

deposits stratigraphically covering the Apula carbonates. These more internal foredeep deposits have been attributed to the Pliocene *Gt. puncticulata* zone (Crescenti, 1975; Balduzzi *et alii*, 1982a; D'Andrea *et alii*, 1993; Patacca & Scandone, 2001). In the High Agri Valley close to the south-western border of the Sant'Arcangelo synform, at a distance of about 40 kilometers from the nappe front, numerous commercial wells (Monte Alpi oil field in fig. 2) show that the allochthonous sheets tectonically overlie more internal foredeep deposits, older than the *Gt. puncticulata* turbidites, that have been attributed to the *Gt. margaritae/Gt. puncticulata* concurrent range zone. These deposits, stratigraphically covering the Mesozoic-Tertiary Apulia carbonates in the axial portion of the buried duplex system, contain in their upper portion olistostromes derived from the Apennine nappes during their displacement towards the Apulia foreland.

The above stratigraphic evidence allows us to establish the following facts:

– The bulk of the Apennine duplex system has been built up after the early Pliocene. The Apulia-Platform domain explored by the commercial boreholes of the High Agri Valley area, in fact, was part of a foredeep basin not yet reached by the compression front and not yet incorporated in the thrust belt in the time corresponding to the *Gt. margaritae/Gt. puncticulata* concurrent range zone;

– The minimum shortening of the Apulia-Platform carbonates of the Apennine duplex system averages 40 Km. This value derives from the amount of forward displacement of the allochthonous sheets from the High Agri Valley to the present day nappe front. We can subdivide these 40 Km into about 25 Km corresponding to the forward nappe transport from the High Agri Valley to the Nocara Ridge after the deposition of the *Gt. puncticulata* turbidites and before the deposition of the *Gt. inflata* turbidites, and about 15 Km corresponding to the forward nappe transport from the Nocara Ridge to the present Apennine front after the deposition of the *Gt. inflata* turbidites;

– The calculated shortening of 40 Km just derives from the forward transport of the Apennine nappes since no internal shortening of the allochthonous sheets has been considered. We will see that internal shortening alternated with forward nappe displacement, as it is testified by the breaching of the Apulia-carbonate duplex system and the growth of huge antiformal stacks in the Lagonegro Units. The thrust-sheet-top deposits of the Ofanto region provided very good stratigraphic data that allowed us to assign to the late Pliocene an important episode of telescopic shortening affecting the Apulia Platform.

2.2. P_{1-2} THRUST-SHEET-TOP DEPOSITS

The 3.70-3.30 Ma and 3.30-1.83 Ma intervals distinguished in the foredeep basin are also recognizable in the terrigenous deposits that unconformably overlie the Apennine thrust sheets. The first group of deposits, well exposed in the CROP-04 area just north of the Ofanto synform, is represented by open-shelf foraminiferal mudstones grading upward into shallow-marine sandstones (3.70-3.30 Ma interval in fig. 6). This mudstone-sandstone couple forms as a whole a shallowing-upward sequence that overlies the Apennine nappes, as well as thrust-sheet-top deposits older than 3.70 Ma. The 3.70-3.30 Ma interval is rather well recognizable in the subsurface as it appears as a reflection-free isopachous drape on top of the allochthonous sheets. The second group of Pliocene deposits still referable to the P_{1-2} sequence forms a complete transgressive-regressive sedimentary cycle well exposed in the Ofanto synform and in other intramontane structural depressions (3.30-1.83 Ma interval in figs. 6 and 9). The transgressive portion of this sedimentary cycle (3.30-2.50 Ma) is basically represented by retrograding coarse-grained fandelta deposits that are laterally and vertically replaced by a diachronous wedge-shaped muddy unit. A thin volcaniclastic layer present in the lower part of the mudstones forms a key horizon useful for stratigraphic correlations of surface sections. The regressive portion of the sequence (2.50-1.83 Ma) is represented by prograding coarse-clastic fandelta deposits. Along the outer margin of the mountain chain, the entire P_{1-2} depositional sequence is represented by cross-bedded bioclastic calcarenites representative of marine bars grading upwards into open-shelf mudstones. The latter, in turn, are overlain by shallow-marine sandstones.

In the area crossed by the CROP-04 line, the deposits of the P_{1-2} depositional sequence have provided important information about the time in which the buried Apulia-carbonate duplex system breached and antiformal-stack structures grew in the Apennine nappes. The lower interval of the sequence (3.70-3.30 Ma) appears as a quite isopachous mudstone-sandstone couple that shows no important lateral change of facies. The retrograding half portion of the 3.30-1.83 Ma interval ends at about 2.50 Ma with a maximum flooding documented from the Adriatic slope of the Apennines (Ofanto Valley) to the Tyrrhenian slope of the mountain chain (Melandro Valley, about 15 kilometers south-east of the San Gregorio Magno 1 wellsite). The generalized transgression on top of the allochthonous sheets around 3.30 Ma and the lack of significant changes in thickness and facies of the 3.30-2.50 Ma deposits indicate that the relief created by the growth of the San Gregorio Magno structural high in the Apulia carbonates and of the San Fele antiformal stack in the allochthonous sheets post-dates 2.50 Ma. The upper half portion of the 3.30-1.83 Ma interval consists of fining-upward fandelta conglomerates and sandstone capped by a few tens of meters of *Gt. inflata* silty mudstones (2.50-2.13 Ma) followed by coarse-clastic prograding fandelta deposits topped by red alluvial conglomerates (2.13-1.83 Ma). The seismic line of fig. 11, crossing the Ofanto synform, shows two wedge-shaped sedimentary bodies, both characterized by growth strata and progressive angular unconformities. The internal unconformities of the Ofanto deposits evidence an early backward (southward) tilt of the basin related to a breach cutting across the entire pile of nappes, and a subsequent tilt toward the north caused by the growth of the San Fele antiformal stack the outer flank of which coincides with the southern flank of the Ofanto synform. The normal fault that in fig. 11 displaces the 3.70-2.50 Ma thrust-sheet-top deposits and gently deforms the Pliocene sediments younger than 2.50 Ma has been interpreted as an accommodation feature in the backlimb of a ramp anticline developed in the allochthonous sheets. Surface data show that the northward tilt of the Pliocene deposits decreases rapidly upsection after the 2.13 Ma surface.

The described Pliocene thrust-sheet-top deposits present in the area crossed by the CROP-04 line allow us to establish the following facts:

– The top of the Apennine nappes exposed along the Adriatic slope of the mountain chain had to correspond in the 3.70-3.30 Ma time span to a very flat sea bottom, as demonstrated by the existence of a continuous and isopachous muddy unit draping the allochthonous sheets;

– The lack of significant changes in thickness and facies of the 3.30-2.50 Ma deposits and the generalized transgression on top of the Apennine nappes culminating with a maximum flooding around 2.50 Ma fixes a lower chronological boundary for the uplift of the Apulia carbonates in correspondence to the crest of the duplex system (3180 meters b.s.l. in San Gregorio Magno 1) and for the growth of the San Fele antiformal stack within the allochthonous sheets;

– The northward tilt of the entire pile of 3.7-2.13 Ma deposits and the progressive unconformities within the 2.50-2.13 Ma interval confine the growth of the San Fele antiformal stack in the late Pliocene just before the forward transport of the Apennine nappes over the *Gt. inflata* turbidites of the foredeep basin.

A stratigraphic description of the San Gregorio Magno 1 and San Fele 1 wells is available in PATACCA E., *Subsurface constraints on the CROP-04 seismic line interpretation: San Fele 1, Monte Foi 1 and San Gregorio Magno 1 wells (Southern Apennines, Italy)*, in this volume. The tectonic repetitions of the Lagonegro Unit II recognized in the Monte Foi 1 well testify to an important telescopic

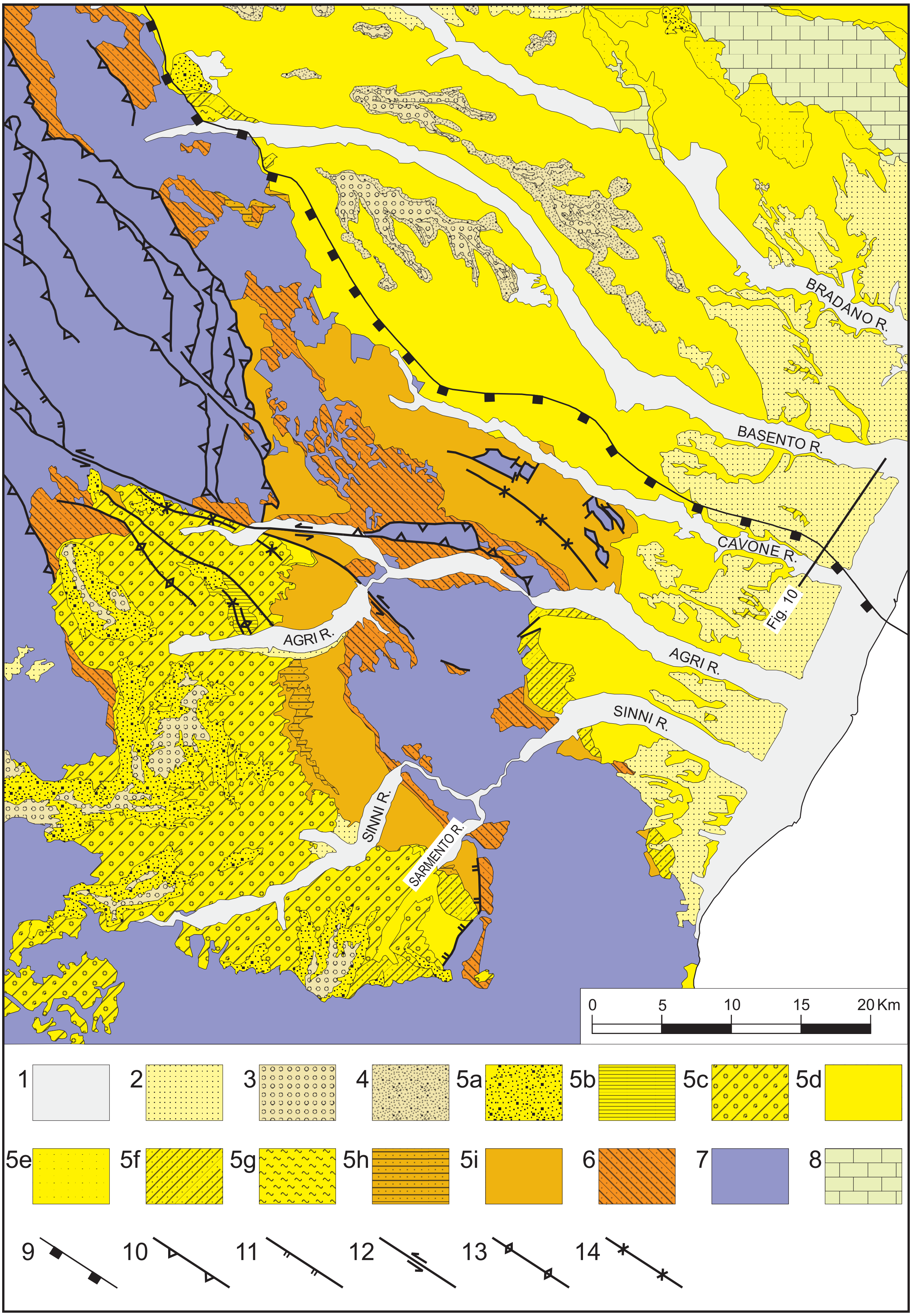
BRADANO R.
BASENTO R.
CAVONE R.
Fig. 10
AGRI R.
AGRI R.
SINNI R.
SINNI R.
SARMENTO R.
0 5 10 15 20 Km
1
2
3
4
5a
5b
5c
5d
5e
5f
5g
5h
5i
6
7
8
9
10
11
12
13
14

Fig. 8

shortening in the Apennine nappes compensating the same amount of shortening in the Apulia-carbonate duplex system at the rear of the San Fele antiformal stack. Fig. 12 is an interpretation of the San Fele structure derived from the borehole stratigraphic data and from a seismic line tied to the San Fele 1 well. According to this interpretation, a minimum shortening of 40-50 kilometers is required, also in the most conservative structural balance based on the hypothesis that the leading edge and the trailing edge of the major imbricates are located close to the margins of the seismic line. An amount of shortening of some tens of kilometers has been also obtained in the Monte Foi antiformal stack, which is the south-eastern continuation of the San Fele structure, by other authors (SCROCCA, SCIAMANNA, DI LUZIO, TOZZI, NICOLAI, GAMBINI, *Structural analysis along the CROP-04 deep seismic profile (Southern Apennines-Italy*, in this volume). If we add these 40-50 km to the 40 km corresponding to the forward nappe displacement in the time span ranging from the *Gt. puncticulata* zone to the lower portion of the *Globigerina cariacoensis* zone (see time table of fig. 4), we obtain a minimum shortening of the Apulia-carbonate duplex system of 80-90 kilometers.

2.3. Q_{1-2} FOREDEEP AND FORELAND DEPOSITS

The foredeep and foreland deposits of the Q_{1-2} depositional sequence are not affected by compressional deformation and have fully preserved their original stratal architecture. Five depositional units have been recognized over the whole study area (see figs. 6, 7, 9 and 10). The lower unit (1.83-1.57 Ma interval) is represented at the scale of the entire basin by a very thin layer of hemipelagic deposits on top of the Q_{1-2}/P_{1-2} sequence boundary testifying to an episode of prolonged sediment starvation during the forward transport of the Apennine nappes over a long thrust flat. The condensed section is overlain by a thick wedge of gravity-driven deposits (1,57-1.50 Ma interval) truncated upsection by the active frontal ramp of the allochthonous sheets. These mass-flow deposits have principally derived from the failure of unconsolidated sediments lying on top of the Apennine nappes in the hangingwall of the frontal ramp. An onlap-slope system consisting of basinal, locally channelized, turbidite deposits onlapping the edge of the allochthonous sheets marks the deactivation of the frontal ramp (1.50-1.25 Ma interval). The onlap-slope system is overlain by a transgressive system made up of muddier basinal deposits landwards replaced by transgressive shelfal mudstones that correspond to the maximum marine flooding on the tectonic wedge (1.25-0.92 Ma interval). A prograding shelf-margin system follows, represented by a thick muddy unit known on the surface as the Sub-Apennine Clay (0.92-0.66 Ma interval). This unit is basinward substituted by prograding basin-floor turbidites. In the Bradano Trough, the Sub-Apenninic Clay unit grades upwards into shallow-water sandstones (Monte Marano Sandstone, 0.66-0.65 Ma interval in figs. 6 and 9) that are

Fig. 8 - Geological map showing the Plio-Pleistocene deposits and the major tectonic features in the Sant'Arcangelo region and in the southern part of the Bradano Trough (after PATACCA & SCANDONE, 2001 with slight modifications): 1) Alluvial and subordinate shore deposits (Holocene); 2) Terraced continental and shallow-marine deposits (upper-middle Pleistocene); 3) Alluvial and prograding fluvio-deltaic deposits (Serra Corneta Conglomerate in the Sant'Arcangelo synform, Irsina Conglomerate in the Bradano Trough, middle Pleistocene); 4) Shallow-marine to backshore deposits (Monte Marano and Staturo sandstones, middle Pleistocene); 5) Q_{1-2} depositional sequence: 5a) alluvial deposits in the Sant'Arcangelo synform (Castronuovo Conglomerate, middle Pleistocene); slope-type fan-delta deposits along the outer margin of the Apennines north of the Nocara Ridge (Serra del Cedro Upper Conglomerate, middle Pleistocene); 5b) lacustrine deposits (San Lorenzo Clay, middle Pleistocene); 5c) fan-delta deposits, including proximal alluvial fans (Sinni Synthem, middle-lower Pleistocene); 5d) prodelta mudstones and subordinate brackish-water lagoonal deposits in the Sant'Arcangelo synform (upper portion of the Sarmento Synthem, lower Pleistocene); nearshore sandstones (Montalbano Sandstone, middle Pleistocene) and open-shelf muddy deposits (Gravina clays, middle Pleistocene; Sub-Apenninic Clay, middle-lower Pleistocene) in the Bradano Trough; 5e) deepening-upward carbonate-ramp deposits (Gravina Calcarenite, middle-lower Pleistocene); 5f) fan-delta to shelf deposits (lower portion of the Sarmento Synthem in the Sant'Arcangelo synform; Tursi Sandstone along the eastern margin of the Nocara Ridge; Serra del Cedro Lower Conglomerate along the outer margin of the Apennines north of the Nocara Ridge, lower Pleistocene); 5g) chaotic slope deposits (lower Pleistocene) in the footwall of the Apennine frontal ramp (High Basento Valley); 5h) shallow-marine sandstones (Sant'Arcangelo and Garaguso sandstones, lower Pleistocene); 5i) shelf mudstones (Craco Clay, lower Pleistocene); 6) P_{1-2} depositional sequence: fan-delta-front to shallow-marine conglomerates and sandstones, lagoon to open-shelf mudstones including subordinate diatomitic clays, fan-delta-front conglomerates and sandstones laterally grading (outer margin of the Apennines) into bioclastic sandstones and siliciclastic calcarenites (upper Pliocene); 7) Apenninic nappes and thrust-sheet-top deposits older than 3.70 Ma; 8) Mesozoic carbonates of the Apulia foreland; 9) Front of the Apennine nappes; 10) Plio-Pleistocene thrusts; 11) Normal faults; 12) Strike-slip faults; 13) Anticline axis; 14) Syncline axis.

– Depositi plio-pleistocenici e principali strutture di superficie post-mioceniche nell'area di Sant'Arcangelo e nella parte meridionale della Fossa Bradanica (da PATACCA & SCANDONE, 2001 con lievi modifiche): 1) Depositi alluviali e subordinatamente di spiaggia (Olocene); 2) Depositi terrazzati continentali e subordinatamente di mare basso (Pleistocene medio e superiore); 3) Depositi alluviali e depositi fluvio-deltaici progradanti (Conglomerato di Serra Corneta nel Bacino di Sant'Arcangelo, Conglomerato di Irsina nella Fossa Bradanica, Pleistocene medio); 4) Depositi da mare basso a spiaggia emersa (Sabbie di Monte Marano e Sabbie dello Staturo, Pleistocene medio); 5) Sequenza deposizionale Q_{1-2}; 5a) depositi alluviali nella sinforme di Sant'Arcangelo (Conglomerato di Castronuovo, Pleistocene medio); depositi di fandelta lungo il margine esterno dell'Appennino a nord della dorsale di Nocara (Conglomerato Superiore della Serra del Cedro, Pleistocene medio); 5b) depositi lacustri (Argille di San Lorenzo, Pleistocene medio); 5c) depositi di fandelta e conoidi alluviali prossimali (Sintema del Sinni, Pleistocene inferiore e medio); 5d) depositi pelitici di prodelta e subordinati depositi lagunari nella sinforme di Sant'Arcangelo (parte superiore del Sintema del Sarmento, Pleistocene inferiore); sabbie di mare basso (Sabbie di Montalbano, Pleistocene inferiore) e depositi pelitici di piattaforma aperta (Argille di Gravina, Pleistocene medio; Argille sub-Appenniniche, Pleistocene inferiore e medio) nella Fossa Bradanica; 5e) depositi carbonatici di rampa (Calcareniti di Gravina, Pleistocene inferiore e medio); 5f) depositi di fandelta e piattaforma (parte inferiore del Sintema del Sarmento nella sinforme di Sant'Arcangelo; Sabbie di Tursi lungo il margine esterno della dorsale di Nocara; Conglomerato Inferiore della Serra del Cedro lungo il margine esterno dell'Appennino a nord della dorsale di Nocara, Pleistocene inferiore); 5g) depositi caotici di scarpata (Pleistocene inferiore) al piede della rampa frontale delle coltri appenniniche (alta Valle del Basento); 5h) sabbie di mare basso (Sabbie di Sant'Arcangelo e Sabbie di Garaguso, Pleistocene inferiore); 5i) depositi pelitici di piattaforma (Argille di Craco, Pleistocene inferiore); 6) Sequenza deposizionale P_{1-2}: conglomerati e arenarie di fronte di fandelta e di mare basso, depositi pelitici da lagunari a marini di piattaforma aperta con subordinate argille diatomitiche, conglomerati e arenarie di fronte di fandelta passanti lateralmente (margine esterno dell'Appennino) ad arenarie bioclastiche e calcareniti silicoclastiche (Pliocene superiore); 7) Coltri appenniniche e depositi discordanti più antichi di 3.70 Ma; 8) Carbonati mesozoici dell'avampaese apulo; 9) Fronte sepolto delle coltri appenniniche; 10) Faglie inverse e sovrascorrimenti plio-pleistocenici; 11) Faglie normali; 12) Faglie trascorrenti; 13) Asse di anticlinale; 14) Asse di sinclinale.

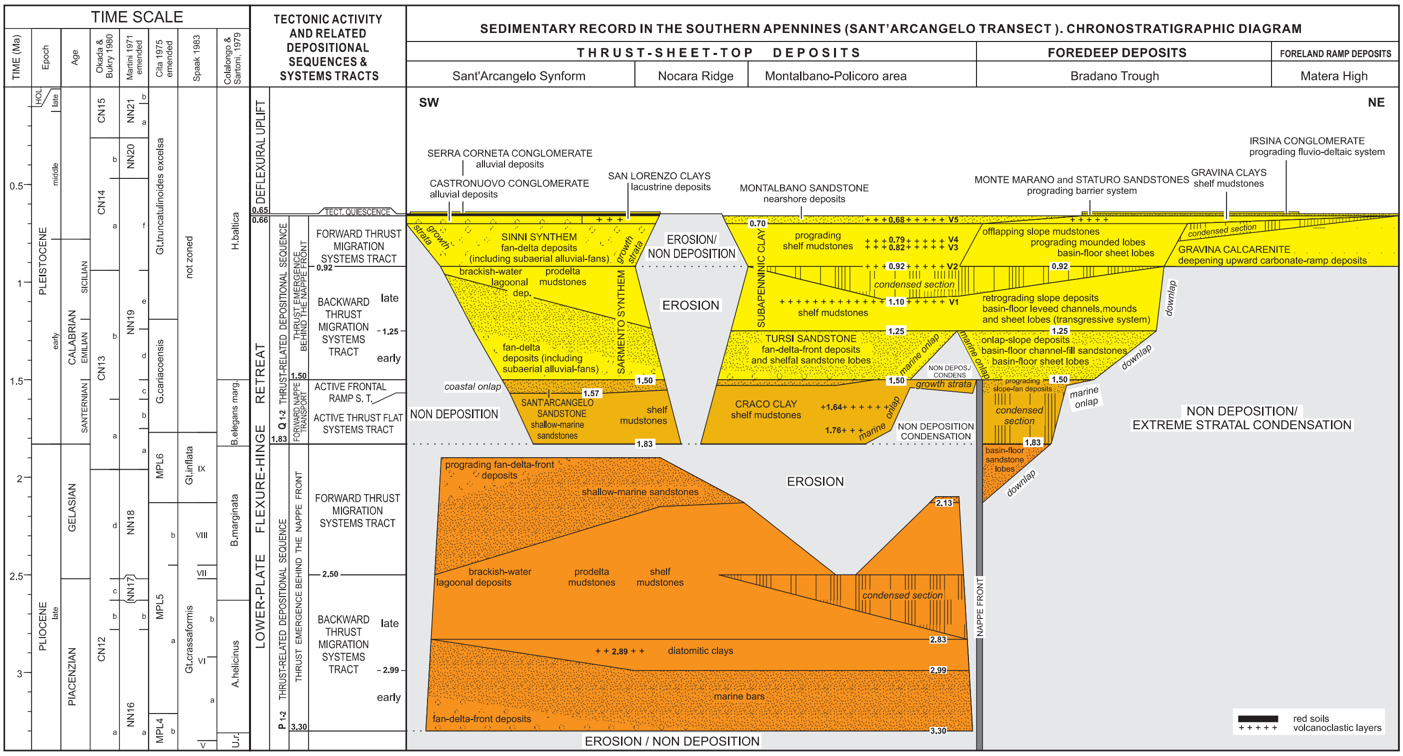

Fig. 9 - Chronostratigraphic diagram showing the principal characteristics of the Plio-Pleistocene thrust-sheet-top, foredeep and foreland deposits in the Sant'Arcangelo synform and in the southern part of the Bradano Trough, about 90 kilometers south of the trace of the CROP-04 line (modified after Patacca & Scandone, 2001).

– Diagramma cronostratigrafico mostrante le principali caratteristiche dei depositi plio-pleistocenici della catena, del bacino di avanfossa e dell'avampaese nella sinforme di Sant'Arcangelo e nella parte meridionale della Fossa Bradanica, circa 90 chilometri a sud della traccia del profilo CROP-04 (modificato da Patacca & Scandone, 2001).

in turn overlain by prograding fluvio-deltaic conglomerates (Irsina Conglomerate).

As concerns evidence of shortening, we have already spoken about the 12-15 kilometers of forward transport of the Apennine nappes after the deposition of the *Gt. inflata* turbidites. The analysis of the Q_{1-2} foredeep deposits clarifies that the transport took place in a time span ranging from 1.87 Ma to 1.50 Ma and that during the 1.83-1.57 Ma time interval the tectonic wedge advanced over a long thrust flat while in the 1.57-1.50 Ma interval a steep frontal ramp was active in correspondence to the tip of the allochthonous sheets.

2.4. Q_{1-2} THRUST-SHEET-TOP DEPOSITS

Thrust-sheet-top deposits referable to the Q_{1-2} sequence are scarcely represented in the area crossed by the CROP-04 seismic line. A very good record of Pleistocene sedimentation on top of the Apennine nappes is preserved in the Sant'Arcangelo synform where a thick sequence of lower Pleistocene thrust-sheet-top deposits is magnificently exposed (see chronostratigraphic diagram of fig. 9). The lower portion of the sequence is represented by a relatively isopachous sheet of lower Pleistocene (Santernian) open-shelf foraminiferal mudstones (Craco Clay Unit) grading upwards into shallow-water sandstones characterized by internal cross-lamination and bioturbation (Sant'Arcangelo Sandstone). Moving basinward, the Craco Clay-Sant'Arcangelo Sandstone couple (1.83-1.50 Ma interval in fig. 9) is laterally replaced by more distal muddy deposits that drape the allochthonous sheets as far as the Apennine nappe front. In the Sant'Arcangelo synform, the Santernian shelfal deposits, together with upper Pliocene thrust-sheet-top deposits of the P_{1-2} sequence, are disconformably overlain by alluvial conglomerates and coarse-clastic paralic deposits referable to a retrograding fandelta system (Sarmento Synthem, 1.50-0.92 Ma interval in fig. 9). East of the Sant'Arcangelo depression, the coarse-clastic deposits are laterally replaced by fandelta-front and shelfal sand lobes known in the geological literature as the Tursi Sandstone. Along the outer margin of the mountain chain, the Tursi sandstones are conformably overlain by open-shelf mudstones (Sub-Apenninic Clay unit). In the Sant'Arcangelo synform, this muddy unit is laterally replaced by prodelta/lagoon deposits representing the backstepping and deepening-upward upper portion of the Sarmento Synthem that recorded a maximum flooding episode at 0.92 Ma. The same maximum-flooding event has been recognized in the area crossed by the CROP-04 line (see fig. 6). The prodelta mudstones of the Sarmento Synthem, together with older lower Pleistocene thrust-sheet-top deposits, are stratigraphically overlain with a remarkable angular unconformity by a thick wedge of alluvial conglomerates and coarse-grained fandelta deposits (Sinni Synthem in fig. 9). Growth strata with internal progressive unconformities widespread in the lower portion of the Sinni Synthem along the eastern margin of the Sant'Arcangelo basin are the surface expression of a forward thrust propagation causing the growth of an anti-

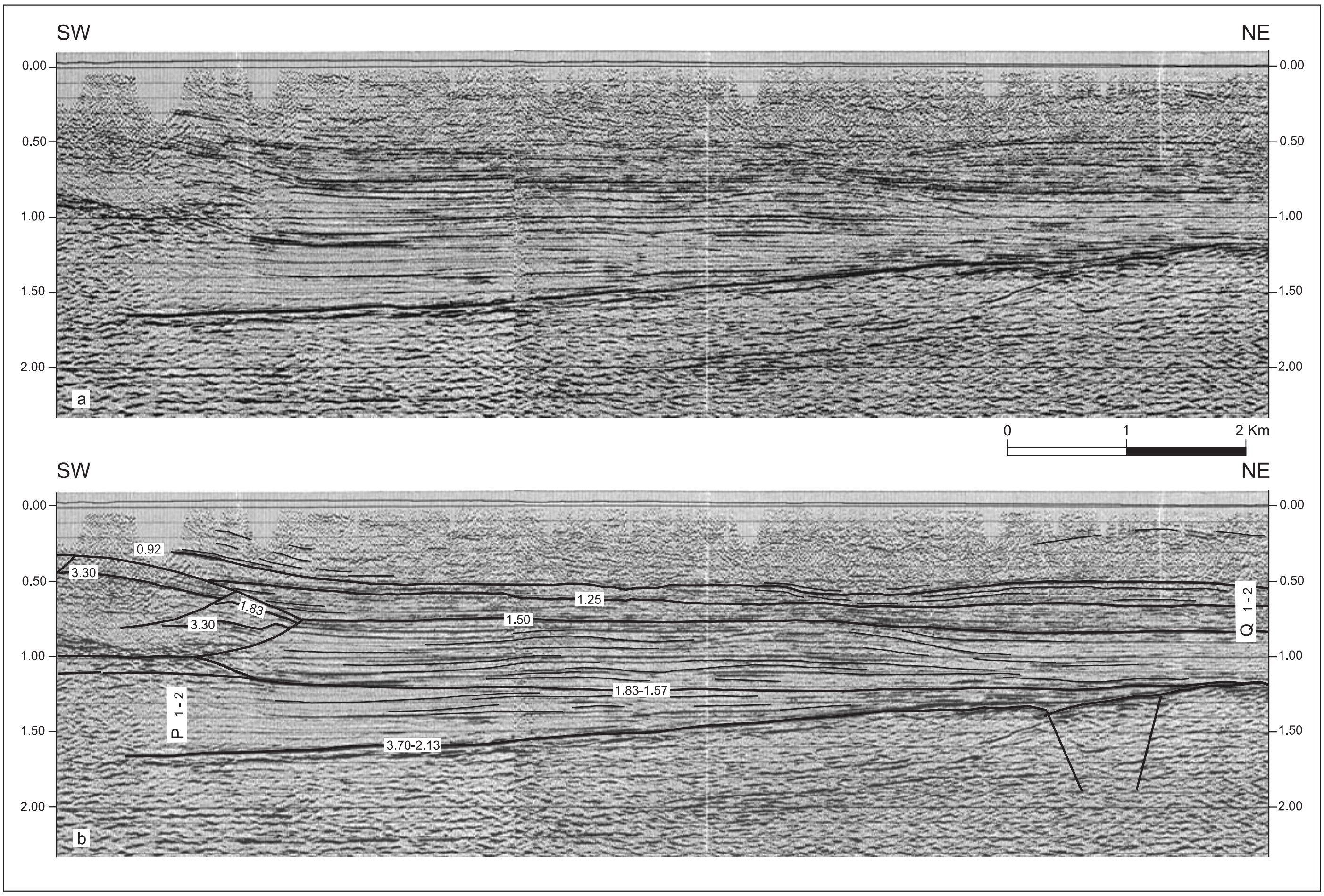

Fig. 10 - Uninterpreted (*a*) and interpreted *b*) seismic profile across the front of the Apennine nappes showing some details of the foredeep configuration in the southern part of the Bradano Trough. Note that the stratal architecture of the Plio-Pleistocene foredeep deposits in this area does not basically differ from the architecture shown in fig. 7 relative to the area crossed by the CROP-04 line.
– *Profilo sismico non interpretato* (a) *ed interpretato* (b) *attraverso il fronte della catena mostrante alcuni dettagli della configurazione del bacino di avanfossa nella parte meridionale della Fossa Bradanica. L'assetto geometrico complessivo non differisce sostanzialmente da quello mostrato in fig. 7 nell'area attraversata dal profilo CROP-04.*

cline in the buried Apulia carbonates in correspondence to the Nocara Ridge (Tursi-Rotondella thrust system in fig. 2). Growth folds and progressive unconformities evidencing tilt movements toward NE are developed in the upper portion of the Sinni Synthem along the south-western margin of the basin. These tectonic features have been attributed to occasional out-of-sequence reactivations of thrust surfaces causing breaches in the Apulia-carbonate duplex system at the foot of the thrust-and-fold cascade forming the north-eastern flank of the Monte Alpi oil-field structural high. Younger Pleistocene deposits in the Sant'Arcangelo synform are represented by braid-plain conglomerates (Castronuovo Conglomerate) interfingering with lacustrine deposits (San Lorenzo Clay) and finally by alluvial conglomerates (Serra Corneta Conglomerate) possibly corresponding to the Irsina Conglomerate in the Bradano Trough.

With the exception of the Craco Clay-Sant'Arcangelo Sandstone couple, which is the equivalent of the 1.83-1.57 Ma condensed section plus the 1.57-1.50 Ma syn-ramp clastic wedge in the foredeep basin, the greatest part of the Q_{1-2} thrust-sheet-top deposits was laid down on a passive shelf facing the foredeep basin and consequently does not provide direct information on tectonic shortening during sedimentation. Only in the Sinni Synthem gives evidence of tectonic shortening, manifested by intraformational angular unconformities and thrust-propagation folds. The areal distribution of the synsedimentary compressional features and the age of the syntectonic deposits allow to identify the geological objects that were undergoing deformation in the subsurface (Tempa Rossa oil field and Tursi-Rotondella thrust system, generated by forward thrust propagation; front of the lower Pleistocene duplex system, reactivated by out-of-sequence thrusts) and on the time in which this deformation took place (0.92-0.70 Ma, see fig. 9). The structural balance of the Tursi-Rotondella thrust system allowed us to calculate a minimum shortening of 5-6 Km during the 0.92-0.70 Ma time span (Patacca & Scandone, 2001).

3. DATA SUMMARY AND FINAL REMARKS

The internal architecture of the Southern Apennines consists of a duplex system mostly made up of shallow-water Mesozoic-Tertiary carbonates («Inner Apulia Plat-

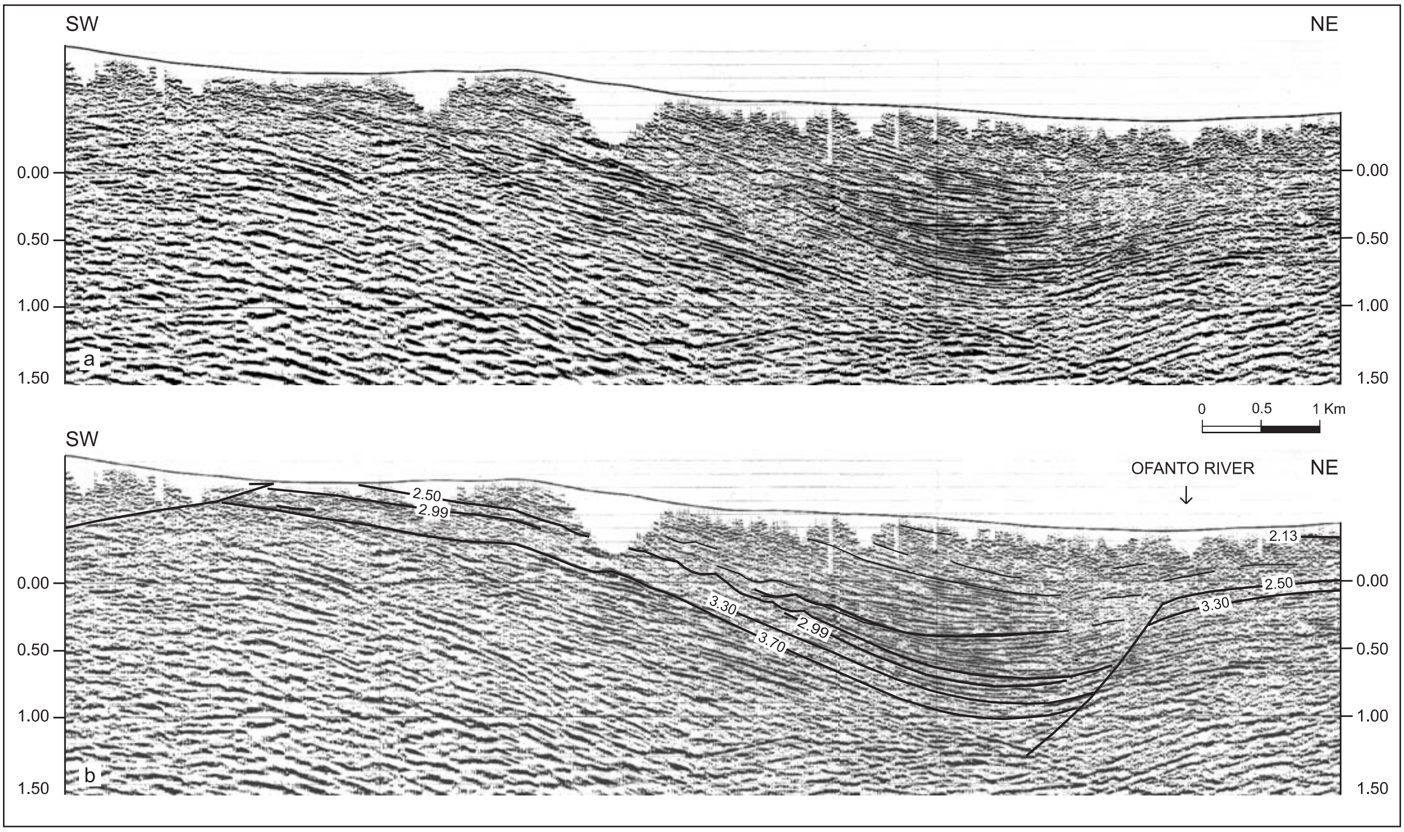

Fig. 11 - Uninterpreted (*a*) and interpreted (*b*) seismic profile across the Pliocene deposits filling the Ofanto synform (compare with Roure *et alii*, 1991 and with Hippolyte *et alii*, 1994b). The backstepping concave-upward reflectors manifest the retrogradational character of the 2.50-2.13 systems tract, well expressed also in surface sections. The ages of the surfaces bounding the systems tracts derive from the chronostratigraphic diagram of fig. 6.

– *Profilo sismico non interpretato* (a) *ed interpretato* (b) *attraverso i depositi pliocenici che riempiono la sinforme dell'Ofanto (v. anche* Roure et alii, *1991 e* Hippolyte et alii, *1994b). I riflettori concavi verso l'alto dell'intervallo 2.50-2.13 Ma mostrano il carattere retrogradazionale di questo tratto di sistema, ben espresso anche in sezioni di superficie. Le età delle superfici che delimitano i tratti di sistema derivano da diagramma cronostratigrafico di fig. 6.*

form» of petroleum geologists) covered by a thick pile of NE-verging rootless nappes. The buried Apulia carbonates are stratigraphically overlain by Plio-Pleistocene foredeep siliciclastic deposits that become progressively younger moving from SW towards NE: early Pliocene, *Gt. margaritae/Gt. puncticulata* concurrent range zone, in the south-west (Monte Alpi oil field and, more in general, High Agri Valley area); early-middle Pliocene, *Gt. puncticulata* and *Gt. crassaformis p.p*. zones in correspondence to the Tempa Rossa oil field, as well as in correspondence to the Sant'Arcangelo synform and the Tursi-Rotondella structural High; middle-upper Pliocene to Pleistocene, *Gt. crassaformis p.p*., *Gt. inflata* and *G. cariacoensis p.p*. zones, in the north-east (outer margin of the Apennines and Bradano Trough). The age of these deposits establishes the timing of the forward nappe transport.

As concerns the timing of the deformation and the amount of shortening of the Apulia-carbonate duplex system, important indications have been provided both from the foredeep deposits and from the thrust-sheet-top deposits.

40 kilometers of forward nappe displacement represent the minimum shortening within the Apulia carbonates between the early Pliocene and the early Pleistocene. This value derives from the distance between the present nappe front and the most internal (south-western) areas in which the allochthonous sheets overlie Pliocene foredeep deposits referable to the *Gt. puncticulata* and *Gt. crassaformis* zones. These 40 kilometers do not include the additional shortening associated to imbricate structures developed along the outer margin of the Apennines in which the lower Pleistocene Craco Clay is involved (see fig. 2). No structural balance has been carried out on these imbricates.

40-50 kilometers of displacement represent the minimum shortening in the Apulia carbonates associated to the breaching of the duplex system and to the growth of antiformal stacks in the Apennine nappes during the late Pliocene. These 40-50 kilometers represent the minimum value obtained by the most conservative structural balance of the San Fele structure.

A slip of 5-6 kilometers represents the minimum shortening related to the growth of the outer thrust system during the last forward thrust propagation in the Apulia carbonates.

In conclusion, 85-95 kilometers represent the minimum shortening related to the stacking the Apulia-carbonate duplex system after the arrival of the Apennine nappes in the Monte Alpi domain and to the growth of antiformal stacks in the Apennine nappes during the late Pliocene. Such a value dramatically conflicts with the modest shortening required by thick-skin structural

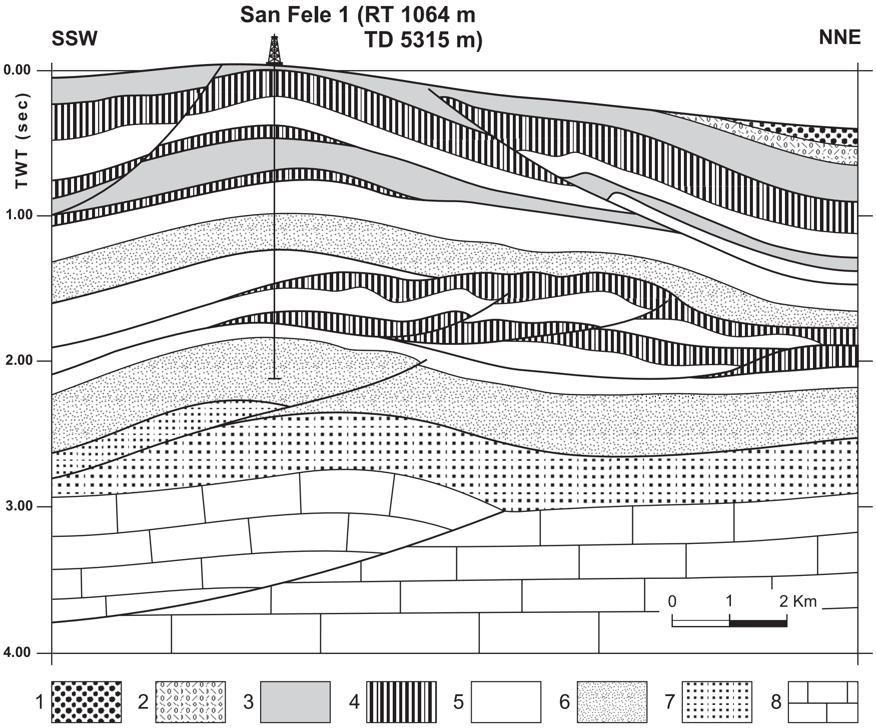

Fig. 12 - Internal geometry of the San Fele antiformal stack based on the interpretation of a seismic line cutting across the structure tied to the stratigraphic log of the San Fele 1 well. Depths in seconds TWT. 1) Thrust-sheet-top deposits of the P_{1-2} depositional sequence; 2) Upper Messinian-Lower Pliocene thrust-sheet-top deposits (Calaggio Chaotic Complex); 3) Sannio Unit. 4-6) Lagonegro Unit II: 4) Galestri Formation (lower Cretaceous); 5) Scisti Silicei and Calcari con Selce Formations (upper Jurassic-upper Triassic); 6) Monte Facito Formation (middle Triassic); 7) Pliocene deposits of the P_{1-2} depositional sequence overlying the buried Apulia-carbonate duplex system; 8) Mesozoic-Tertiary Apulia carbonates.
– Assetto geometrico dell'antiformal stack di San Fele basato sull'interpretazione di una linea sismica commerciale che taglia trasversalmente la struttura in corrispondenza del pozzo San Fele 1. Profondità in secondi, tempi doppi. 1) Depositi discordanti della sequenza deposizionale P_{1-2}; 2) Depositi del Messiniano superiore-Pliocene inferiore (Complesso Caotico del Torrente Calaggio); 3) Unità Sannio; 4-6) Unità Lagonegrese II; 4) Formazione dei Galestri (Cretaceo inferiore); 5) Formazione degli Scisti Silicei e Formazione dei Calcari con Selce (Giurassico superiore-Trias superiore); 6) Formazione di Monte Facito (Trias medio); 7) Depositi pliocenici della sequenza P_{1-2} che ricoprono il sistema duplex sepolto di carbonati apuli; 8) Carbonati mesozoico-terziari apuli.

reconstructions that postulate an important role of the crystalline basement in the deep structure of the Southern Apennine thrust belt.

ACKNOWLEDGMENTS

The authors thank Agip, Edison Gas, Enterprise and Texaco for the access to numerous confidential data. Figures and plates presented in this paper have been prepared by Barbara Taccini.

REFERENCES

BALDUZZI A., CASNEDI R., CRESCENTI U., MOSTARDINI F. & TONNA M. (1982a) - *Il Plio Pleistocene del sottosuolo del Bacino Lucano (Avanfossa Appenninica)*. Geologica Rom., **21**, 89-111.

BALDUZZI A., CASNEDI R., CRESCENTI U. & TONNA M. (1982b) - *Il Plio-Pleistocene del sottosuolo del Bacino Pugliese (Avanfossa Appenninica)*. Geologica Rom., **21**, 1-28.

CANDE S.C. & KENT D.V. (1995) - *Revised calibration of the geomagnetic polarity time scale for the Late-Cretaceous and Cenozoic*. Journ. Geophys. Research, **100** (B4), 6093-6095.

CASERO P., ROURE F., ENDIGNOUX L., MORETTI I., MÜLLER C., SAGE L. & VIALLY R. (1988) - *Neogene geodynamic evolution of the Southern Apennines*. Mem. Soc. Geol. Ital., **41**, 109-120.

CASERO P., ROURE F. & VIALLY R. (1991) - *Tectonic framework and petroleum potential of the southern Apennines*. In SPENCER A.M. Ed., Generation, accumulation, and production of Europe's hydrocarbons, Spec. Publ. European Assoc. Petroleum Geosci., **1**, 381-387.

CELLO G. & MAZZOLI S. (1999) - *Apennine tectonics in southern Italy: a review*. Journ. Geodynamics, **27**, 191-211.

CELLO G., PALTRINIERI W. & TORTORICI L. (1987) - *Caratterizzazione strutturale delle zone esterne dell'Appennino molisano*. Mem. Soc. Geol. Ital., **38**, 155-161.

CINQUE A., PATACCA E., SCANDONE P. & TOZZI M. (1993) - *Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures*. Annali di Geofisica, **36**, 249-260.

CITA M.B. (1975) - *Planktonic foraminiferal biozonation of the mediterranean Pliocene deep sea record. A revision*. Riv. Ital. Paleont Stratigr., **81**, 527-544.

COLALONGO M.L. & SARTONI S. (1979) - *Schema biostratigrafico per il Pliocene e il basso Pleistocene in Italia*. Note Preliminari alla Carta Neotettonica d'Italia, CNR Progetto Finalizzato Geodinamica, **251**, 645-654.

CRESCENTI U. (1975) - *Sul substrato pre-pliocenico dell'avanfossa appenninica dalle Marche allo Ionio*. Boll. Soc. Geol. Ital., **94**, 583-634.

D'ANDREA S., PASI R., BERTOZZI G. & DATTILO P. (1993) - *Geological model, advanced methods help unlock oil in Italy's Apennines*. Oil and Gas Journ., Aug. 1993, 53-57.

DOGLIONI C., HARABAGLIA P., MARTINELLI G., MONGELLI F. & ZITO G. (1996) - *A geodynamic model of the Southern Apennines accretionary prism*. Terra Nova, **8**, 540-547.

ENDIGNOUX L., MORETTI I. & ROURE F. (1989) - *Forward modeling of the southern Apennines*. Tectonics, **8**, 1095-1104.

HIPPOLYTE J.C., ANGELIER J. & ROURE F. (1994a) - *A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy)*. Tectonophysics, **230**, 199-210.

HIPPOLYTE J.C., ANGELIER J., ROURE F. & CASERO P. (1994b) - *Piggyback basin development and thrust belt evolution: structural and palaeostress analyses of Plio-Quaternary basins in the Southern Apennines*. Journ. Structur. Geol., **16**, 159-173.

LA BELLA G., BERTELLI L. & SAVINI L. (1996) - *Monte Alpi 3D, a challenging 3D survey in the Apenninic Range, Southern Italy*. First Break, **14** (7), 285-294.

LENTINI F., CARBONE S., DI STEFANO A. & GUARNIERI P. (2002) - *Stratigraphical and structural constraints in the Lucanian Apennines (southern Italy): tools for reconstructing the geological evolution*. Journ. Geodynamics, **34**, 141-158.

LENTINI F., CATALANO S. & CARBONE S. (1996) - *The external thrust system in Southern Italy: a target for petroleum exploration*. Petroleum Geosci., **2**, 333-342.

MARTINI E. (1971) - *Standard Tertiary and Quaternary calcareous nannoplankton zonation*. In Farinacci A. Ed., Proc. 2nd Planktonic Conference (Roma, 1970), Ed. Tecnoscienza, **2**, 739-777.

MATTAVELLI L., PIERI M. & GROPPI G. (1993) - *Petroleum exploration in Italy: a review*. Marine Petroleum Geol., **10**, 410-425.

MAZZOLI S., BARKHAM S., CELLO G., GAMBINI R., MATTIONI L., SHINER P. & TONDI E. (2001) - *Reconstruction of continental margin architecture deformed by the contraction of the Lagonegro Basin, southern Apennines, Italy*. Journ. Geol. Soc. London, **158**, 309-319.

MAZZOLI S., CORRADO S., DE DONATIS M., SCROCCA D., BUTLER R.W.H., DI BUCCI D., NASO G., NICOLAI C. & ZUCCONI V. (2000) - *Time and space variability of «thin skinned» and «thick-skinned» thrust tectonics in the Apennines (Italy)*. Rend. Fis. Accad. Lincei, **11** (9), 5-39.

MAZZOTTI A., STUCCHI E., FRADELIZIO G.L., ZANZI L. & SCANDONE P. (2000) - *Seismic exploration in complex terrains: a processing experience in the Southern Apennines*. Geophysics, **65** (5), 1402-1417.

MENARDI-NOGUERA A. & REA G. (2000) - *Deep structure of the Campanian-Lucanian Arc (Southern Apennine, Italy)*. Tectonophysics, **324**, 239-265.

MONACO C., TORTORICI L. & PALTRINIERI W. (1998) - *Structural evolution of the Lucanian Apennines, southern Italy*. Journ. Struct. Geol., **20**, 617-638.

MOSTARDINI F. & MERLINI S. (1986) - *Appennino centro-meridionale. Sezioni geologiche e proposta di modello strutturale*. Mem. Soc. Geol. Ital., **35**, 177-202.

OKADA H. & BUKRY D. 1980 - *Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (BUKRY, 1973; 1975)*. Marine Micropaleont., **5**, 321-325.

PATACCA E. & SCANDONE P. (1989) - P*ost-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab*. In BORIANI A., BONAFEDE M., PICCARDO G.B. & VAI G.B. Eds., The lithosphere in Italy. Advances in Earth Science Research. It. Nat. Comm. Int. Lith. Progr., Mid-term Conf. (Rome, 5-6 May 1987), Atti Conv. Lincei, **80**, 157-176.

PATACCA E. & SCANDONE P. (2001) - *Late thrust propagation and sedimentary response in the thrust belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene)*. In VAI G.B. & MARTINI I.P. Eds., Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publ., 401-440.

PATACCA E., SCANDONE P., BELLATALLA M., PERILLI N. & SANTINI U. (1992) - *La zona di giunzione tra l'arco appenninico settentrionale e l'arco appenninico meridionale nell'Abruzzo e nel Molise*. In TOZZI M., CAVINATO G.P. & PAROTTO M. Eds., Studi preliminari all'acquisizione dati del profilo CROP-11 Civitavecchia-Vasto, AGIP-CNR-ENEL. Studi Geol. Camerti, Vol. spec. 1991-2, 417-441.

PATACCA E., SCANDONE P. & TOZZI M. (2000) - *Il Profilo CROP-04*. Protecta, Dossier: Italia Profonda, **10-12**, 49-52.

RIO D., RAFFI I. & VILLA G. (1990) - *Pliocene-Pleistocene calcareous nannofossil distribution patterns in the western Mediterranean*. Proc. ODP, Sci. Results, 107: College Station, TX (Ocean Drilling Program), 513-533.

ROURE F., CASERO P. & VIALLY R. (1991) - *Growth processes and melange formation in the southern Apennines accretionary wedge*. Earth and Planet. Sci. Lett., **102**, 395-412.

ROURE F. & SASSI W. (1995) - *Kinematics of deformation and petroleum system appraisal in Neogene foreland fold-and-thrust belts*. Petr. Geosci., **1**, 253-269.

SPAAK P. (1983) - *Accuracy in correlation and ecological aspects of the planktonic foraminiferal zonation of the mediterranean Pliocene*. Utrecht Micropaleont. Bull., **28**, 158 pp.

Received 20 Maj 2002; revised version accepted 12 March 2004; last proofs received 11 December 2006.