THE PLIO-PLEISTOCENE THRUST BELT - FOREDEEP SYSTEM IN THE SOUTHERN APENNINES AND SICILY (ITALY)

PATACCA E. & SCANDONE P.
Dipartimento di Scienze della Terra - Università di Pisa
Via Santa Maria, 53. 56126 PISA. Italy

ABSTRACT: The upper Pliocene-lower Pleistocene terrigenous deposits of the Southern Apennines and Sicily have significantly contributed to the understanding of the primary relationships between tectonics and sedimentation in an active thrust belt-foredeep system. An integrated stratigraphic and structural investigation allowed the identification of thrust-related depositional sequences with systems tracts defined by specific stratigraphic signatures recording the complex migration path of the active thrusts in the mountain chain.

In the foredeep basin, where thrust-related depositional sequences are better preserved, five basic depositional units have been distinguished:

1. Condensed section, underlying at the scale of the entire basin the major truncation surface at the base of the sequence. The deposition of this unit, indicative of a strongly reduced sediment supply, corresponds to a moment of forward transport of the allochthonous sheets over a long thrust flat (active-thrust-flat systems tract);
2. Syn-ramp wedge, made up of a prograding slope-fan system constituted of a thick body of gravity-driven deposits truncated upsection by the active frontal ramp of the allochthonous sheets (active-frontal-ramp systems tract).
3. Onlap-slope system, represented by retrograding basinal deposits onlapping the edge of the allochthonous sheets and featuring a backstepping passive margin (early stage of the backward-thrust-migration systems tract).
4. Transgressive system, made up of basinal deposits matching the maximum marine flooding of the tectonic wedge (late stage of the backward-thrust-migration systems tract);
5. Prograding shelf-margin system laterally grading into a prograding system of basin-floor turbidites (forward-thrust-migration systems tract).

In the foreland areas, these depositional units grade into more or less condensed pelagic deposits, with the exception of unit 5 that may laterally pass towards the foreland into a shallower, flexure-related transgressive system.

On top of the allochthonous sheets, both the active-thrust-flat systems tract and the active-frontal-ramp systems tract are represented by shallowing-upward shelfal deposits (nappe sheet drape). In an early stage of the backward-thrust-migration systems tract, a retrograding fandelta/shelf system represents in the mountain chain the counterpart of the onlap-slope system. In a late stage, the retrograding fandelta/shelf system is overlain by a muddier transgressive system recording the progressive flooding of the tectonic wedge. The forward-thrust-migration systems tract is commonly represented by a prograding shoal-water delta/shelf system. Two different depositional settings, depending on the trajectories of the active thrusts in the mountain chain, have been recognized: mobile piggyback basin, developed in the hangingwall of an active thrust and flanked toward the foreland by an active ridge; wide passive shelf developed in the footwall of an active thrust, open toward the foredeep basin.

INTRODUCTION

Around the end of the Paleogene, when continent-continent collision had already taken place in the Alps, important rollback processes began to develop along the subducting western margin of Adria. The rapid flexure-hinge retreat of the lower plate, largely exceeding the rate of the Africa-Europe convergence, determined the opening of the Western Mediterranean and Tyrrhenian back-arc basins and the simultaneous forward (hinterland-to-foreland) migration of the thrust belt-foredeep system (see among many authors, MALINVERNO & RYAN, 1986; CHANNEL & MARESCHAL, 1989; PATACCA & SCANDONE, 1989; PATACCA *ET ALII*, 1990; DOGLIONI, 1991; KELLER *et alii*, 1994). The foredeep migration has been well recorded in the Apennines by the diachronism of the siliciclastic flysch deposits becoming progressively younger moving from the internal (western) paleogeographic domains (Tuscan domains in the Northern Apennines, Silicide and Campania-Lucania domains in the Southern Apennines) toward the present-day stable foreland. During subduction, deep-seated lithospheric tear faults (free boundaries *sensu* ROYDEN *et alii*, 1987) allowed slab segmentation and accommodation of different amounts of slab sinking across adjacent segments of the same plate margin. Differential slab sinking was responsible for differential extension in the back-arc basins and differential shortening in the mountain chain. In addition, the non-cylindrical flexure-hinge retreat of the subducting slab was accommodated at shallow depths by large-scale distortions of the orogenic belt simulating orocline features *sensu* CAREY (1958). The present structural configuration of the Apennine-Calabrian Arc-Sicilian Maghrebide mountain system into two major orogenic arcs (Northern Apenninic Arc and Southern Apenninic Arc, see fig. 1) has been interpreted as the final result of a differential passive sinking of the foreland lithosphere during the Africa-Europe convergence in Neogene and Quaternary times (PATACCA & SCANDONE 1989).

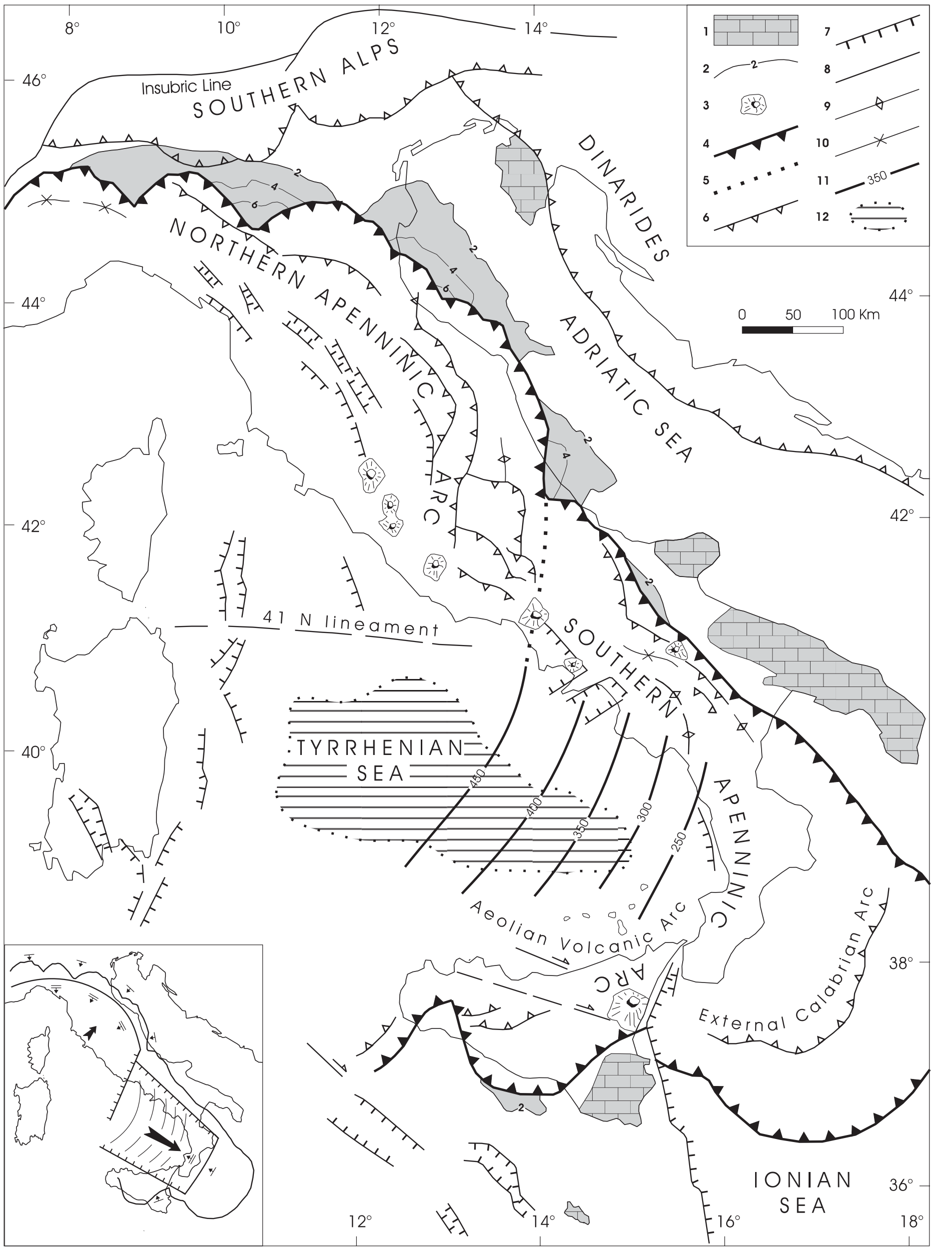


Fig. 1 - First-order structural features of the Italian Peninsula and surrounding areas showing the partition of the Apennine mountain chain into two major arcs: the Northern Apenninic Arc and the Southern Apenninic Arc (after PATACCA *et alii*, 1993 with slight modifications). In lower left, present-day differential sinking of the foreland lithosphere in the Northern and Southern Apenninic arcs. Large arrows indicate the directions of the orogenic transport; the length of the arrows is proportional to the flexure-hinge retreat of the sinking plate. Small arrows indicate the dip of the lower plate.

1 Pre-Pliocene carbonates and subordinate volcanites in the foreland region. 2 Isobaths (in kilometres) of the base of the Plio-Pleistocene deposits in the foredeep basins. 3 Major subaerial Quaternary volcanoes. 4 Quaternary thrust front in the Apennines, Calabrian Arc and Sicily. 5 Boundary between the Northern Apenninic Arc and the Southern Apenninic Arc (Majella-Roccamonfina Line *Auct.*). 6 Major thrusts in the Southern Alps, Dinarides, Apennines, Calabrian Arc and Sicily. 7 Normal faults. 8 High-angle faults, mostly strike-slip faults. 9 Anticline axis. 10 Syncline axis. 11 Wadati-Benioff zone in the Southern Tyrrhenian region (depths in kilometres). 12 Tyrrhenian areas with positive Bouguer gravity anomalies exceeding 200 mgals, floored by oceanic crust or thinned continental crust.

In the Southern Apennines and Sicily, imbricate-fan configurations have irregularly alternated with duplex configurations through Neogene and Quaternary times. At present, the thrust-belt structural configuration is characterized in both regions by huge duplex systems developed at the regional scale. In the Calabrian Arc, on the contrary, duplex configuration has represented the rule, at least from Tortonian times. The two different architectures of the mountain chain determined by imbricate fans and by duplex systems, are reflected by two different configurations of the foredeep basins: wide and deep foredeep basins in front of imbricate fans, narrow and shallower foredeep basins in front of duplex systems. Figure 2, schematically showing the two thrust belt-foredeep basic configurations (upper right side of fig. 2), provides two simplified sections (location in the upper left side of fig. 2) across the Southern Apennines in which the second type of foredeep configuration is well represented.

The Plio-Pleistocene thrust belt-foredeep system in the Southern Apennines has been investigated by PATACCA & SCANDONE (2001). In this area, the rich subsurface information derived from the petroleum exploration (CRESCENTI, 1975; BALDUZZI *et alii*, 1982 A, B; MOSTARDINI & MERLINI, 1986; PIERI & MATTAVELLI, 1986: CASNEDI, 1988 A, B; SELLA *et alii*, 1988; MATTAVELLI & NOVELLI, 1990; CASERO *et alii*, 1991; D'ANDREA *et alii*, 1993; MATTAVELLI *et alii*, 1993; ROURE & SASSI, 1995; ANELLI *et alii*, 1996; LA BELLA *et alii*, 1996; HOLTON, 1999; PIERI, 2001), together with the existence of numerous natural sections along the outer (eastern) margin of the mountain chain, allowed a detailed analysis of the foredeep siliciclastic deposits and a reliable correlation between foredeep deposits and coeval thrust-top deposits overlying the allochthonous sheets. The study, carried out in a region in which the original thrust belt-foredeep configuration is perfectly preserved, has revealed close relations between tectonic activity and sedimentation, so that several thrust-controlled depositional sequences have been identified (see PATACCA & SCANDONE, 2001).

The type of investigation carried out in the Southern Apennines was extended to Sicily, where structural style of the mountain chain and overall depositional setting of the Plio-Pleistocene thrust belt-foredeep system do not basically differ from the Apennines.

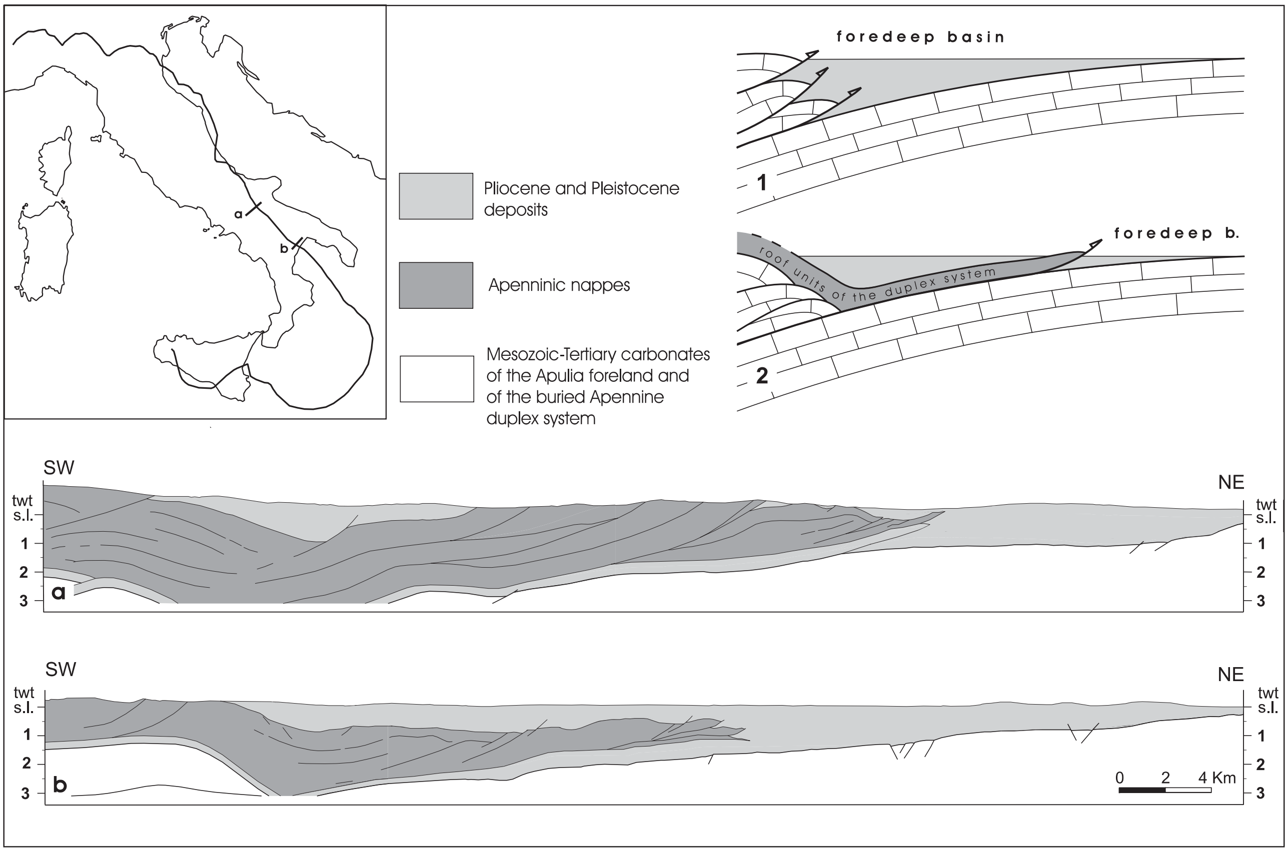


Fig. 2a, b - Simplified cross-sections showing the overall geometry of the thrust belt-foredeep-foreland system and the distribution of the Pliocene to Pleistocene deposits in the Southern Apennines (location in the upper left box; thickness in times, twt). The box in the upper right side of the picture schematizes the foredeep basin configurations in front of an imbricate fan (1) and in front of a duplex system (2). Modified after PATACCA & SCANDONE (2001).

Also in this region, the results of the surface investigation have been integrated with a great deal of subsurface information derived from the extensive petroleum exploration (ROCCO 1959; COGGI 1968; VERCELLINO & RIGO, 1970; SCHARMM & LIVRAGA, 1984; PIERI & MATTAVELLI, 1986; SESTINI & FLORES, 1986; ANTONELLI et alii, 1988; MATTAVELLI & NOVELLI, 1990; RONCO *et alii*, 1990; ANELLI *et alii*, 1996; PIERI, 2001). The wide range of data allowed us to identify and typify several depositional systems and to improve their correlation across the different tectonic settings. Our subsurface analysis is based on numerous offshore seismic lines tied to several commercial wells, biostratigraphically constrained by the detailed micropaleontological analyses carried out on the ODP 963 holes and on the Pina 1 well (DI STEFANO *et alii*, 1993; SHIPBOARD SCIENTIFIC PARTY, 1996; DI STEFANO, 1998).

In this paper we will integrate the general results obtained in the Southern Apennines (PATACCA & SCANDONE, 2001) with the new case history derived from Sicily with the aim of reaching a more detailed understanding of the relationships between thrust activity in the mountain chain and sedimentary response in the adjacent foredeep basin and on top of the allochthonous sheets.

GEOLOGICAL OUTLINES OF THE SOUTHERN APENNINIC ARC

Figure 3 is a simplified structural-kinematic map of the Southern Apenninic Arc with the tectonic units grouped according to the age of incorporation in the thrust belt. The ages become progressively younger moving from west to the east and from the uppermost tectonic units to the lowermost ones. The same trend is shown by the temporal distribution of the siliciclastic flysch deposits that testify to a forward migration of the foredeep basin according to a progressive flexure-hinge retreat of the foreland plate.

In the Southern Apenninic Arc, duplex configuration represents the most common structural feature. Consequently, Plio-Pleistocene thrust-top deposits are widely represented in the whole area whilst the coeval foredeep deposits, buried beneath the roof units of the duplex system, are usually lacking on the surface.

The Southern Apennines structurally consist of a buried carbonate duplex system tectonically overlain by a thick pile of NE-verging rootless nappes (MOSTARDINI & MERLINI 1986; CELLO *et alii* 1987; CASERO *et alii*, 1988, 1991; PATACCA & SCANDONE 1989, 2001, 2004A, B; PATACCA *et alii* 1992; ROURE *et alii*. 1991 MATTAVELLI *et alii* 1993; ROURE & SASSI 1995; LENTINI *et alii* 1996, 2002; MONACO *et alii* 1998; CELLO & MAZZOLI 1999: MENARDI NOGUERA & REA 2000).

The buried duplex system is made up of imbricates of Mesozoic-Tertiary shallow-water carbonates detached from the western margin of the Apulia platform. This system forms the backbone of the mountain chain from Southern Abruzzi to Northern Calabria. Along the axis of the chain, the top of the Apulia carbonates lies at depths ranging from 1500 to more than 6000 metres below sea level. On the surface, Mesozoic-Tertiary carbonates belonging to the Apulia-carbonate duplex system crop out only in Basilicata (Monte Alpi tectonic window) where they rise abruptly to about 2000 m above sea level. The Mesozoic-Tertiary carbonates of the buried duplex system represent in the Southern Apennines the main target of oil research (see CASERO *et alii*, 1991; LA BELLA *et alii*, 1996).

The autochthonous portion of the Apulia platform crops out in the Gargano-Murge-Salento foreland. Between this area and the buried leading edge of the duplex system, the flexured Apulia carbonates dip beneath the Apennine nappes giving origin to a structural depression. This depression represents the youngest foredeep basin of the Southern Apennines, active in late Pliocene and Pleistocene times, the southern portion of which has been called in the geological literature the Bradano Trough.

The allochthonous sheets lying above the Apulia-carbonate duplex system are constituted of Mesozoic-Tertiary sedimentary sequences derived from platform-and-basin paleogeographic domains.

Tectonic shortening and extensive nappe stacking took place mainly in Miocene times. Subsequently, during the early Pliocene, the entire pile of nappes overthrust the Apulia carbonates before they were reached by the compressional deformation. In middle-late Pliocene times, finally, also the Apulia platform was affected by compressional deformation. The tectonic shortening produced duplexing in the Apulia carbonates and considerable forward displacement of the allochthonous sheets. Duplex-breaching processes alternating with the forward nappe transport caused re-imbrications of the allochthonous sheets and generation of huge 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 the lower plate and shortening in the mountain chain suddenly ceased and the entire region began to undergo generalized uplift processes (CINQUE *et alii*., 1993; HIPPOLYTE *et alii*, 1994a).

The Calabrian Arc, i.e. the segment that links the NW-SE trending Southern Apennines with the W-E trending Sicilian Maghrebides, is characterized by crystalline-basement-derived and ocean-floor-derived rootless nappes overlying the highest Apennine and Sicilian-Maghrebian units (AMODIO MORELLI *et alii*, 1976; SCANDONE, 1982; BONARDI *et alii*, 2001 and references therein). The boundaries of the Calabrian Arc have been conventionally identified with the Sangineto Line in the north and with the Taormina Line in the south.

Both features likely represent the emergence of lateral/oblique ramps (sinistral and dextral rails

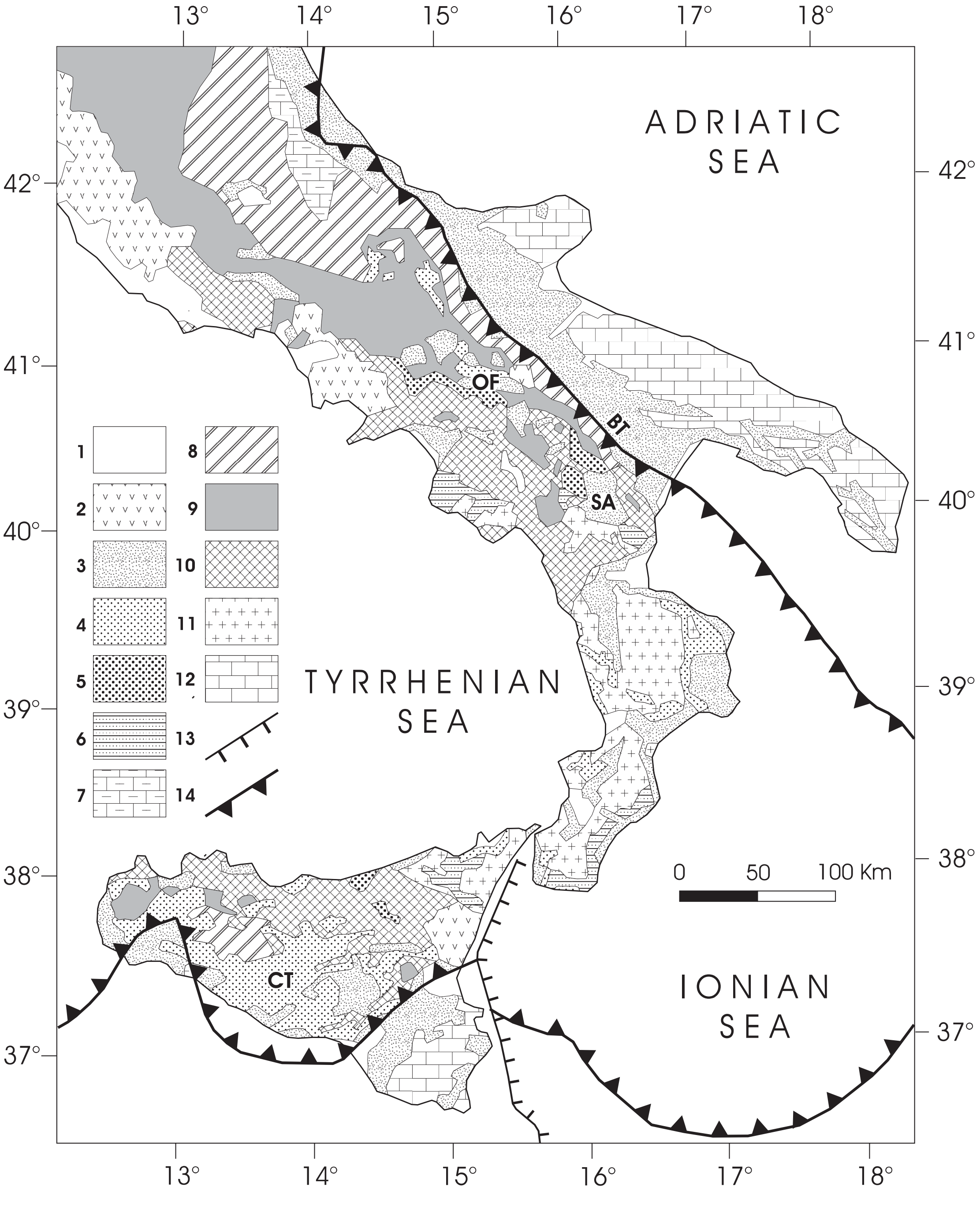


Fig. 3 - Structural-kinematic map of the Southern Apenninic Arc (after CNR-PROGETTO FINALIZZATO GEODINAMICA, 1991 with modifications).

1 Continental and subordinate shallow-marine deposits (upper Pleistocene-Holocene). 2 Volcanites and volcaniclastites (Middle Pleistocene-Holocene). 3-6 Upper Oligocene to Pleistocene thrust-top deposits in the Southern Apennines, Calabrian Arc and Sicilian Maghrebides; Plio-Pleistocene deposits and subordinate volcanites in the foreland areas: 3 Plio-Pleistocene; 4 Upper Tortonian-lower Pliocene; 5 Langhian-Tortonian; 6 Upper Oligocene-lower Miocene. 7-11 Tectonic units of the Southern Apenninic Arc, arranged according to the time of incorporation in the mountain chain: 7 Plio-Pleistocene units (Casoli-Bomba, Majella, Queglia and Morrone-Porrara in the Apennines, Sciacca in Sicily); 8 Messinian units (Molise, Montagna dei Fiori, Gran Sasso-Genzana and W. Marsica in the Apennines; Sicani in Sicily); 9 Tortonian units (Matese, Lagonegro and Sannio in the Apennines; Trapanese in Sicily); 10 Burdigalian-Langhian units (Monti della Maddalena, Alburno-Cervati, Monte Foraporta, Capri-Bulgheria, Verbicaro, San Donato and Sicilide in the Apennines; Imerese, Panormide and Sicilide in Sicily); 11 Cretaceous-Paleogene units (North-Calabrian units and ophiolite-bearing nappes in the Southern Apennines, ophiolite-bearing and crystalline-basement nappes in the Calabrian Arc). 12 Pre-Pliocene carbonates in the Apulia and South-Sicily foreland areas. 13 Major extensional features in the Eastern Sicily offshore. 14 Quaternary thrust front in the Apennines, Calabrian Arc and Sicily. **BT**: Bradano Trough. **CT**: Caltanissetta Trough. **OF**: Ofanto synform. **SA**: Sant’Arcangelo synform.

respectively) that guided the forward transport of the Calabrian edifice toward the Ionian foreland before the Messinian salinity crisis. The frontal part of the Calabrian Arc (Outer Calabrian Arc), drowned by the Ionian Sea, has been interpreted as an accretionary wedge developed along the northwestern margin of the subducting Ionian lithosphere (ROSSI & SARTORI, 1981; BARONE *et alii*, 1982). The overall structural architecture of the Sicilian Maghrebides consists, as in the case of the Southern Apennines, of a buried duplex system overlain by a thick pile of rootless nappes derived from shallow-platform and deeper-basin paleogeographic realms (BIANCHI *et alii*, 1987; CATALANO *et alii*, 1997, 2000; VITALE, 1997a; BELLO *et alii* 2000). The buried duplex system, constituted of Mesozoic-Tertiary carbonates detached from the Sicani and Sciacca-Siracusa domains, reaches the surface in Western Sicily in correspondence to an axial culmination of the tectonic structures and to a lateral change in the structural architecture from a duplex configuration to an imbricate-fan configuration.The frontal part of the allochthonous sheets in Central and Southern Sicily, formerly interpreted as an olistostrome by BENEO (1957) and ROCCO (1959), is known in the geological literature as the "Gela nappe" (OGNIBEN, 1969). Two structural interpretations of the Gela nappe are available:

- Roof of a buried duplex system made up of Cretaceous-Paleogene Sicilide-derived varicoloured clays and of upper Oligocene-lower Miocene Imerese(?)-derived Numidian sandstones, unconformably overlain by Miocene to Pleistocene thrust- top deposits (see VITALE 1997a; BELLO *et alii* 2000);
- Accretionary wedge made up of Miocene terrigenous deposits detached from a foredeep basin originally located NW of the Hyblean Plateau. The wedge would be unconformably overlain by upper Messinian to Pleistocene thrust-top deposits (ARGNANI 1987; GRASSO *et alii* 1990; BUTLER *et alii* 1992; CATALANO *et alii* 1993b, c, 1996; CATALANO 1997; LICKORISH *et alii* 1999; NIGRO & RENDA 2000). According to ARGNANI (1987) this dismembered foredeep basin possibly represented the onshore continuation of a Tortonian-Messinian foredeep basin still preserved in the Adventure Bank (see also ARGNANI *et alii* 1986, 1989; ANTONELLI *et alii* 1988).

It is commonly assumed that the Gela nappe extends eastward into the Outer Calabrian Arc. The differential forward migration of the thrust fronts in Sicily and in the Calabrian Arc is evident in figures 1 and 3. The differential thrust propagation, related to the differential flexure-hinge retreat of the foreland plate, has been accommodated by a complex system of dextral lateral/oblique ramps. The eastward lateral continuation of the Gela nappe, on the contrary, is not clear and is still matter of debate. According to CATALANO *et alii* (1996) a sheet of Miocene to Pliocene deposits tectonically overlying a carbonate duplex system, the leading edge of which would be located in proximity to the River Belice mouth near Sciacca, is the equivalent of the Gela nappe in Western Sicily. We agree with this interpretation that requires a remarkable dextral offset between the Pleistocene front of the Gela nappe in South-eastern Sicily and coeval out-of-sequence thrust fronts in Western Sicily. The bulk of the stratigraphic knowledge on the foreland areas derives from the extensive onshore and offshore petroleum exploration (PATACCA *et alii*, 1979; ANTONELLI *et alii*, 1988). Only the Cretaceous-Tertiary portion of the sequence, in fact, is exposed in the Hyblean Plateau (GRASSO & LENTINI 1982).

THE PLIO-PLEISTOCENE THRUST-TOP, FOREDEEP AND FORELAND DEPOSITS OF THE SOUTHERN APENNINES

The stratigraphic reconstruction of the Plio-Pleistocene thrust belt-foredeep system in the Southern Apennines is based on a considerable amount of surface and subsurface information. The foredeep deposits do not crop out in the Southern Apennines but are widespread in the subsurface of the Bradano Trough where have been extensively investigated by means of seismic lines tied to several wells. The information on the age of the foredeep deposits mostly derives from the detailed micropaleontological analyses carried out by CRESCENTI (1975) and BALDUZZI *et alii* (1982a, b) integrated with the basic stratigraphic data coming from the available logs of commercial boreholes. The thrust-top deposits, widely exposed in natural sections along the outer margin of the Apennines and in the major structural depressions of the mountain belt such as the Ofanto and Sant'Arcangelo synforms, have been carefully studied by several authors by means of micropaleontological and sedimentological analyses (see PATACCA & SCANDONE, 2001 and references therein).

Figures 4 and 5 are chronostratigraphic diagrams schematizing the key sedimentary features of the Plio-Pleistocene deposits along two transects cutting across the front of the Apennine nappes and the adjacent foredeep basin (sections a and b in figure 2). The isochrones, expressed as absolute ages, derive from biostratigraphic data (integrated nannofossil and microfossil analyses) calibrated according to the time scale of figure 6 (bioevent calibrations in tables 1-3). A careful time correlation between the thrust-top, foredeep and foreland deposits allowed us to recognize depositional sequences closely controlled by the tectonic activity in the mountain chain (P_{1-2} and Q_{1-2} thrust-related depositional sequences in PATACCA & SCANDONE, 2001). A thrust-related depositional sequence has been defined as the sedimentary record of a tectonic cycle that starts with an important forward displacement of the allochthonous sheets over a long thrust flat and ends with the incorporation in the mountain chain of new tectonic units detached from the foreland block. Every depositional sequence has been divided into four systems tracts, each tract being representative of a well-defined array of the active-thrust trajectories.

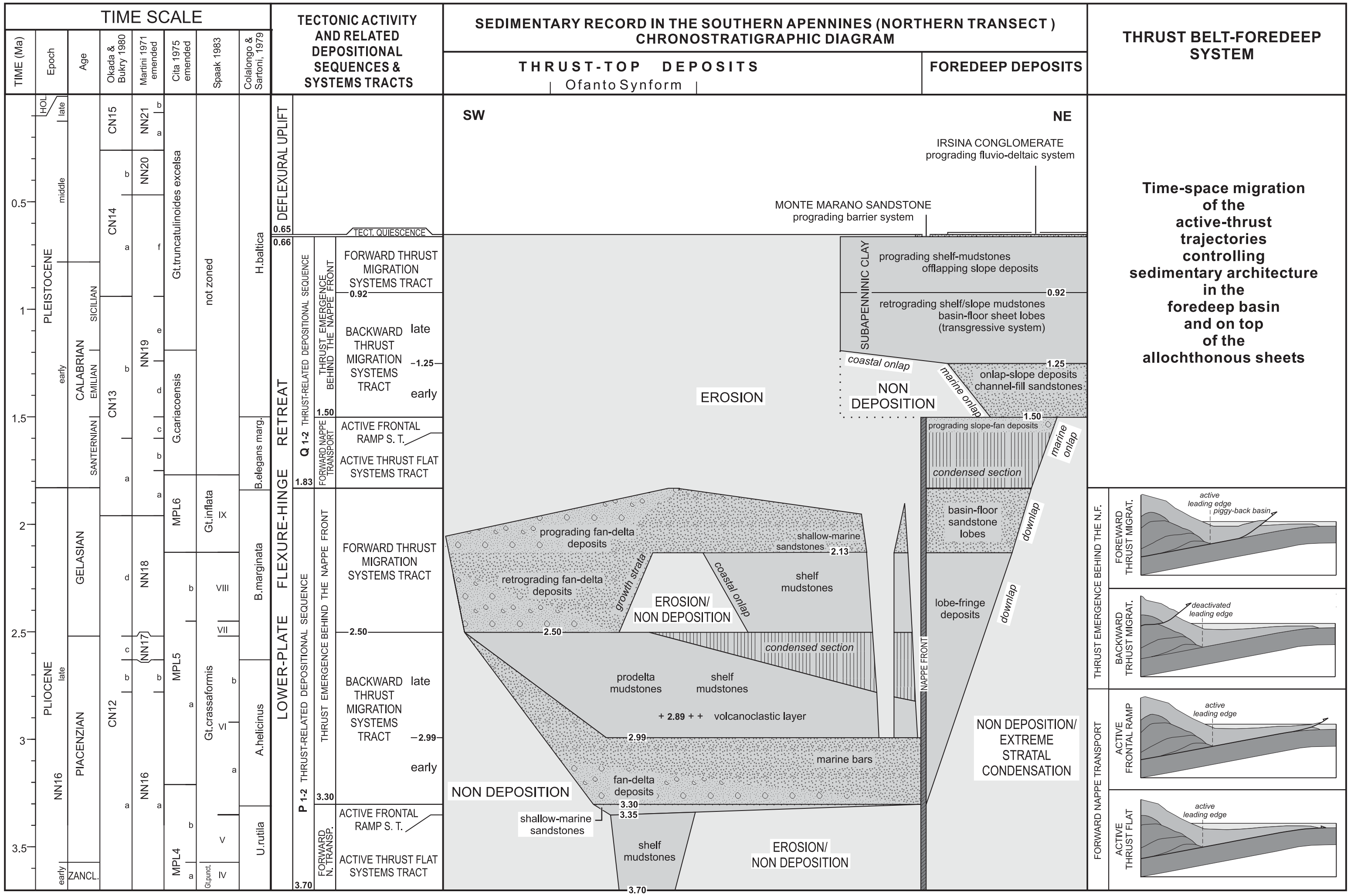


Fig. 4 - Plio-Pleistocene thrust-top, foredeep and foreland deposits in the Southern Apennines (northern transect, **a** in fig. 2): chronostratigraphic diagram and thrust-related depositional sequences. In the right side of the picture, schematic representation of the time-space migration of the active thrusts in the different systems tracts. Modified after PATACCA & SCANDONE (2001).

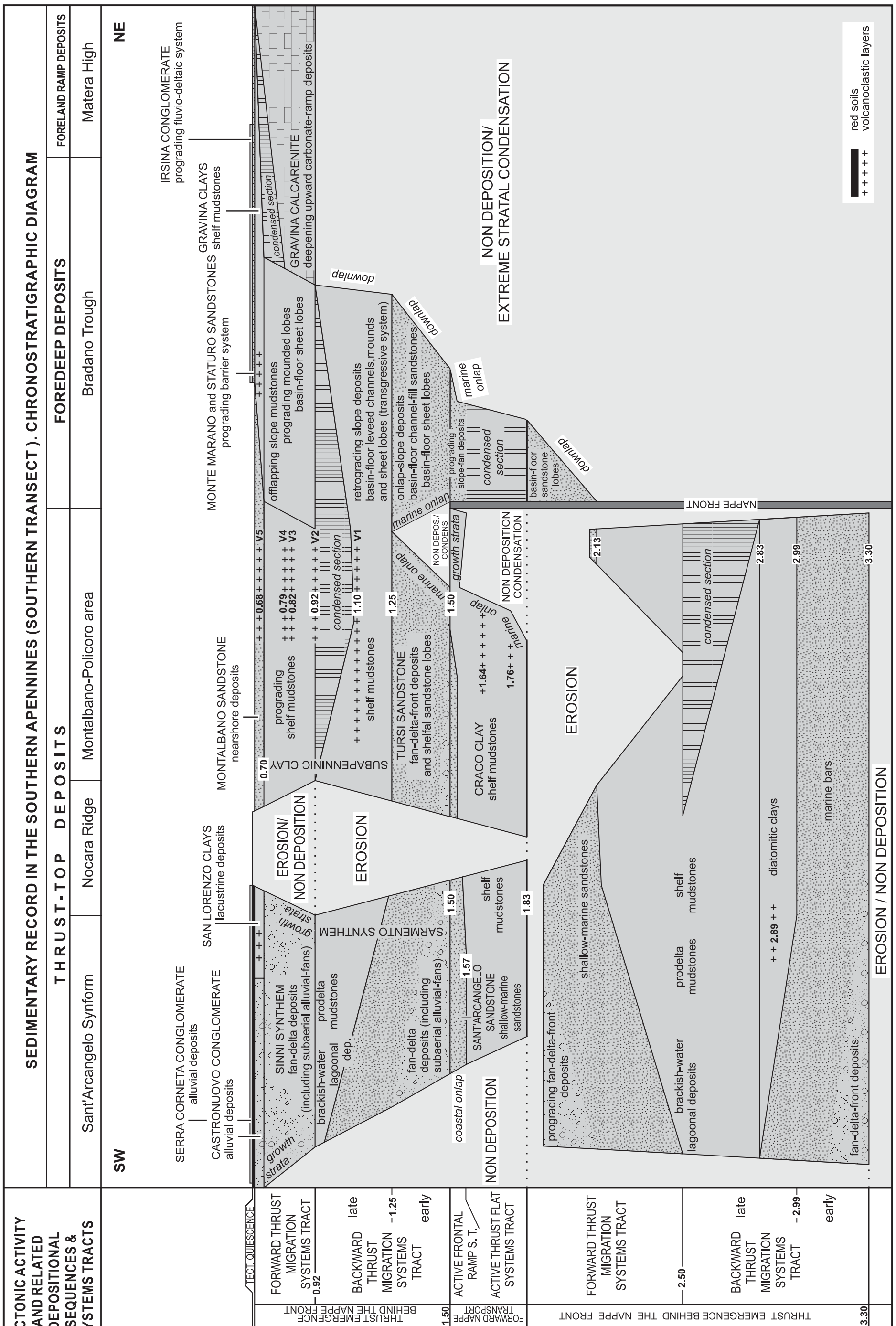


Fig. 5 - Plio-Pleistocene thrust-top, foredeep and foreland deposits in the Southern Apennines (southern transect, **b** in fig. 2): chronostratigraphic diagram and thrust-related depositional sequences. Modified after PATACCA & SCANDONE (2001).

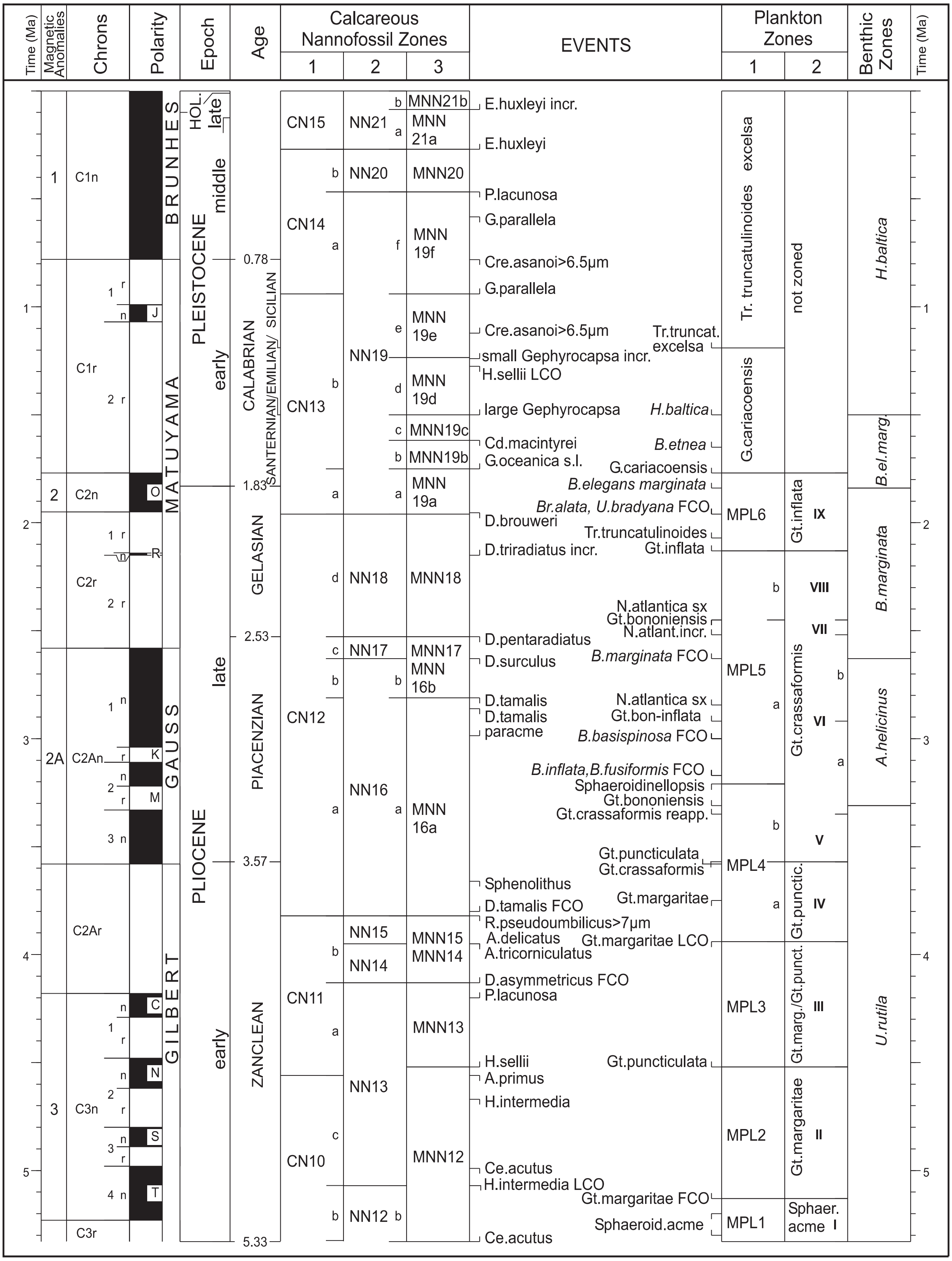


Fig. 6 - Plio-Pleistocene biostratigraphic scheme showing the most significant bioevents of the Mediterranean region re-calibrated according to the global polarity time scale of CANDE & KENT (1995). After PATACCA & SCANDONE, (2001) with slight modifications. Calcareous Nannofossil Zones after OKADA & BUKRY, 1980 (1); MARTINI, 1971 (2); RIO *et alii*, 1990 (3). Plankton Zones after CITA, (1975) (1); SPAAK, 1983 (2). Benthic Zones after COLALONGO & SARTONI, 1979.

TABLE 1 - Pliocene to Pleistocene calcareous nannofossil bioevents used to delineate the zonal boundaries shown in figure 6.

BIOCHRONOLOGY OF LATE NEOGENE TO QUATERNARY CALCAREOUS NANNOFOSSILS		
Datum event	**Reference**	**Age (Ma)**
Emiliania huxleyi increase	Shipboard Scientific Party, 1996a	0.085
Emiliania huxleyi FO	De Kaenel *et alii*, 1999	0.27
Pseudoemiliania lacunosa LO	Castradori, 1993	0.468
Gephyrocapsa parallela LO	Castradori, 1993	0.584
Crenalithus asanoi > 6.5 µm LO	De Kaenel *et alii*, 1999	0.781
Gephyrocapsa parallela FO	Castradori, 1993	0.94
Crenalithus asanoi > 6.5 µm *FO*	De Kaenel *et alii*, 1999	1.122
small *Gephyrocapsa* spp. increase	Berggren *et alii,*1995	1.24
Helicosphaera sellii LCO	De Kaenel *et alii*, 1999	1.276
large *Gephyrocapsa* spp. FO	Sprovieri, 1993	1.5
Calcidiscus macintyrei LO	De Kaenel *et alii*, 1999	1.619
Gephyrocapsa oceanica sl. FO	Sprovieri, 1993	1.75
Discoaster broweri LO	Shackleton *et alii*, 1995	1.954
Discoaster triradiatus increase	Shipboard Scientific Party, 1996a	2.15
Discoaster pentaradiatus LO	Rio *et alii*, 1997	2.528
Discoaster surculus LO	Shackleton *et alii*, 1995	2.63
Discoaster tamalis LO	Rio *et alii*, 1997	2.811
Discoaster tamalis paracme end	Sprovieri, 1993	2.86
Discoaster tamalis paracme begin	Sprovieri, 1993	2.99
Sphenolithus spp. LO	Shackleton *et alii*, 1995	3.66
Discoaster tamalis FCO	Shipboard Scientific Party, 1996a	3.8
Reticulofenestra pseudoumbilicus > 7 µm LO	Shackleton *et alii*, 1995	3.82
Amaurolithus delicatus LO	Shipboard Scientific Party, 1996a	3.95
Amaurolithus tricorniculatus LO	Shipboard Scientific Party, 1996a	3.95
Discoaster asymmetricus FCO	Shackleton *et alii*, 1995	4.13
Pseudoemiliana lacunosa FO	Shipboard Scientific Party, 1996a	4.2
Helicosphaera sellii FO	Shipboard Scientific Party, 1996a	4.52
Amaurolithus primus LO	Shackleton *et alii,* 1995	4.56
Helicosphaera intermedia LO	Shipboard Scientific Party, 1996a	4.67
Ceratolithus acutus LO	Shackleton et *alii*, 1995	4.99
Helicosphaera intermedia LCO	Shipboard Scientific Party, 1996a	5.07
Ceratolithus acutus FO	Shackleton *et alii*, 1995	5.33

TABLE 2 - Pliocene to Pleistocene planktonic foram bioevents used to delineate the zonal boundaries shown in figure 6.

BIOCHRONOLOGY OF LATE NEOGENE TO QUATERNARY PLANKTONIC FORAMINIFERA		
Datum event	**Reference**	**Age (Ma)**
Truncorotalia truncatulinoides excelsa FO	Sprovieri, 1993	1.19
Globigerina cariacoensis FO	Berggren *et alii,* 1995	1.77
Truncorotalia truncatulinoides FO	Sprovieri, 1993	2.07
*Globorotalia inflata*FO	Sprovieri, 1993	2.13
Neogloboquadrina atlantica sinistral LO	Sprovieri 1993	2.45
Globorotalia bononiensis LO	Sprovieri, 1993	2.45
Neogloboquadrina atlantica increase	Rio *et alì*, 1990	2.52
Neogloboquadrina atlantica sinistral FO	Rio *et alii*, 1997	2.844
Globorotalia bononiensis-Globorotalia inflata intermediate morphotypes (appearance)	Spaak, 1983	2.92
Sphaeroidinellopsis spp. LO	Berggren *et alii*, 1995	3.21
Globorotalia bononiensis FO	Sprovieri, 1993	3.31
Globorotalia crassaformis reappearance	Berggren *et alii*, 1995	3.35
Globorotalia puncticulata LO	Sprovieri, 1993	3.57
Globorotalia crassaformis FO	Berggren *et alii,* 1995	3.58
Globorotalia margaritae LO	Sprovieri, 1993	3.75
Globorotalia margaritae LCO	Sprovieri, 1993	3.94
Globorotalia puncticulata FO	Sgarrella *et alii*, 1999	4.52
Globorotalia margaritae FCO	Sgarrella *et alii*, 1999	5.13
Sphaeroidinellopsis spp. acme end	Sgarrella *et alii*, 1999	5.20
Sphaeroidinellopsis spp. acme beginning	Sgarrella *et alii*, 1999	5.30

TABLE 3 - Pliocene to Pleistocene benthonic foram bioevents used to delineate the zonal boundaries shown in figure 6.

BIOCHRONOLOGY OF SELECTED LATE NEOGENE TO QUATERNARY BENTHONIC FORAMINIFERA		
Datum event	**Reference**	**Age (Ma)**
Hyalinea baltica FO	Pasini & Colalongo, 1982, 1994	1.5
Bulimina etnea FO	Pasini & Colalongo, 1982, 1994	1.65
Bulimina elegans marginata FO	Pasini & Colalongo, 1982, 1994	1.84
Brizalina alata FCO	original data	1.96 *
Uvigerina bradyana FCO	original data	1.96
Bulimina marginata FCO	original data	2.63 *
Bulimina basispinosa FCO	original data	3.0
Bulimina inflata FCO	original data	3.17 *
Bulimina fusiformis FCO	original data	3.17 *

* Age estimation derived from an integrated biostratigraphic analysis (calcareous nannofossils, planktonic and benthonic foraminifera) of several Pliocene-Pleistocene sections in the Southern Apennines.

The different sedimentary evolution of the P_{1-2} and Q_{1-2} deposits in the final tract of the sequence (see chronostratigraphic diagrams of figs. 4 and 5) is related to the different tectonic history. The Pliocene P_{1-2} deposits, in fact, were accumulated in an active thrust belt-foredeep system while flexure-hinge retreat was the major driving mechanism for new accommodation space in the foredeep basin and for thrust activity in the mountain chain (see PATACCA & SCANDONE, 1989). The Pleistocene Q_{1-2} sequence, on the contrary, stopped around 0.66 Ma because of the end of the flexural subsidence near the early Pleistocene-middle Pleistocene boundary and because of the subsequent de-flexural uplift (CINQUE *et. alii*, 1993; HIPPOLYTE *et alii*, 1994a).

P_{1-2} DEPOSITIONAL SEQUENCE (LOWER PLIOCENE P.P.-UPPER PLIOCENE)

It is evident from a comparison of figures 4 and 5 that the Pliocene sedimentary record in the northern transect is more complete both in the foredeep basin and on top of the allochthonous sheets. In the southern transect the 3.70-3.30 shelf deposits are absent on top of the Apenninic nappes and the 3.30-2.13 deposits are extremely condensed in the foredeep basin. In addition, the thrust-top deposits referable to the 2.50-1.83 Ma interval in the northern transect, considerably coarser that those exposed in the southern one, suggest a different basin physiography and a closer proximity to the sediment source.

P_{1-2} foredeep and foreland deposits

In the northern portion of the Bradano Trough, where a more complete foredeep sequence is recognizable in the subsurface, two units have been distinguished (figs 4 and 7). The lower unit is represented by a package of thin-bedded turbidite sandstones and mudstones interpreted as lobe-fringe deposits (highly continuous parallel reflectors with low frequency and moderate amplitude in seismic lines) laterally grading into muddy deposits containing *Globorotalia* gr. *crassaformis* (3.30-2.13 Ma interval). A widespread calcarenite key bed, seismically expressed by a strong and continuous flat reflector (left side of the seismic profile in fig. 7 immediately below the 2.13 Ma reflector), acts as a key horizon for subsurface correlation in the whole area. The low-density turbidites stratigraphically overlie a nearly continuous veneer of condensed hemipelagic lime deposits characterized by the presence of *Gt. puncticulata* and *U. rutila* (3.70-3.30 Ma interval). The upper unit, commonly containing *Gt. inflata*, is represented by a stack of turbidites displaying a higher sand/mud ratio (2.13-1.83 Ma interval)

In correspondence to the southern transect, the *Gt. inflata* turbidites directly overlie the Apulia carbonates by means of a laterally continuous thin layer of condensed foraminiferal limestones and marls (3.70-2.13 Ma interval) partly coeval with the *Gt. crassaformis* turbidites of the northern transect (figs 5 and 8).

In the northern and southern transects, the *Gt. inflata* turbidites form as a whole a clastic wedge of aggrading to prograding basin-floor sandstone lobes showing evident onlap terminations against the foreland ramp. These sandy turbidites are expressed in seismic profiles by rather continuous flat reflectors passing laterally toward the east into weaker reflectors with a gently-prograding mounded configuration displaying subtle bi-directional downlap terminations (e.g. fig. 8 below the 1.83-1.57 Ma reflector). Toward the foreland, backward (southwestward) tilted reflectors, truncated by the overlying clastic wedge, testify to active flexure-hinge retreat between 2.13 and 1.83 Ma. The important terrigenous supply in the foredeep basin is systematically related to a coeval progradation of fandelta systems on top of the nappes, as indicated by the correlations shown in the chronostratigraphic diagrams of figs 4 and 5.

P_{1-2} thrust-top deposits

The oldest thrust-top deposits referable to the P_{1-2} depositional sequence, cropping out north of the Ofanto synform, are represented by open-shelf foraminiferal mudstones grading upward into shallow-marine sandstones (3.70-3.30 Ma interval in fig. 4). The mudstone-sandstone couple forms, as a whole, a shallowing-upward sequence draping the Apenninic nappes and older thrust-top deposits without significant lateral changes of facies. These deposits are rather well recognizable in the subsurface as a reflection-free isopachous drape on top of the allochthonous sheets.

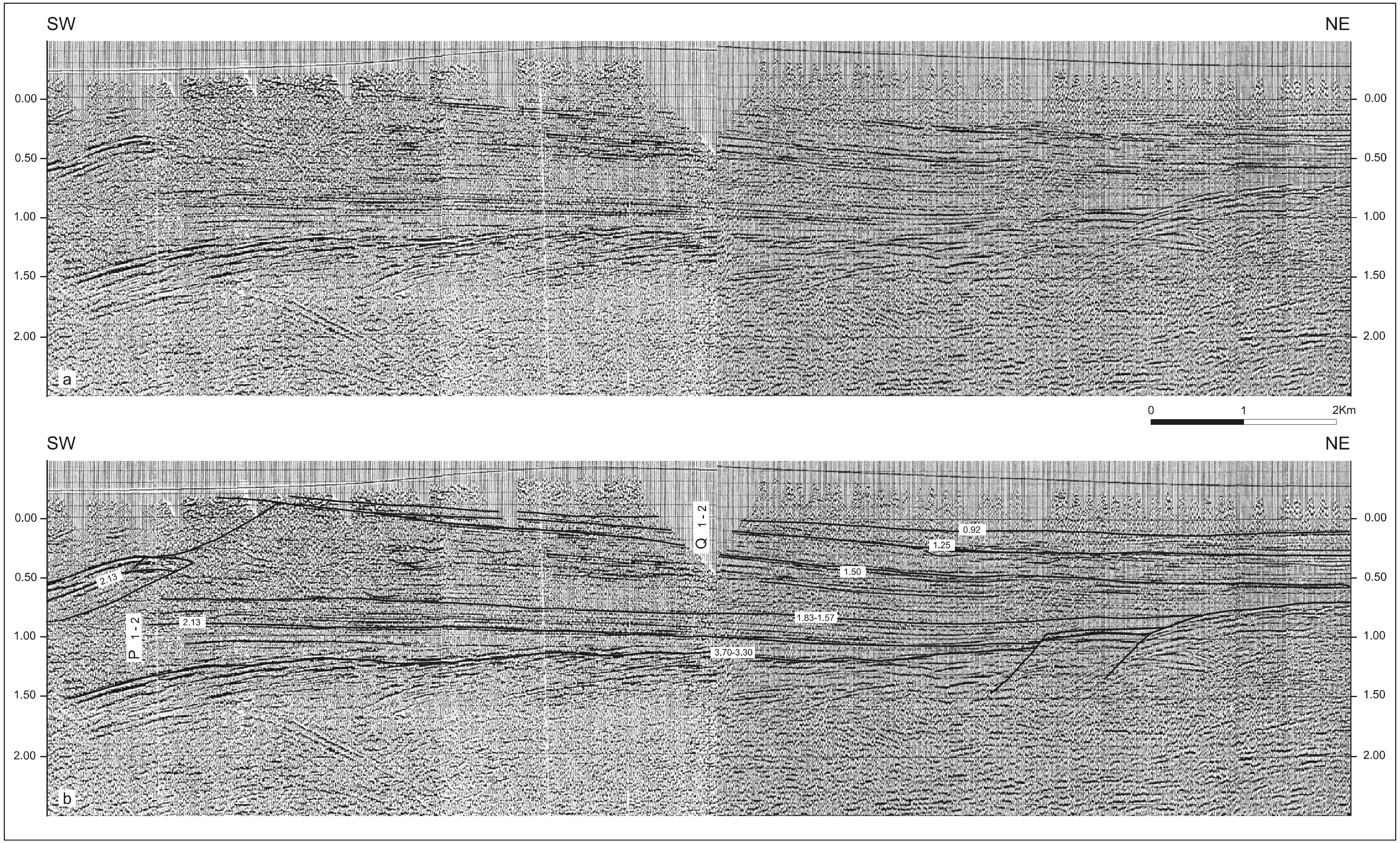


Fig. 7 - Uninterpreted (a) and interpreted seismic profile (b) across the Apennine front in the northern part of the Bradano Trough. Depositional sequences and ages of the surfaces bounding sequences and systems tracts derive from the chronostratigraphic diagram of figure 4. Near the edge of the tectonic wedge, foredeep Pliocene deposits of the P_{1-2} sequence have been incorporated in the thrust belt

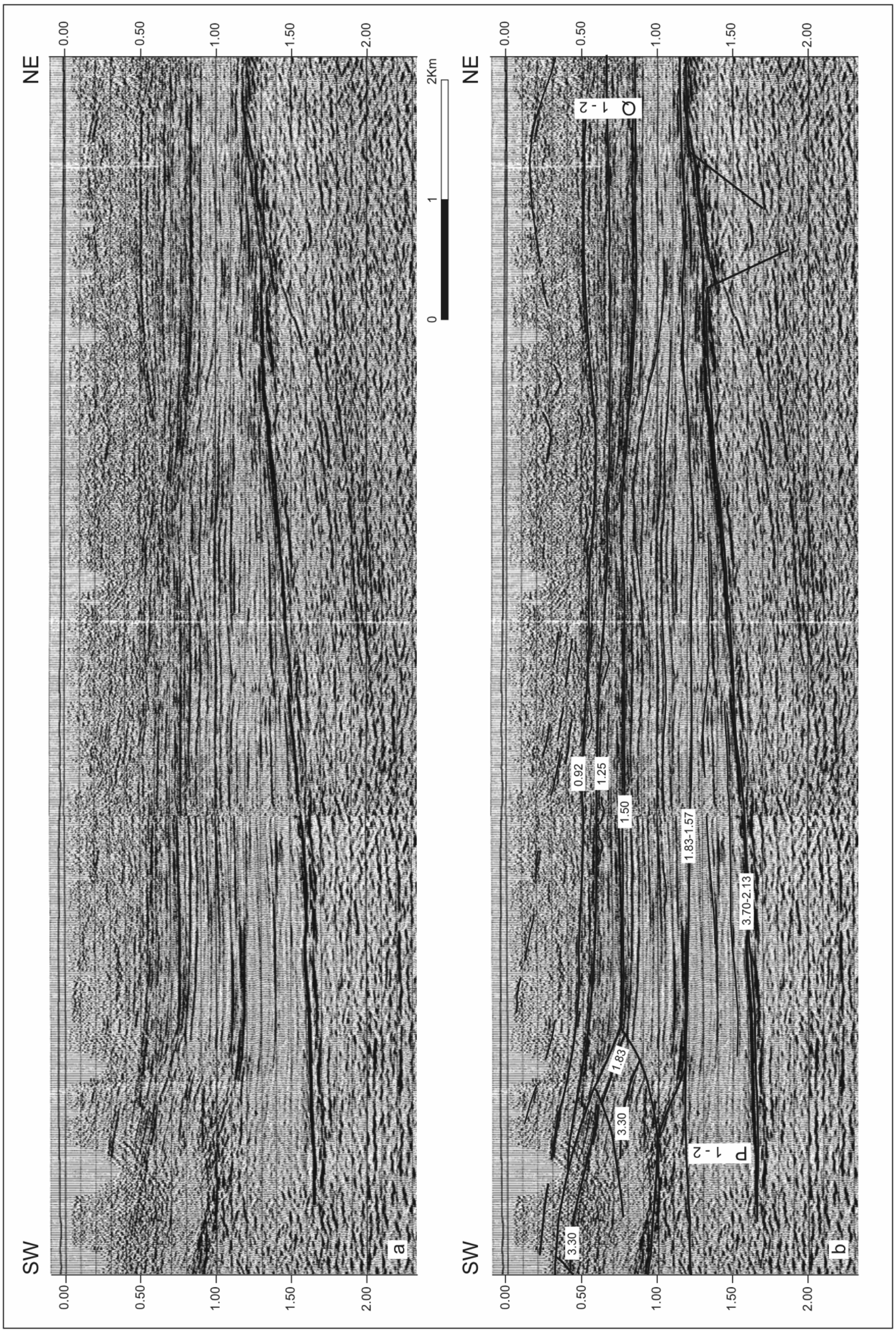


Fig. 8 - Uninterpreted (a) and interpreted seismic profile (b) across the Apennine front in the southern part of the Bradano Trough. Depositional sequences and ages of the surfaces bounding sequences and systems tracts derive from the chronostratigraphic diagram of figure 5

A second group of Pliocene deposits still referable to the P_{1-2} depositional sequence forms a transgressive to regressive complete sedimentary cycle (3.30-1.83 Ma interval in figs. 4 and 5). The transgressive portion of the 3.30-1.83 sedimentary cycle is described by retrograding fandelta deposits laterally replaced, along the outer margin of the Apennines, by cross-stratified bioclastic sandstones indicative of wide marine-bar deposits These coarse-clastic deposits grade laterally and vertically into a diachronous wedge-shaped muddy unit (2.99-2.13 Ma interval) landward represented by prodelta mudstones and brackish-water lagoonal deposits and basinward represented by locally condensed open-shelf clays and silty clays. A thin volcaniclastic layer preserved in the lower part of the muddy unit represents a useful key horizon for stratigraphic correlations of surface sections. The upper boundary of the prodelta/open-shelf mudstones is not isochronous at the regional scale. The top of the muddy unit, in fact, is referable to the Spaak's VII foraminiferal zone in the most internal areas of the mountain chain and to the *Gt. inflata* zone, i.e. to the Spaak's IX foraminiferal zone, along the outer margin of the Apennines. In that region, the open-shelf mudstones and the overlying shallowing-upward inner-shelf clastic deposits form a quite isopachous sheet some hundreds of metres thick that spans through the late Pliocene until about 2.13 Ma.

The regressive portion of the P_{1-2} depositional sequence is represented by coarse-clastic fandelta deposits grading eastward into shallow-marine sandstones (2.50-1.83 Ma interval). They have been deposited into two different physiographic settings, both closely controlled by the trajectories of the active thrusts:

- Mobile piggy-back basins developed in the hangingwall of active thrusts, flanked toward the foredeep by rising ridges;
- Wide passive shelves developed in the footwall of active thrusts, open toward the foredeep basin.

The first case is represented by Pliocene deposits filling the Ofanto basin that testify to an active and well supplied source from NNW. The entire tract of the sequence (2.50-1.83 Ma interval of fig. 4) is here organized into a lower portion made up of retrograding coarse-grained fandelta deposits ending with a few tens of metres of *Gt. inflata* silty mudstones (2.50-2.13 Ma) and a coarse-clastic upper portion made up of prograding fandelta deposits topped by red alluvial deposits, eastward grading into shallow-marine sandstones (2.13-1.83 Ma). The seismic line of figure 9, 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 a huge antiformal stack within the allochthonous sheets.

The normal fault in figure 9 displacing the 3.70-2.50 Ma thrust-top deposits and gently deforming the Pliocene sediments younger than 2.50 Ma may be considered an accommodation feature in the backlimb of the ramp anticline developed in the hangingwall of the active thrust. The second case of thrust-top physiography (wide passive shelves developed in the footwall of active thrusts, open toward the foredeep basin). is represented by the entire 3.30-1.83 Ma sedimentary sequence deposited in the Sant'Arcangelo synform and along the outer margin of the Apennines where the Pliocene deposits form as a whole a quite isopachous transgressive-regressive cycle with no evidence of internal unconformities.

Q_{1-2} DEPOSITIONAL SEQUENCE (LOWER PLEISTOCENE-MIDDLE PLEISTOCENE P.P.)

The lower-middle Pleistocene thrust-top deposits of the Q_{1-2} sequence, poorly represented in the northern transect, are well known in the southern part of the Bradano Trough and in the Sant'Arcangelo depression where numerous natural sections, associated with a wide range of data coming from petroleum exploration, allowed detailed biostratigraphic and sedimentological analyses. The foredeep deposits are very well represented in the subsurface of both transects. Time-correlations between the thrust-top and the foredeep deposits are described in the chronostratigraphic diagrams of figures 4 and 5.

Q_{1-2} foredeep and foreland deposits

The foredeep and foreland deposits of the Q_{1-2} depositional sequence, not affected by the compressional deformation, have fully preserved their original stratal architecture. The basin-fill deposits are everywhere characterized by the occurrence of five basic depositional units (see figs. 4, 5, 7 and 8):

6. Condensed unit (1.83-1.57 Ma interval) represented by a very thin layer of hemipelagic deposits overlying the master sequence boundary at the scale of the entire basin;
7. Syn-ramp wedge (1,57-1.50 Ma interval), made up of a thick wedge of gravity-driven deposits upward truncated by the active frontal ramp of the allochthonous sheets;
8. Onlap-slope system (1.50-1.25 Ma interval), built by basinal, locally channelized deposits onlapping the edge of the allochthonous sheets. These deposits mark the deactivation of the frontal ramp;
9. Transgressive system (1.25-0.92 Ma interval), made up of muddier basinal deposits marking the maximum flooding of the tectonic wedge;
10. Prograding shelf-margin system (0.92-0.66 Ma interval), basinward substituted by a widespread prograding unit of basin-floor turbidites.

The base of the syn-ramp wedge, the most prominent depositional unit in the foredeep basin, is frequently stressed in seismic profiles by a relatively strong and

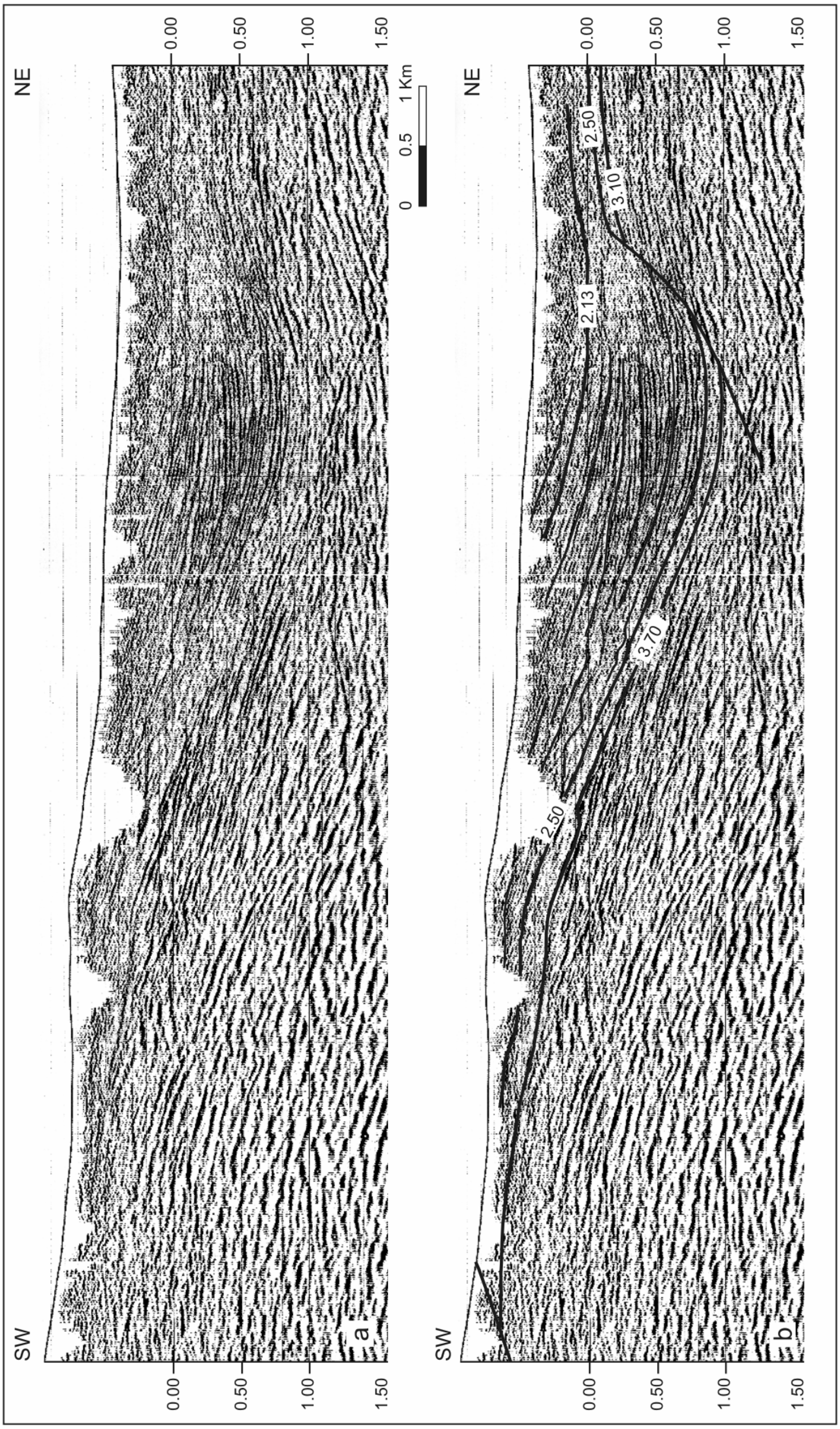


Fig. 9 - Uninterpreted (a) and interpreted seismic profile (b) across the Pliocene deposits of the Ofanto piggyback basin (see also ROURE *et alii*, 1991; HIPPOLYTE *et alii*, 1994b). The backstepping concave-upward reflectors manifest the retrogradational character of the 2.50-2.13 systems tract well expressed also in surface sections. The ages of the surfaces bounding the systems tracts derive from the chronostratigraphic diagram of figure 4

quite continuous reflector testifying to an episode of prolonged sediment starvation (1.83-1.57 Ma reflector in figs. 7 and 8). This reflector overlies the master Q_{1-2} sequence boundary that may be traced in correspondence to an unconformity surface gently truncating the underlying reflectors. The syn-ramp clastic wedge (1.57-1.50 Ma interval), locally exceeding 1000 metres in thickness, is usually made up of at least two prograding slope-fan units landward truncated by the rising nappe front. The slope-fan system basically consists of gravity-driven sediments principally derived from the failure of unconsolidated deposits lying on top of the Apennine nappes in the hangingwall of the frontal ramp. The overall geometry and internal facies architecture of the syn-ramp wedge have been closely controlled by the relief of the thrust toe and by the physiography of the drainage-feeder system controlling volume and grain size of the sediment supply. An additional control on the basin geometry and on the sediment transport and distribution has been exerted by faults dissecting the foreland "homocline" that determined a more ore less confined basin-fill geometry. Figure 7 is a case of confined gravel/sand-prone foredeep basin fed by fandelta systems facing steep slopes related to the high-relief thrust toe configuration (slope-type fandelta). Figure 8, on the contrary, represents a case of mud-prone unconfined foredeep basin bordered by a wide shallow shelf with a near flat morphology inherited from a low-relief thrust toe configuration. In both cases, four basic architectural elements with clear laterally interbedded relationships have been recognized. The first proximal portion, directly fed by the catastrophic mass wasting of the uprising edge of the allochthonous sheets, bear the signature of the frontal-ramp elevation and acclivity. These deposits, characterized by chaotic seismic facies, are volumetrically important in correspondence to steep slopes (fig. 7). In other cases (fig. 8), the chaotic deposits of the proximal portion are substituted by a monotonous stack of predominantly muddy turbidites evidenced by a relatively flat package of weak reflectors. The inner portion of the syn-ramp wedge grades downdip into a channel-overbank system as indicated by the occurrence of multiple concave-upward strong reflectors. Toward the basin, the channel-fill system grades into mounded packages of turbidites (bi-directional downlapping reflectors more evident in mud-rich/high-efficiency systems as in the case of figure 8. A broadly parallel-layered turbidite unit, finally, progressively onlaps the outer margin of the foredeep basin.

Along the Apennine front, the described syn-ramp wedge is systematically overlain by an onlap-slope system (1.50-1.25 Ma interval) made up of thin-bedded turbidites. Small channels filled with coarse-clastic deposits showing longitudinal dispersal locally dissect the turbidite beds. The onlap-slope turbidite system, lapping landwards over weakly eroded portions of the syn-ramp clastic wedge, is systematically draped by a transgressive shelfal mudstone sheet (1.25-0.92 Ma interval). The latter extends basinward into fine-grained turbidite lobe deposits characterized by weak reflectors and subtle mounded configuration. The absence of an offlapping delta-fed slope apron reflects the poor sediment supply from the adjacent shelf margin. The decreasing volume and grain size of the sediments in the basin during the 1.50-0.92 Ma interval points to a progressive reduction of the alluvial gradients in the feeder system, in agreement with the increase in the accommodation space on top of the allochthonous sheets. However, in spite of the increase in the accommodation space during the 1.25-0.92 Ma interval, only a relatively small, flat area corresponding to the present-day Sant'Arcangelo synform experienced a generalized marine flooding. In the bulk of the Southern Apennines, the marine transgression was limited to the frontal part of the mountain chain because of the high topographic relief created by a tight nappe imbrication.

The 1.25-0.92 Ma transgressive system is overlain by a thick muddy unit (0.92-0.66 Ma interval in figs. 4 and 5) known on the surface as Sub-Apenninic Clay. Gently dipping sigmoid reflectors in correspondence to the inactive nappe front (fig. 8) indicate a relatively low-energy depositional slope with a renewed, though modest, terrigenous supply from the contiguous shelf. The persistent muddy character of the prograding slope points to a feeder system with a low topographic relief. The offlapping configuration of the slope mudstones is substituted toward the basin by a complex array of concave-upward reflectors testifying to a delta-fed apron cut by longitudinal channels. The channel-fill system is in some cases basinward substituted by a package of weak reflectors displaying an overall aggrading to prograding mounded configuration (prograding mounded lobes in the chronostratigraphic diagram of fig. 4). The mounded deposits pass basinward into thin-bedded sandy turbidites with an overall thinning-upward stacking pattern (basin-floor sheet-lobes in the chronostratigraphic diagram of fig. 4).

The Sub-Apenninic clays of the Bradano Trough upward grade into shallow-water sandstones (Monte Marano Sandstone, 0.66-0.65 Ma interval in figs. 4 and 5). The latter are overlain by prograding fluvio-deltaic conglomerates (Irsina Conglomerate). The shallowing-upward configuration of the Monte Marano Sandstone indicates the cessation of the flexural subsidence in the foredeep basin; the Irsina Conglomerate corresponds to the beginning of a generalized uplift related to a viscous-elastic rebound of the entire mountain chain (see CINQUE *et alii*, 1993 and HIPPOLYTE *et alii* 1994a).

Q_{1-2} thrust-top deposits

Thrust-top deposits referable to the Q_{1-2} sequence are poorly preserved in the Southern Apennines, with the exception of a narrow strip along the outer margin of the mountain chain and with the exception of the Sant'Arcangelo synform where a thick sequence of lower Pleistocene terrigenous deposits is exposed (see southern transect of fig. 5). The oldest thrust-top deposits of the

Q_{1-2} sequence are represented by a relatively isopachous sheet of Lower Pleistocene (Santernian) open-shelf foraminiferal mudstones (Craco Clay unit) grading landwards (westwards) into a monotonous sequence of inner-shelf clays and silty clays and basinward into a progressively more condensed pelagic layer. The latter merges in the foredeep basin with the 1.83-1.57 Ma reflector at the base of the previously described syn-ramp wedge. Two volcaniclastic horizons are present in the Craco clays, the upper one probably corresponding to the well-known *m* horizon of the Vrica section in Calabria (PASINI & COLALONGO, 1994). The Santernian mudstones grade upwards into shoal-water shell-rich sandstones characterized by internal cross-lamination and bioturbation (Sant'Arcangelo Sandstone). Moving eastward, the Craco Clay-Sant'Arcangelo Sandstone couple (1.83-1.50 Ma interval in fig. 4) 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 and the previously described upper Pliocene thrust-top deposits of the P_{1-2} sequence are disconformably overlain by a thick pile of backstepping and deepening-upward coarse-clastic deposits referable to a retrograding fandelta system (Sarmento Synthem, 1.50-0.92 Ma interval in fig. 5). This unconformity-bounded unit is represented by alluvial conglomerates and coarse-grained fandelta deposits grading upward into marine-bar bioclastic sandstones and finally into prodelta clays and silty clays landward interfingering with brackish-water lagoonal mudstones. East of the Sant'Arcangelo depression, the alluvial conglomerates and the coarse-clastic fandelta deposits are laterally replaced by fandelta-front and shelfal sandstone lobes known in the geological literature as Tursi Sandstone. Seismic profiles available in the area show that the Tursi sandstones disconformably overlie the Craco clays smoothing topographic irregularities on top of the Apenninic nappes.

Along the margin of the mountain chain, the Tursi sandstones are conformably overlain by the open-shelf mudstones of the Sub-Apenninic Clay unit. We have divided the Sub-Apenninic clays into two portions (1.25-0.92 Ma and 0.92-0.70 Ma intervals) separated by a condensed muddy unit upward bounded by a volcaniclastic layer (V_2 horizon in fig. 5). In the subsurface, the 1.25-0.92 Ma interval is represented by quite homogeneous mudstones seismically expressed by an isopachous reflection-free unit draping the Tursi sandstones. This widespread muddy sheet is upward bounded by a very strong reflector corresponding to the above-described condensed unit of the surface sections. In the Sant'Arcangelo synform, the muddy interval is laterally replaced by prodelta/lagoon deposits that represent the uppermost portion of the Sarmento Synthem.

The time-space facies relationships between the Sarmento fandelta deposits, the Tursi sandstones and the lower portion of the Sub-Apenninic clays clearly depicts a backstepping and deepening-upward clastic wedge with a maximum flooding event around 0.92 Ma. This Emilian-Sicilian wedge was deposited on top of the allochthonous sheets when the latter were shaped as a wide passive shelf extended from the western flank of the present day Sant'Arcangelo synform to the buried front of the Apenninic nappes, gently dipping toward the foredeep basin. Therefore, as in the case of the underlying 3.30-2.13 Ma deposits of the P_{1-2} sequence, sedimentation took place on top of an inactive thrust toe and not in a piggyback basin forward limited by an active ridge, as commonly reported in the geological literature.

In the Sant'Arcangelo synform, the prodelta mudstones of the Sarmento Synthem and the older lower Pleistocene thrust-top deposits are overlain, with a remarkable angular unconformity, by a thick clastic unit of alluvial conglomerates and coarse-grained fandelta deposits showing a backstepping configuration and a broadly progradational facies architecture. This unit (Sinni Synthem in fig. 5) may be divided into two intervals. The lower interval is featured along the southern and western margins of the Sant'Arcangelo synform by retrograding alluvial conglomerates and subaerial fandelta-plain deposits grading into more distal fandelta-front deposits in the central part of the depression. The upper interval is characterized by prograding massive red alluvial conglomerates locally interrupted by *Planorbis*-rich black mudstones indicative of ephemeral ponds/marshes cropping out along the western and northern margins of the Sant'Arcangelo synform. The widespread occurrence of growth strata with internal progressive unconformities in the lower deposits of the Sinni Synthem in correspondence to the eastern margin of the Sant'Arcangelo basin (also recognizable in the subsurface in the few available lines crossing the synform) has been related to a forward thrust propagation responsible for the growth of a ramp anticline in the buried Apulia carbonates in correspondence to the Nocara Ridge (fig. 5). Growth folds and intraformational unconformities evidencing tilt movements toward NE are developed along the western margin and in correspondence to the northeastern corner of the basin. These tectonic features have been attributed to the occasional out-of-sequence reactivation of the previously abandoned leading edge of the lower Pleistocene Apennine duplex system.

The coarse-grained deposits of the Sinni Synthem, finally, are unconformably overlain by braid-plain conglomerates (Castronuovo Conglomerate) that interfinger with lacustrine deposits containing several volcaniclastic layers (San Lorenzo Clay). We do not know whether the Castronuovo conglomerates and the San Lorenzo clays are chronologically confined in the uppermost part of the lower Pleistocene or they reach the lower part of the middle Pleistocene. The correlation of the volcaniclastic levels of the San Lorenzo clays with the V_5-V_9 levels of the Montalbano sandstones east of the Nocara Ridge (see fig. 5) is merely hypothetic.

Younger Pleistocene deposits are represented in the Sant'Arcangelo synform by the Serra Corneta Conglomerate (PIERI *et alii*, 1994), likely corresponding to the Irsina Conglomerate in the Bradano Trough.

East of the Nocara Ridge (Montalbano-Policoro area), the coarse-grained deposits of the Sinni Synthem and the overlying Castronuovo conglomerates *plus* San Lorenzo clays are substituted by the upper portion (0.92-0.70 Ma interval in fig. 5) of the Sub-Apenninic clays grading upward into the nearshore Montalbano sandstones (0.70-0.66 Ma interval in fig. 5). The upper portion of the Sub-Apenninic clays and the overlying Montalbano sandstones, together with the several volcaniclastic layers, have been carefully investigated by CIARANFI *et alii* (1996 a, b) and MARINO (1996a). The Sub-Apenninic clays and the overlying Montalbano sandstones testify to a coarsening-upward prograding shelf system, the sedimentary evolution of which was controlled by the forward propagation of the active thrusts after a period of maximum out-of-sequence migration corresponding to the maximum retrogradation of the Sarmento Synthem.

THE PLIO-PLEISTOCENE THRUST-TOP, FOREDEEP AND FORELAND DEPOSITS OF SICILY

In the Plio-Pleistocene deposits of Sicily, several allostratigraphic units (Trubi, Enna, Gela, Selinunte and Sciacca groups *plus* Pina Group, the latter restricted to offshore foredeep areas) organized into 3rd and 4th-order depositional sequences have been recognized by CATALANO *et alii* (1993a, 1997). These sequences, recognized both in onshore and offshore sections, have been interpreted by these authors as eustatically controlled sedimentary cycles. A sea-level cycle chart, biostratigraphically calibrated on a high-resolution chronology of Mediterranean bioevents, has also been proposed. The new Plio-Pleistocene sequence chart resulted in good agreement with the cycle chart of the Gulf of Mexico formerly proposed by WORNARDT & VAIL (1991). CATALANO *et alii* (1997) emphasized the regional synchronicity of the sequence boundaries in all analyzed sections, from open-marine foreland areas to piggyback basins located on top of the Gela nappe. According to these authors, synsedimentary tectonics locally influenced the shape of the basins, as well as volume, thickness and stacking pattern of the basin-fill deposits, but did not control the timing of the sequence boundaries.

BUTLER *et alii* (1995), LICKORISH & BUTLER (1996) and BUTLER & LICKORISH (1997) disagree with a major eustatic control of the sequence boundaries and highlight the importance of the tectonics in the sedimentary evolution of piggyback basins in Central and Southern Sicily. The authors document well evident growth folds with progressive unconformities that have conditioned both the overall geometry of the basin and the internal facies architecture (see also BUTLER & GRASSO, 1993 and LICKORISH *et alii*, 1999). According to these authors, eustatic events would have influenced only minor sequences and parasequences within tectonically controlled major sequences. A strong influence of the tectonic activity on the sedimentation in Western and Central Sicily during Plio-Pleistocene times has also been recognized by VITALE (1997a, b) and by VITALE and SULLI (1997) who agree, anyway, with the eustatically-controlled cycle chart of CATALANO *et alii* (1997).

In this paper, we will stress the importance of periodicity in the tectonic activity as one of the controlling factors for cyclical processes in the stratigraphic record. We have distinguished in Sicily three tectonically controlled depositional sequences separated by major angular unconformities or disconformities (see figs. 10-12) the ages of which broadly match the sequence boundaries recognized by CATALANO *et alii* (1997). The boundaries of a thrust-related depositional sequence are placed in correspondence to well-defined tectonic events that follow each other, in Sicily as in the Apennines, according to a recurrent leitmotif that describes the "caterpillar-like" motion of the tectonic wedge (PATACCA & SCANDONE, 2001). Thrust-related depositional sequences include more eustatically-controlled sequences *sensu* CATALANO *et alii* (1997).

Figure 10 is a simplified geological map of Southern Sicily showing the distribution of the Plio-Pleistocene thrust-top deposits arranged according to the tectonostratigraphic scheme of figure 11. The map also provides the location of the analyzed seismic profiles in the offshore and the location of the wells that have been used to constrain and calibrate the seismic facies. The heavy dotted line represents the front of the Gela nappe in the subsurface. Figure 11 is a chronostratigraphic diagram along a N-S transect collecting different sources of information: surface data derived from the investigation of the basin-fill deposits lying on top of the Gela nappe and of the Hyblean Plateau and subsurface data derived from the seismostratigraphic interpretation of the offshore foredeep/foreland deposits integrated by well log analyses. The diagram indicates the Plio-Pleistocene thrust-related sequences and systems tracts as they result from the stratigraphic correlation of coeval thrust-top, foredeep and foreland deposits. The virtual section of figure 12 shows the overall sedimentary geometry and the internal stratal architecture of the P_{1-2}, P_2-Q_1 and Q_{1-3} sequences from the Caltanissetta Trough to the offshore foreland areas.

The lower thrust-related sequence (P_{1-2} depositional sequence) pre-dates the incorporation of the most external depositional domains such as the Sciacca domain in the duplex system. The intermediate sequence (P_2-Q_1), pre-dating the growth of the frontal ramp of the allochthonous sheets, testifies to a complex tectonic history during which periods of southward nappe displacement over a long thrust flat alternated with periods of breaching of the tectonic wedge and creation of piggyback basins on top of the allochthonous sheets. The upper sequence (Q_{1-3}), though strongly influenced by eustatic sea-level changes, shows anyway a major tectonic control, the tectonic activity being expressed by the growth of the Gela-nappe frontal ramp and by a subsequent out-of-sequence migration of the thrust trajectories. The timing of the P_{1-2} and P_2-Q_1 depositional sequences and related systems tracts is very well constrained because of the existence, in mainland Sicily, of extensive and careful biostratigraphic analyses coupled with detailed cyclostratigraphic and magnetostratigraphic investigations (e.g. CITA & GARTNER, 1973; RUGGIERI & SPROVIERI, 1975; BROLSMA 1978; SPAAK, 1983; GUERRERA *et alii*, 1984; RIO *et alii*, 1984, 1991, 1994; DE VISSER *et alii*, 1989; HILGEN, 1991; LANGEREIS & HILGEN, 1991; CHANNEL *et alii*, 1992; SPROVIERI, 1992, 1993; HILGEN & LANGEREIS, 1993; DI STEFANO *et alii*, 1993, 1996; SPROVIERI *et alii*, 1996; SGARRELLA *et alii*, 1997, 1999). The biostratigraphic calibration of the time-correlative surfaces of the P_{1-2} and P_2-Q_1 sequences in the foredeep deposits is based on the Pina 1 well. The ages of the key boundary surfaces of the Q_{1-3} sequence, finally, derive from correlations with the pelagic foreland deposits drilled by ODP Hole 963 (SHIPBOARD SCIENTIFIC PARTY, 1996b).

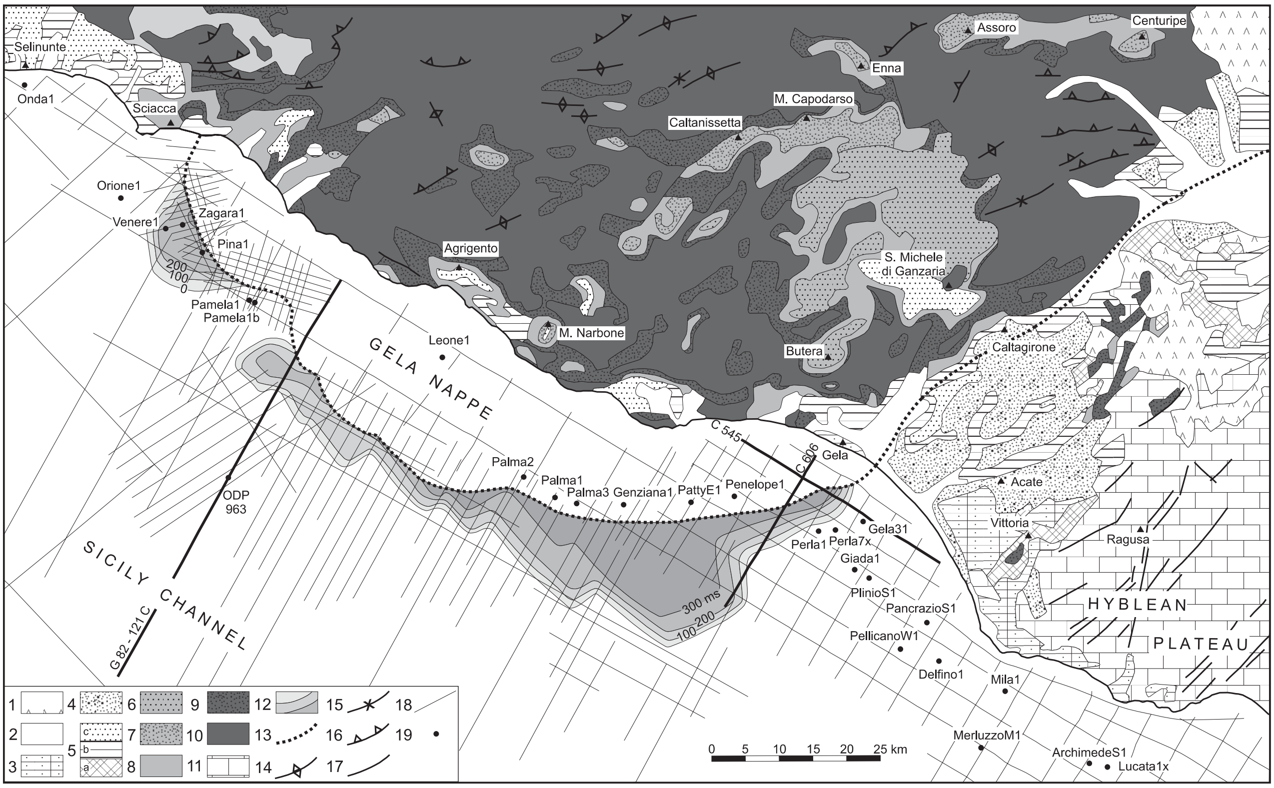


Fig. 10 - Geological-structural map of Southern Sicily with the grid of the analyzed seismic lines and the location of the wells used to tie the seismic profiles. Isochronopachs (in milliseconds) along the front of the Gela nappe express the thickness of the lower Pleistocene syn-ramp clastic wedge.

1 Volcanites and volcaniclastites (upper Pliocene-Holocene). 2 Continental and subordinate shallow-marine deposits (upper Pleistocene p.p.-Holocene). 3-5 Q_{1-3} depositional sequence: 3 terraced coastal-marine deposits (Vittoria Group, middle Pleistocene p.p.-upper Pleistocene p.p.); 4 continental to coastal-marine deposits unconformably overlying the Gela nappe and the Hyblean foreland. They have filled the foredeep basin in correspondence to the northwestern margin of the Hyblean Plateau (Acate Group, lower Pleistocene p.p.-middle Pleistocene p.p.); 5c shallow-marine sandstones (San Michele di Ganzaria sandstones, lower Pleistocene p.p.); 5b open-shelf clays and silty clays with subordinate sandstones and dominantly clayey deposits in the Hyblean foreland (Caltagirone clays, lower Pleistocene p.p.); 5a shallow-water bioclastic calcarenites at the base of the clayey sequence in the Hyblean foreland (lower Pleistocene p.p.). 6-8 P_2-Q_1 depositional sequence: 6 shallow-marine sandstones (Butera sandstones, lower Pleistocene p.p.); 7 shallow-marine sandstones and bioclastic calcarenites (Capodarso calcarenites, upper Pliocene p.p.); 8 deeper-marine clays and silty clays with subordinate sandstones (Monte Narbone Formation, upper Pliocene p.p.-lower Pleistocene p.p.); dominantly muddy deposits in the Hyblean foreland (upper Pliocene p.p.-lower Pleistocene p.p.). 9 P_{1-2} depositional sequence: pelagic lime deposits (Trubi Formation, lower Pliocene-upper Pliocene p.p.) with local olistostromes of exotic materials; “Marnoso-Arenacea” Formation of the Belice Valley (lower Pliocene-upper Pliocene p.p.). 10 Undifferentiated Sicilian Maghrebide thrust sheets and overlying upper Miocene thrust-top deposits. 11 Cretaceous-Miocene deposits of the Hyblean Plateau. 12 Isochronopachs (contour in milliseconds) of the syn-ramp clastic wedge in front of the Gela nappe. 13 Front of the Gela nappe. 14 Anticline axis. 15 Syncline axis. 16 Thrust emergence behind the front of the Gela nappe. 17 Normal faults and strike-slip faults.

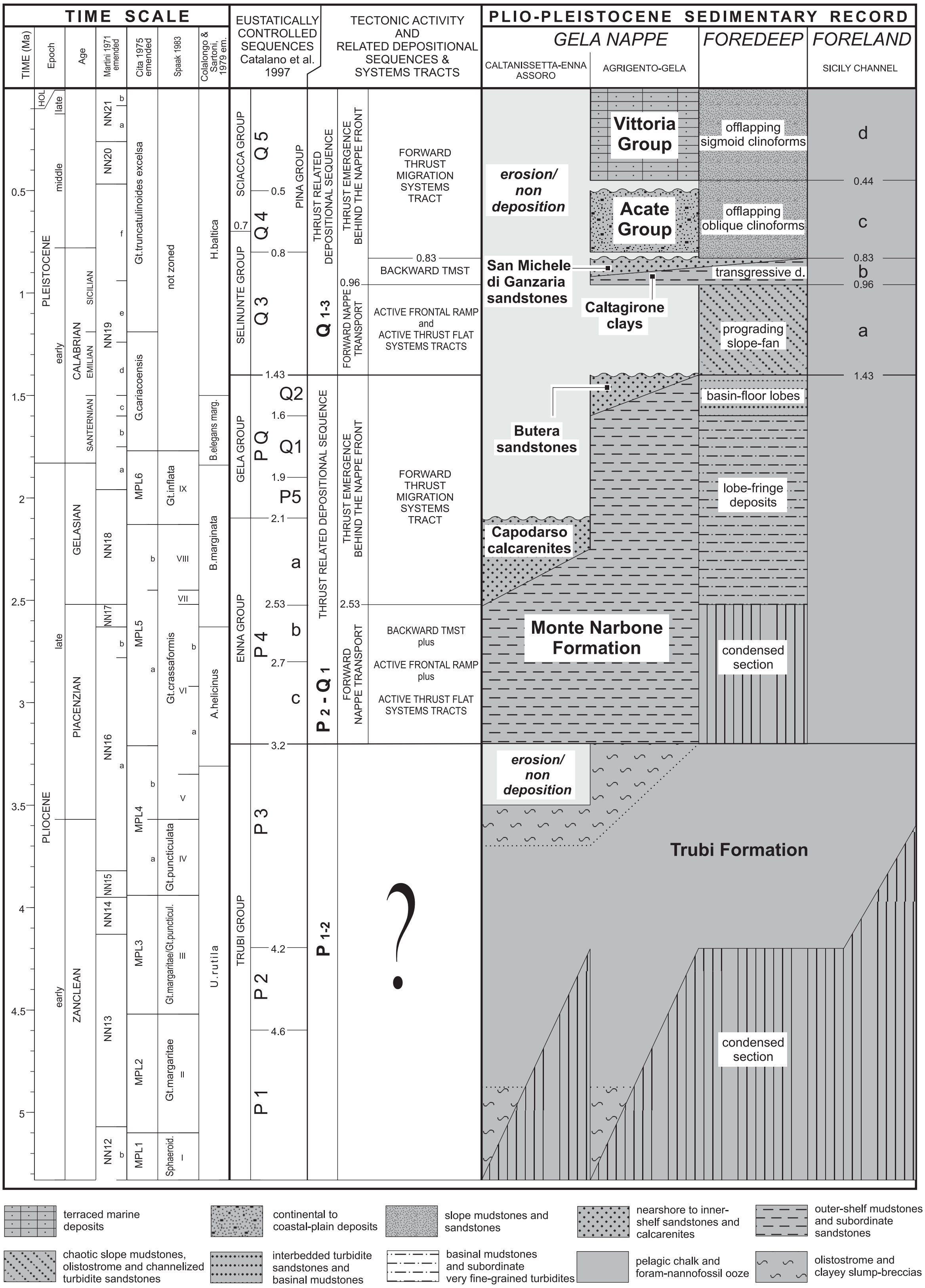


Fig. 11 - Chronostratigraphic diagram showing the correlation between the thrust-top, foredeep and foreland deposits in Sicily along a N-S transect. The thrust-related depositional sequences recognized in this paper have been linked, together with the relative systems tracts, to the eustatically-controlled sequences of CATALANO *et alii* (1997). The a-d intervals are seismostratigraphic units distinguished in the offshore foreland areas correlatable with the lower-upper Pleistocene systems tracts defined in thrust belt-foredeep areas.

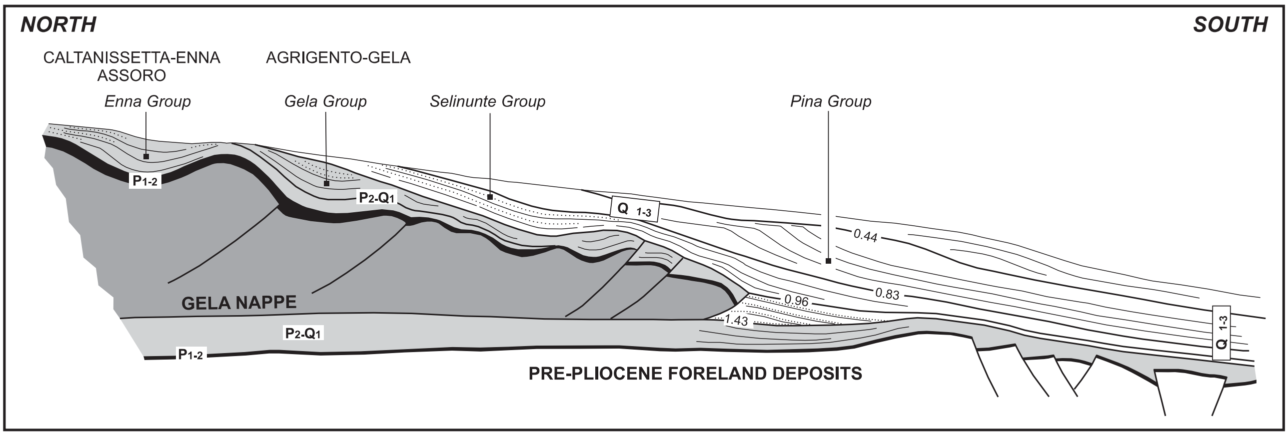


Fig. 12 - Not-to-scale virtual section across the thrust belt-foredeep system in Southern Sicily. The section shows the overall sedimentary geometry and the internal stratal architecture of the P_{1-2}, P_2-Q_1 and Q_{1-3} sequences from the Caltanissetta Trough to the offshore foreland areas. The ages identifying the surfaces bounding the sequences and the systems tracts derive from correlations with the pelagic foreland deposits drilled by ODP Hole 963. Eustatically controlled sequences of CATALANO *et alii* (1997) have been also indicated.

P_{1-2} DEPOSITIONAL SEQUENCE (LOWER PLIOCENE-UPPER PLIOCENE p.p.)

The P_{1-2} depositional sequence is everywhere represented by the well-known Trubi Formation (see figs. 10 and 11), except in Western Sicily where the Trubi pelagic ooze has been laterally replaced by terrigenous deposits (Belice sequence in CATALANO *et alii*, 1997; Formazione Marnoso-Arenacea del Belice in RUGGIERI & TORRE, 1973 and VITALE, 1997a).

The Trubi Formation, consisting of rhythmically bedded marly limestones and marlstones rich in calcareous plankton, has been classically investigated by means of microfossil and nannofossil analyses that have significantly improved, together with a detailed cyclostratigraphy, the astronomically-calibrated time scale based on the Mediterranean bioevents (see SGARRELLA *et alii*, 1997, 1999 and references therein).

In Southern Sicily and in the adjacent offshore areas, the Trubi Formation forms an almost continuous sheet on top of the Gela nappe and on top of the gently deformed pre-Pliocene foreland deposits (see fig. 12). Because of topographic irregularities on top of the allochthonous substratum, the base of the Trubi Formation in mainland Sicily is a diachronous surface ranging in age from the *Sphaeroidinellopsis* acme zone to the *Gt. margaritae-Gt. puncticulata* concurrent range zone. Owing to the extreme stratal condensation, in offshore foreland areas the base of the Trubi Formation may correspond to the top of the *Gt. puncticulata* zone (see fig. 11). The upper part of the formation reaches the lower part of the Spaak's VIa *Gt. crassaformis* zone (WEZEL, 1963; CITA & GARTNER, 1973; DI GRANDE *et alii*, 1976; DI GERONIMO *et alii*, 1978; LANGEREIS & HILGEN, 1991; CHANNEL ET *ALII*, 1992; BUTLER & GRASSO, 1993; BUTLER & LICKORISH, 1997; CATALANO *et alii*, 1997; LICKORISH *et alii*, 1999).

According to ARGNANI (1987) the draping geometry of the Trubi Formation on top of the Gela nappe suggests that the tectonic wedge in Southern Sicily had reached the critical taper before the beginning of the Pliocene and was able to move southward during Pliocene and Pleistocene times in the absence of significant internal deformations. However, the widespread occurrence of olistostromes in the hemipelagic lime carbonates (DI GRANDE *et alii*, 1976) testifies to the occurrence of breaches in the advancing nappes. Breaching phenomena in a tectonic wedge commonly take place when the length of the thrust flat at the base of the wedge reaches the critical length. In such a case, telescopic shortening and consequent thickening of the allochthonous sheets re-establish favourable mechanical conditions for basal sliding. The absence of significant terrigenous supply in the early Pliocene, in any case, suggests the absence of an important drainage systems fed by high-energy reliefs and consequently the absence of important tectonic imbrications in the northern areas of the mountain chain.

P_2-Q_1 DEPOSITIONAL SEQUENCE (UPPER PLIOCENE p.p.-LOWER PLEISTOCENE p.p.)

Thrust-top deposits referable to the P_2-Q_1 depositional sequence are widespread and well exposed in the Assoro-Centuripe basin, in the Enna region and in the whole Caltanissetta Trough, as well as in the Agrigento-Gela area (see figs. 10-12.). Foredeep and foreland deposits belonging to this depositional sequence are known in the subsurface and have been extensively investigated for petroleum exploration. Sporadically, upper Pliocene-lower Pleistocene muddy deposits crop out in the foreland area north of Ragusa.

P_2-Q_1 foredeep and foreland deposits

The bulk of the foredeep deposits of the P_2-Q_1 depositional sequence has been tectonically covered by the Gela nappe during the southward transport of the allochthonous sheets. Seismic analyses allowed us to investigate the facies architecture of the distal portion of the original sedimentary body, well preserved ahead of the nappe front. The stratigraphic analysis of more internal portions of the clastic wedge, buried beneath the allochthonous sheets, is based on data derived from commercial wells located 3-4 kilometres at the rear of the nappe front.

In front of he Gela nappe, the outermost portion of the foredeep deposits is represented by mudstones with intercalations of very thin-bedded sandstones grading upward into deposits with a slightly higher sand/mud ratio. They form as a whole a relatively confined clastic wedge a few hundred metres thick systematically overlying a few tens of metres of condensed silty shales. On seismic profiles the condensed deposits are expressed by a strong and more or less continuous reflector marking the master sequence boundary between the P_{1-2} and the Q_{1-3} sequences. The overlying deposits are represented by two seismostratigraphic units (2.53-1.60 and 1.60-1.43 Ma intervals in figs. 13 and 14). The lower unit is characterized by low-amplitude continuous faint reflectors, interpreted as lobe-fringe deposits, laterally grading into a reflection-free facies. The upper unit is imaged by higher-amplitude even parallel reflectors, interpreted as basin-floor lobes, showing evident downlap (e.g. fig. 13) or onlap terminations (e.g. fig. 14) depending on the local basin physiography. These reflectors appear to have been truncated by the overlying seismic unit, suggesting a deformation of the primary geometry caused by a northward tilt of the foredeep substratum. Moving from the nappe front toward the south, the fine-grained sandstones are laterally replaced by hemipelagic marls and clays that form together with the underlying Trubi chalk a reflection-free drape widespread over the whole offshore foreland area.

The ages of the key surfaces bounding the recognized seismostratigraphic units derive from the micropaleontological information contained in the available well logs and by the results of the nannofossil analyses carried out by DI STEFANO *et alii* (1993) on the Pina 1 well. This well documents:

- A condensed interval between 2100 and 2075 m, ranging from the upper portion of the NN 16a (*D. tamalis*) nannofossil zone (tuned with the MPL 5 foraminiferal zone, the base of which is marked by the last occurrence of *Sphaeroidinellopsis spp.*) to the upper portion of the NN17 (*D. pentaradiatus*) zone. This interval represents the condensed section between 3.2 and 2.53 Ma in figure 11;
- A muddy interval with very thin-bedded sandstones between 2075 and 1925 m, spanning the time interval between the NN18 (*D. broweri*) nannofossil zone (tuned with the *Gt. crassaformis* foraminiferal zone) and the NN 19b (*C. macintyrei*) zone p.p. This interval represents the lobe fringe deposits between 2.53 and 1.60 Ma in figure 11;
- A slightly sandy interval between 1925 and 1830 m, ranging from the NN19b (*C. macintyrei*) zone p. p. to the NN19d (Large *Gephyrocapsa*) nannofossil zone p.p. This interval represents the basin-floor lobe deposits between 1.60 and 1.43 Ma in figure 11.

P_2-Q_1 thrust-top deposits

In mainland Sicily, the Trubi pelagic chalk is unconformably overlain by thrust-top deposits of the P_2-Q_1 sequence filling piggyback basins located in the hangingwall of active thrusts. In the Assoro-Centuripe and Enna basins, as well as in the northern areas of the Caltanissetta Trough (DI GRANDE *et alii*, 1976; DI GERONIMO *et alii*, 1978; BUTLER & GRASSO, 1993; CATALANO *et alii*, 1993a; BUTLER *et alii*, 1995; LICKORISH & BUTLER, 1996; BUTLER & LICKORISH, 1997; VITALE 1997b) the lower part of the sequence consists of basin to outer shelf clayey mudstones and subordinate sandstones (Monte Narbone Formation or Enna marls of RODA, 1967) reaching the maximum thickness (around 300 metres) in the Assoro area. The muddy deposits of the Monte Narbone Formation are overlain by inner shelf to nearshore bioclastic calcarenites organized into offlapping progradational sequences (Capodarso calcarenites). Evident progressive unconformities and growth strata testify to an important synsedimentary deformation of the substratum. The Capodarso calcarenites reach a maximum thickness of 450 metres in the Assoro area. Moving toward the central-southern areas of the Caltanissetta Trough, the coastal carbonate sands of the Capodarso calcarenites are laterally replaced by outer-shelf clays and silty clays referable to the upper Pliocene portion (tuned with the NN 18 p.p. nannofossil zone) of the Monte Narbone Formation. The clayey mudstones of the Monte Narbone formation extend upward to the early Pleistocene and are stratigraphically overlain by shallow-marine sandstones and by calcarenites containing *Arctica islandica* (Butera sandstones) that reach a maximum thickness of about 500 metres in the type area (e.g. Monte San Nicola and Monte Narbone sections, WEZEL, 1963; DI GERONIMO, 1969; DI GERONIMO *et alii*, 1978 CHANNEL, *et alii* 1992; SPROVIERI, 1992; DI STEFANO *et alii*, 1993b; RIO *et alii*, 1991, 1994; CATALANO *et alii*, 1997). The lower Pleistocene Butera sandstones, as the upper Pliocene Capodarso calcarenites, are characterized by an overall prograding geometry. Local internal unconformities have been recognized also in the Butera sandstones by CATALANO *et alii* (1997).

The Monte Narbone-Capodarso *plus* Butera deposits display some similarities with the deposits of the P_{1-2} sequence in the Southern Apennines. The Capodarso calcarenites, in particular, displaying spectacular progressive unconformities and growth strata, are the equivalent of the previously described upper portion of the P_{1-2} sequence in the Ofanto synform where a thick pile of overall prograding clastic deposits characterized by evident progressive unconformities was accumulated at the front of a growing antiformal stack (see figs. 4 and 9). Unlike the Southern Apennines, however, no important fandelta system seems to have developed in Sicily during

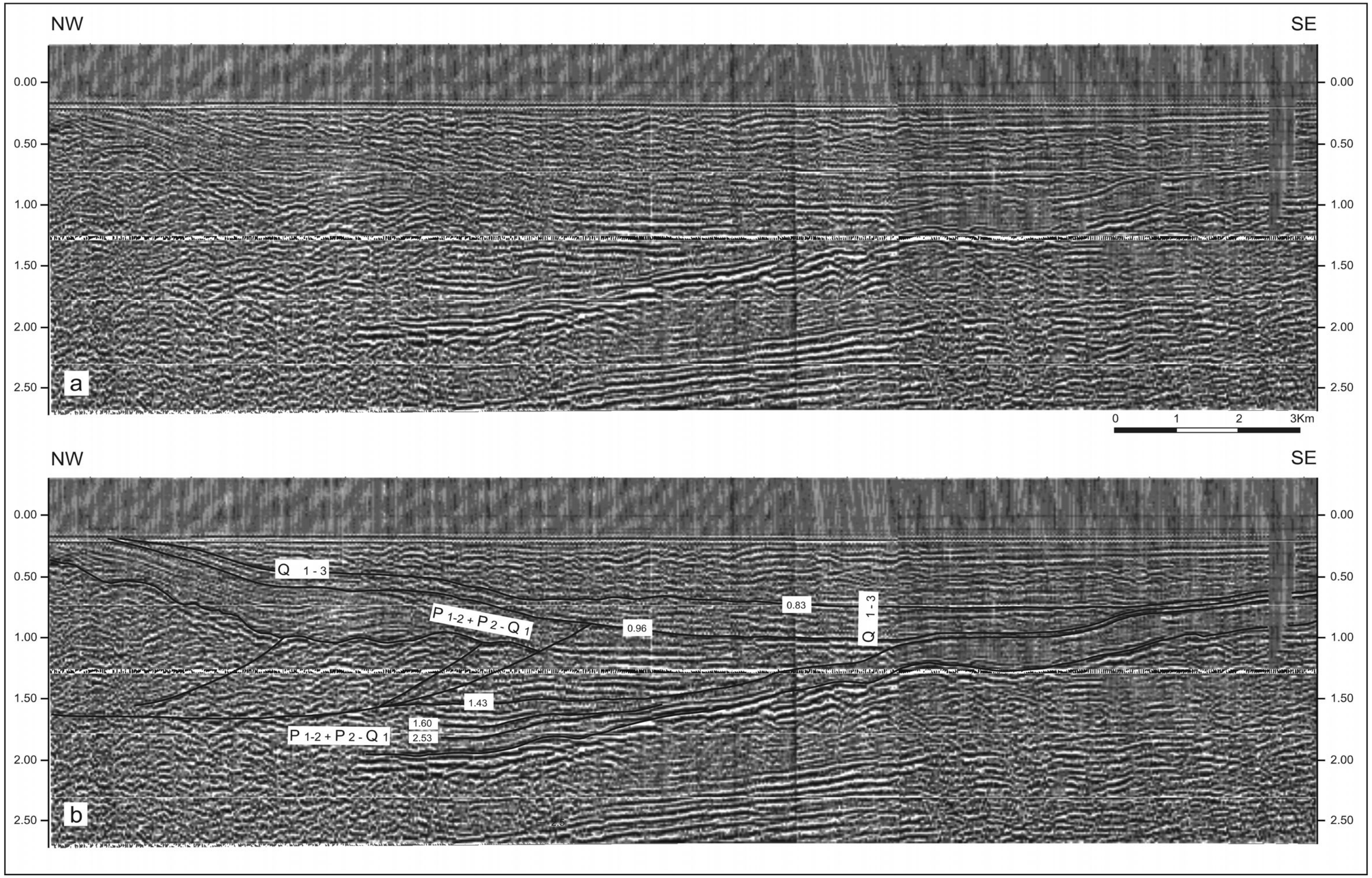


Fig. 13 - Seismic line C 545 (a uninterpreted; b: interpreted) illustrating a complete section from the front of the Gela nappe to the foreland area. The seismic profile evidences the basic seismostratigraphic signatures of the Plio-Pleistocene thrust-top, foredeep and foreland deposits. Depositional sequences and ages of the surfaces bounding sequences and systems tracts derive from the chronostratigraphic diagram of figure 11. Location of the seismic section in figure 10.

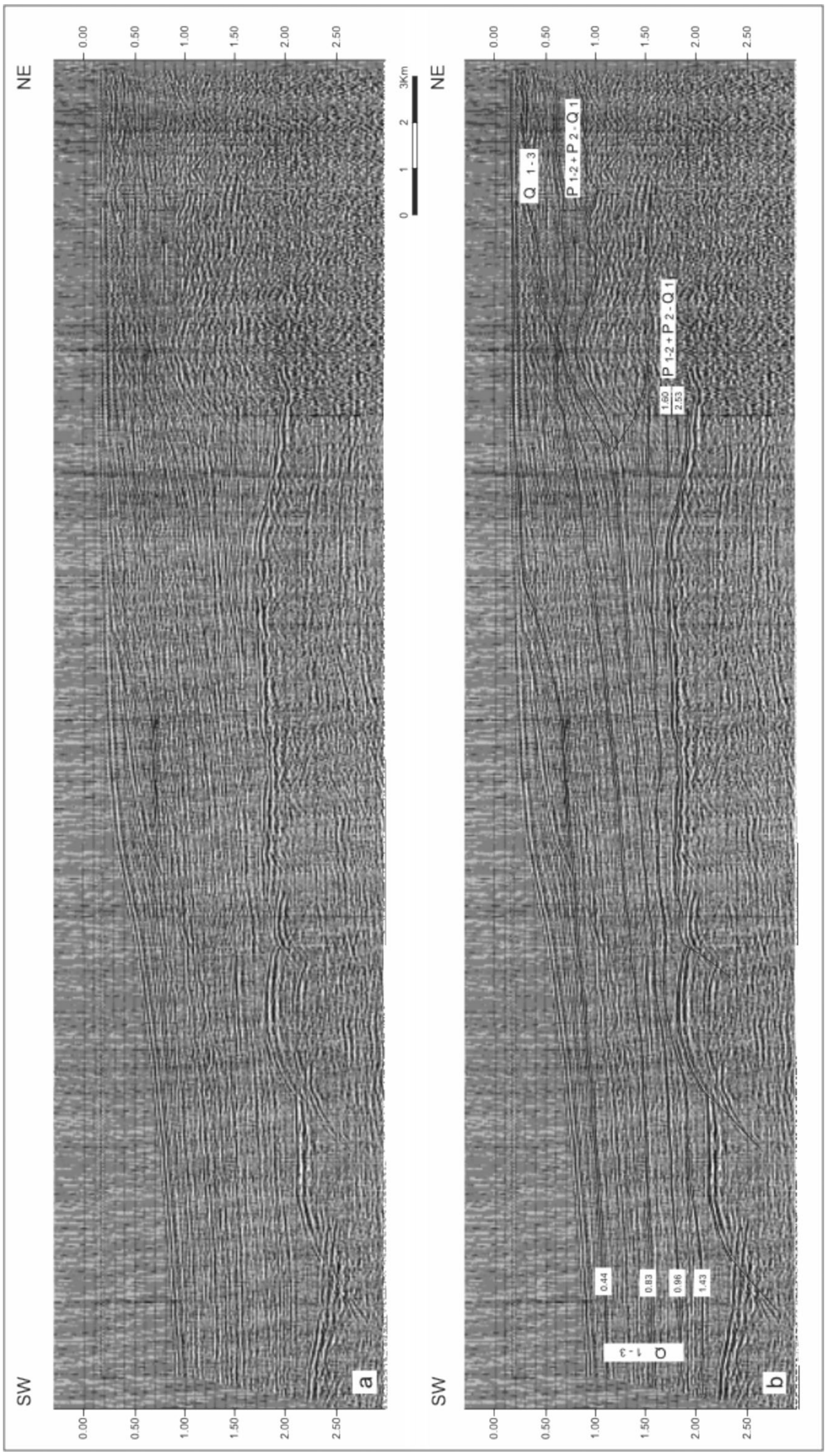


Fig. 14 - Seismic line C 606 (a: uninterpreted; b: interpreted) crossing the front of the Gela nappe and the Plio-Pleistocene foredeep basin (location in fig. 10). Depositional sequences and ages of the surfaces bounding sequences and systems tracts derive from the chronostratigraphic diagram of figure 11.

late Pliocene times, probably because of the limited extent and the scarce elevation of the drainage basins feeding the Caltanissetta depression.

In our opinion, this difference partly derives from the different rock volumes incorporated in the mountain chain because of the different rates of shortening in the two regions (about 1 cm/year in Sicily versus more that 4 cm/year in the Southern Apennines, see PATACCA & SCANDONE, 2001), and partly derives from the different partition of the deformation. In the southern Apennines, in fact, the upper Pliocene forward thrust propagation created huge antiformal stacks, both in the buried Apulia carbonates and in the roof units of the duplex system, with a consequent drastic rejuvenation of the mountain chain. In Sicily, on the contrary, forward thrust propagation seem to have distributed the cumulative shortening over a wider area creating a number of southward-migrating active ridges and associated piggyback-basins in the hangingwall of possible blind thrusts.

Q_{1-3} DEPOSITIONAL SEQUENCE (LOWER PLEISTOCENE p.p.-UPPER PLEISTOCENE)

During the early Pleistocene, the South-Sicily foredeep basin was divided into two portions, the first one developed in the Agrigento-Gela offshore south of the front of the Gela nappe and the second one developed along the northwestern margin of the Hyblean Plateau. In the Agrigento-Gela offshore, flexural subsidence allowed the persistence of a well-developed foredeep basin known in the geological literature as Gela basin. Along the northwestern boundary of the Hyblean Plateau, on the contrary, sedimentation rate exceeded subsidence and consequently the foredeep basin was progressively filled until paralic to continental clastic deposits prograded over the foreland.

The general configuration and the internal stratal architecture of the Q_{1-3} depositional sequence appear to have been closely controlled by active thrust propagation *plus* flexural subsidence, even though a glacio-eustatic influence is clearly recognizable. In the offshore areas, where foredeep deposits are preserved, the Q_{1-3} depositional sequence is more complete and four major seismostratigraphic units have been distinguished (see figs. 11-14): 1) a clastic wedge of prograding slope-fan deposits (1.43-0.96 Ma interval), 2) a transgressive muddier unit (0.96-0.83 Ma interval), 3) a prograding shelf-margin unit consisting of offlapping oblique clinoforms (0.83-0.44 Ma interval) and finally 4) a prograding shelf-margin unit of offlapping sigmoid clinoforms younger that 0.44 Ma. The seismostratigraphic units 3 and 4 are landward separated by a pronounced disconformity interpreted as an erosional surface that marks an important eustatic sea-level fall (0.44 Ma surface in fig. 12). The above-mentioned foredeep units grade laterally, toward the foreland, into a homogeneous nannofossil clay unit explored by the ODP 963 holes (see seismic line G82-121 in fig. 15). The seismostratigraphic interpretation of the entire G82-121 line allowed us to distinguish the pelagic counterparts of the four seismostratigraphic units recognized in the foredeep basin (a-d units in figures 11 and 15). The projection of the ODP Hole 963B on the seismic line G-82-121 (fig. 16) has provided important chronological constraints allowing the age calibration of the surfaces bounding the a-d units (fig. 17). The age calibration derives from the integration of all stratigraphic data available in the ODP Initial Reports and ODP Scientific Results (SHIPBOARD SCIENTIFIC PARTY, 1996b; DI STEFANO, 1998; RICHTER *et alii*, 1998).

In mainland Sicily, the Q_{1-3} sequence is represented by transgressive open-shelf mudstones (Caltagirone clays). This muddy unit, overlying in the Hyblean foreland a discontinuous veneer of shallow-water bioclastic calcarenites, grade upward into shallow-marine sandstones (San Michele di Ganzaria sandstones). Coastal-plain to continental deposits (Acate Group) disconformably overlie with retrograding geometry Plio-Pleistocene deposits of older sequences and the carbonates of the Hyblean Plateau. These deposits and the overlying terraced marine deposits if the Vittoria Group represent the topsets of the previously described subsurface shelf-margin deposits.

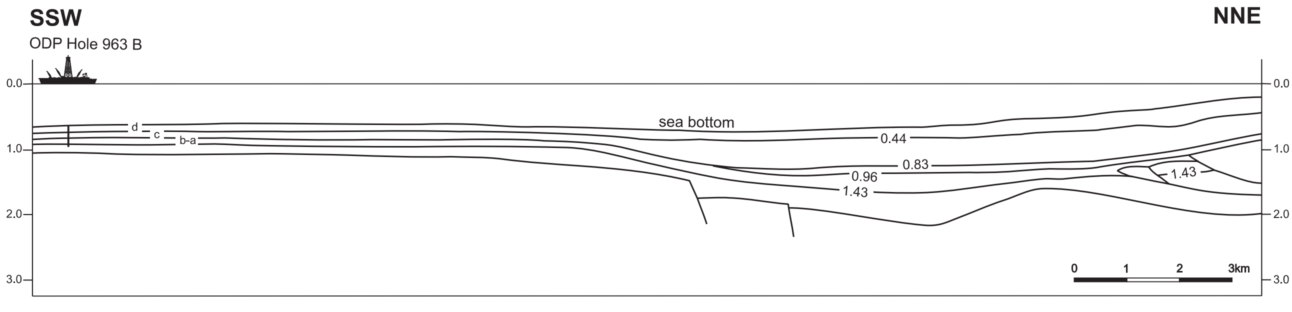


Fig. 15 - Line drawing of the seismic line G82-121 showing the correlation between the thrust-top *plus* foredeep deposits recognized along the front of the Gela nappe and the pelagic deposits drilled by the ODP 963 holes. Note near the front of the allochthonous sheets the presence of Plio-Pleistocene foredeep deposits detached from their original substratum and incorporated in the tectonic wedge.

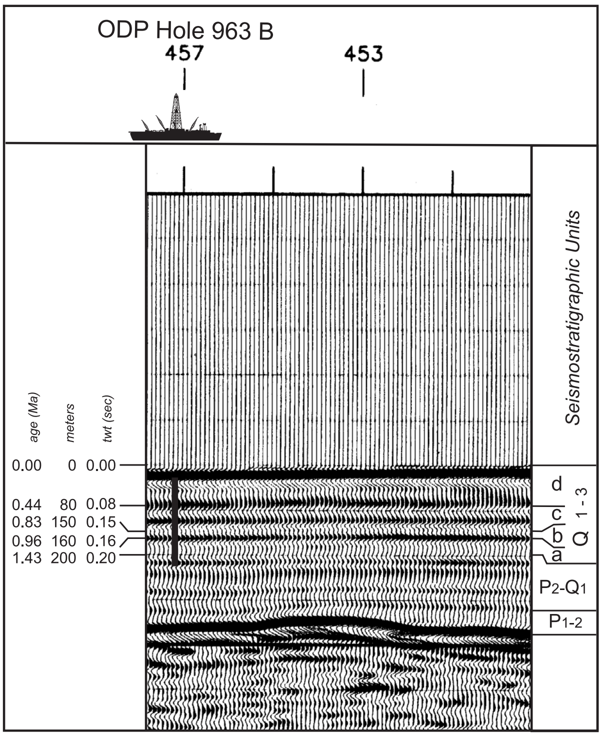


Fig. 16 - Portion of the seismic line G-82-121C showing the setting of the ODP site 963 and the projection of Hole 963B with the approximate penetration depth (TD=207 m bsf). The boundaries of the a-d intervals of the Q_{1-3} deposits on the right side of the picture (pelagic units correlatable with the lower-upper Pleistocene systems tracts defined in thrust belt-foredeep areas) derive from the interpretation of the entire seismic profile, starting from the front of the Gela nappe. Depths in twt and inferred absolute ages of the Q_{1-3} intervals have been indicated on the left side of the picture.

Q_{1}-3 thrust-top, foredeep and foreland deposits in the offshore areas

The lower portion of the Q_{1-3} depositional sequence in the Gela foredeep basin (1.43-0.96 Ma interval in fig. 11 and 12) is represented by a wedge-shaped clastic unit truncated upsection by the frontal ramp of the allochthonous sheets (syn-ramp clastic wedge).

This unit, organized into a gently prograding slope-fan system (figs. 13 and 14), is seismically characterized by a stack of quite continuous strong reflectors with mounded configuration laterally replaced by weak parallel reflectors. The latter vanish laterally, converging into a thin reflection-free layer that drapes the foreland (unit a in fig. 11 and unit Q_{1-3}a in fig. 16). Reflection termination obviously depends on the local basin morphology. An onlap configuration is evident in figure 13 where a still persisting relatively deep and confined basin is progressively filled by the Q_{1-3} syn-ramp deposits. Figure 14, on the contrary, shows a downlap termination of the Q_{1-3} syn-ramp deposits that spread out on a flat morphology. The submarine smooth topography derived from the progressive filling of the previous P_2-Q_1 foredeep basin in the absence of a very important flexure-hinge retreat toward SE.

An Emilian p.p.-early Sicilian age of the syn-ramp wedge derives from the biostratigraphic data contained in the available commercial wells and from the ODP Hole 963B. The absolute age of the lower and upper boundaries of the Q_{1-3}a interval (figs. 16 and 17) has been estimated from the sedimentation rate values reported in the Initial Reports of the ODP Site 963. An age not older than the Emilian has also been recognized in the Pina 1 well by DI STEFANO *et alii* (1993).

The syn-ramp clastic wedge is overlain by a transgressive system (0.96-0.83 Ma interval in figs. 11-14) represented by a coarsening-upward sequence that seals the frontal ramp of the Gela nappe. On seismic lines, these deposits are everywhere characterized by an almost reflection-free interval corresponding to a sheet of muddy deposits and by an upper sandy unit characterized by packages of rather continuous medium to high-frequency and medium to high-amplitude reflectors. This seismic couple, representing a transgressive shallowing-upward shelfal sequence on top of the Gela nappe, overlies with gentle angular unconformity older deposits of the P_2-Q_1 sequence and is upward deeply incised by the overlying coarse-clastic deposits of the Acate Group (figs. 13 and 14). Basinward, the transgressive system is represented by a stack of down-sloping parallel to sub-parallel reflectors showing slope-front fill configuration. The package of sloping reflectors merges downdip into a thin-bedded turbidite unit seismically imaged by rather continuous thin parallel reflectors. Moving toward distal foreland areas, the turbidite beds onlap against persisting submarine reliefs smoothing topographic irregularities or converge into a transparent thin pelagic drape laterally merging with a strong continuous reflector corresponding to the highly condensed pelagic deposits of the interval b in figure 11. The Q_{1-3}b interval has been chronologically constrained by the biostratigraphic and magnetostratigraphic data deriving from the ODP 963B Hole (see fig. 17). The absolute ages of the boundaries were estimated from the sedimentation rates given in the ODP 963 Initial Reports.

A sand-rich unit (0.83-0.44 Ma interval in figs. 11-14) displaying in NE-SW oriented seismic lines evident south-dipping oblique clinoforms builds an overall prograding depositional slope above the rather starved transgressive system (fig. 14). This unit overlies the Q_{1-3} transgressive deposits with a local disconformity along the margin of the Gela nappe. On WNW-ESE oriented seismic lines the offlapping system of clinoforms evidences a rather complex network of erosional channels probably related to eustatic sea-level falls.

The general shape of the oblique clinoforms, the foresets of which form concave-upward strata that join the gently dipping bottomset reflectors, suggests a quite important sediment supply together with a rather high rate of subsidence in the foreland areas. The oblique-tangential clinoforms pass toward the foreland into thinner bottomsets represented by even parallel continuous reflectors distally vanishing into hemipelagic deposits (c interval of fig.11 and Q_{1-3}c interval of figures 16 and 17). The absolute age of the surfaces bounding the Q_{1-3}c seismic unit have been derived from the ODP data assuming a constant sedimentation rate of 180 Bubnoff units from the sea floor to the depth of 150 metres (see fig. 17). We have preferred to use in this interval a single average velocity because the different rates indicated in the ODP Site 963 (SHIPBOARD SCIENTIFIC PARTY, 1996b) are based on bioevents (*P. lacunosa* LO and E. *huxley* FO) the position of which in the sedimentary record of the ODP 963 holes is uncertain (see fig. 17).

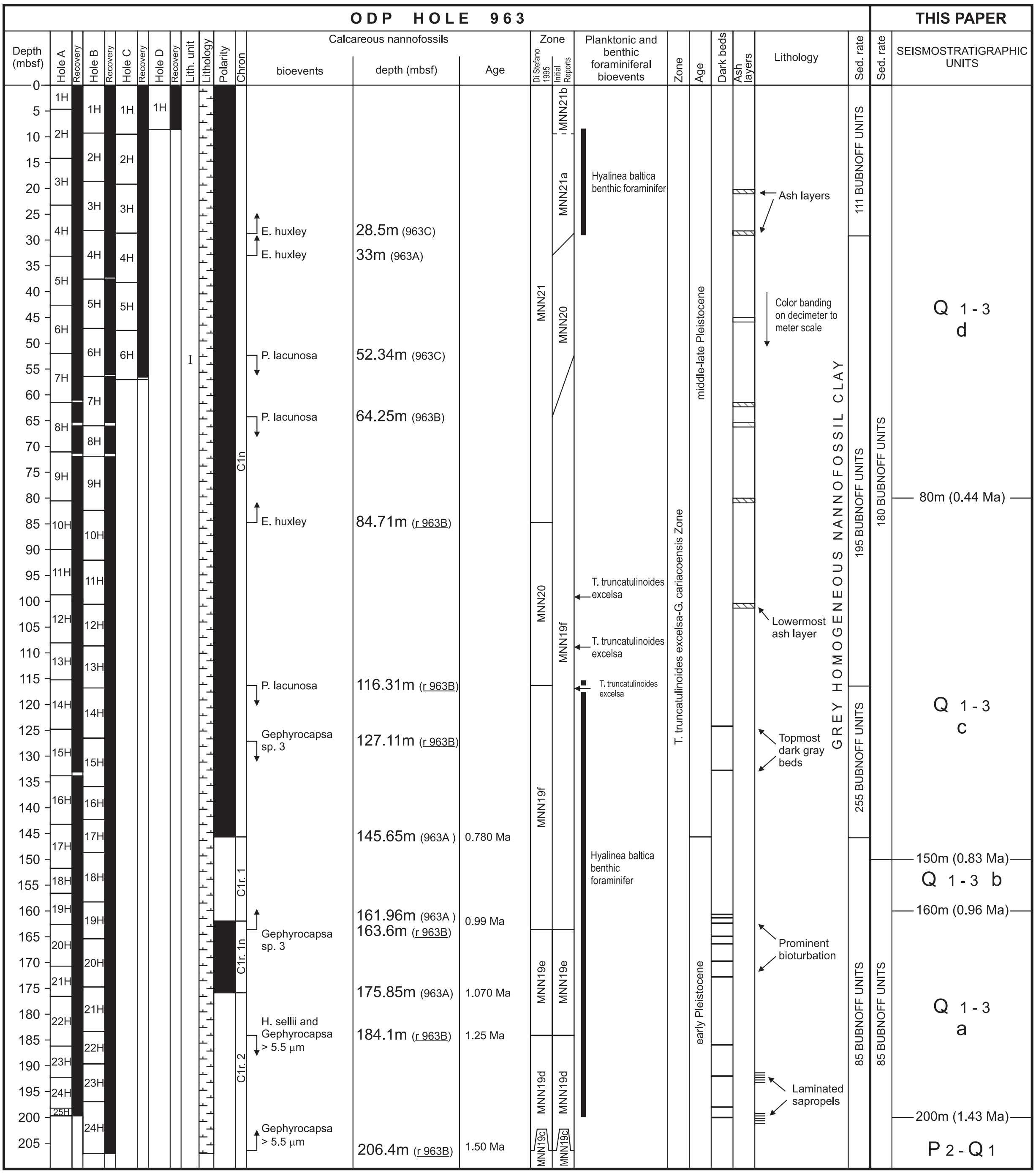


Fig. 17 - Age calibration of the Q_{1-3} pelagic intervals (seismostratigraphic units recognized in the seismic line G82-121C) crossed by ODP Hole 963. The boundary ages are based on all stratigraphic data available in the ODP Site 963 Initial Reports and Scientific Results. The heavy black lines mark the distribution of *Hyalinea baltica*. Depths and ages of the magnetostratigraphic events derive from RICHTER *et alii* (1998). Depths and ages of the biostratigraphic events labeled r 963B (revised Hole 963B) are from DI STEFANO (1998).

Along the front of the Gela nappe, gravitational slides are quite common features. TRINCARDI & ARGNANI (1990) have described a large-scale submarine slide related to the widespread collapse of a sediment around 700 metres thick that we have referred to the offlapping oblique-clinoform system.

An offlapping seismostratigraphic unit characterized by sigmoid clinoforms disconformably overlies topset segments of the previous oblique-clinoform system (figs. 11, 12 and 14). This unit, displaying a mud-prone facies, is well represented in the Sciacca and Acate offshore areas. In both areas the erosional truncation at the base of this unit evidences a major glacio-eustatic fall of the sea level probably corresponding to the marine isotope stage 12 occurring at the top of the NN 19f (*P. lacunosa*) nannofossil zone (see MASSARI *et alii*, 2002). Moving from the buried front of the Gela nappe toward the foreland areas, the gently-sigmoid clinoforms basinward converge at very low angle with a reflection-free layer (d interval in fig. 11 and Q_{1-3}d interval in figs. 16 and 17) made up of grey homogeneous nannofossil clays explored by the ODP Hole 963B from the sea floor to a depth of 80 metres. The absolute age of the lower boundary of the Q_{1-3}d unit is based on a sedimentation rate evaluation assuming a constant velocity as discussed above.

Q_{1-3} thrust-top and foreland deposits in mainland Sicily

In mainland Sicily, the lower portion of the Q_{1-3} depositional sequence is represented by a shallowing-upward transgressive system made up of open-shelf clays and silty clays (Caltagirone clays) grading upward into the San Michele di Ganzaria sandstones, a cross-stratified inner-shelf to nearshore clastic unit containing *Arctica islandica* (WEZEL, 1963: RODA, 1965; ARUTA *et alii*, 1972; SPROVIERI & CUSENZA, 1972 A, B; DI GERONIMO & COSTA, 1978; DI GERONIMO *et alii*, 1978; CARBONE *et alii*, 1984; GRASSO 1999). The base of this unit is everywhere marked by an erosional surface locally affected by gentle compressional deformation. Along the northwestern margin of the Hyblean Plateau, shallow-water bioclastic calcarenites are present at the base of the silty-clayey unit. The thickness of the Caltagirone clays ranges from a maximum of 30-40 metres in the San Michele di Ganzaria and Agrigento areas to about 400 metres in the Caltagirone area. The San Michele di Ganzaria sandstones reach a maximum thickness of about 500 metres in the type area. The lower Pleistocene Caltagirone clays with the underlying bioclastic calcarenites and the overlying San Michele di Ganzaria sandstones are the equivalent of the Gravina clays of the Southern Apennines with the underlying Gravina calcarenites and the overlying Monte Marano sandstones (compare chronostratigraphic diagrams of figs. 5 and 11).

The San Michele di Ganzaria sandstones are unconformably overlain by transgressive paralic to continental coarse-grained deposits *plus* lacustrine muddy sediments widely developed in the Acate-Caltagirone region (Acate Group). The continental-paralic deposits of the Acate Group represent the onshore topset segment of the previously described oblique clinoform system in the offshore areas. The Acate Group is finally unconformably overlain by terraced coastal-marine deposits (Vittoria Group) representing the topset segment of the sigmoid clinoforms in the offshore area.

PLIO-PLEISTOCENE SYNSEDIMENTARY TECTONICS IN THE SOUTHERN APENNINIC ARC CONTROLLING SEDIMENTATION IN THE FOREDEEP BASINS AND ON TOP OF THE ADVANCING NAPPES

In active thrust belt-foredeep systems, no addition of accommodation space would be possible above a hinterland-to-foreland advancing orogenic wedge, apart from the space created by a possible sea-level rise. However, out-of-sequence thrusts are able to split the mountain chain into an inner portion, lying in the hangingwall of the active thrust, affected by tectonic uplift and an outer portion, lying in the footwall of the active thrust, affected by flexural subsidence. Maximum addition of accommodation space above the tectonic wedge obviously takes place during periods of duplex breaching, when large areas of the mountain chain facing the foredeep basin are inactive and the accommodation space created on top of the allochthonous sheets equals the flexural subsidence of the lower plate. Conversely, minimum addition or subtraction of accommodation space, i.e. minimum migration of the equilibrium points on top of the allochthonous sheets, takes place when the tectonic wedge moves over a flat and gently dipping sole thrust. In such a case, the vertical component of the forward displacement roughly equals the flexural subsidence.

In the thrust belt, in the foredeep basin and in the foreland areas, changes of the relative sea level and consequent variations in the accommodation space are basically controlled by three factors:

1. Flexural subsidence *plus* lower-plate flexure-hinge retreat, strongly influencing, together with the structural architecture of the mountain chain, the overall geometry in the foredeep basin (see upper right side of fig. 2 and lower right side of fig.18);
2. Interaction between the flexural deflection causing passive deepening of the sole thrust and the vertical component of the active thrusts responsible for tectonic uplift in the mountain chain (fig. 18a-e);
3. Eustatic sea level changes, able to produce simultaneous variations in the mountain chain, in the foredeep basin and in the foreland areas.

A fourth factor, represented by the compaction, has not been considered because of its weak effects on the poorly consolidated Plio-Pleistocene terrigenous deposits of the Southern Apennines and Sicily.

The maximum rate of the eustatic sea level changes approximates 1 cm/y in correspondence to major glaciations (among many authors, see MÖRNER, 1996). The computed rates of flexure-hinge retreat in the whole

Southern Apenninic Arc are in the order of centimetres per year, whilst the rates of flexural subsidence in the same region do not exceed 1-2 mm/y. The rates of flexure-hinge retreat in the Southern Apennines, ranging between 3.7 and 4.5 cm/y during Plio-Pleistocene times (PATACCA & SCANDONE, 2001), largely exceed the Sicily rate values. The latter, roughly equaling the rate of the Africa-Europe convergence (DE METZ *et alii*, 1990; MAZZOLI & HELMAN, 1994 and references therein), are generally lower than 1 cm/y. The slip rates of the active thrusts, finally, roughly equaled the flexure-hinge retreat of the lower plate both in the Southern Apennines and Sicily, allowing the time-space migration of the thrust belt-foredeep system and causing the progressive incorporation in the foredeep basin (and subsequently in the thrust belt) of progressively more distal foreland segments. Because of the remarkable difference in the rate values (slip rate of the active thrusts, tectonic uplift in the mountain chain and flexure hinge retreat of the lower plate versus eustatic sea-level changes), the influence of the eustatic changes on the sedimentation in the Apennines has been largely overprint by the effects of the tectonics, so that sequence boundaries and systems tracts in the foredeep basin and on top of the allochthonous sheets appear to have been closely controlled by the flexure-hinge retreat and by the trajectories of the active thrusts.

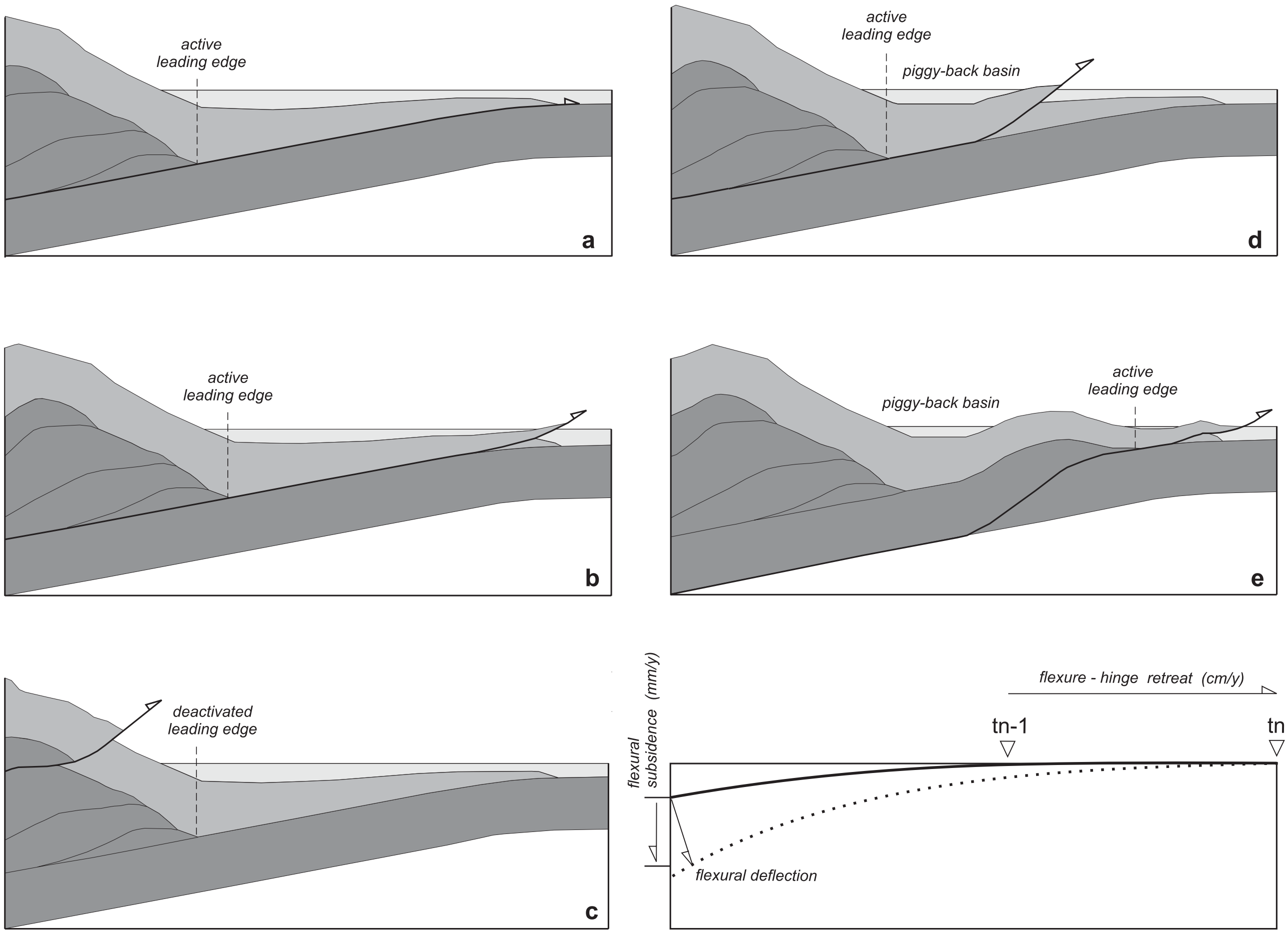


Fig. 18 - Thrust propagation pattern in the Southern Apennine and Sicily duplex systems (after PATACCA & SCANDONE, 2001 with slight modifications) reconstructed by the stratigraphic analysis of the Plio-Pleistocene thrust top, foredeep and foreland deposits correlated according to the diagrams of figures 4, 5 and 11.
a Forward (hinterland-to-foreland) displacement of the allochthonous sheets over a long thrust flat.
b Development of a steep frontal ramp near the tip of the thrust toe.
c Deactivation of the frontal ramp, backward migration of the active thrusts and breaching of the duplex system.
d Forward thrust migration, reactivation of the previously abandoned leading edge and creation of a piggyback basin in the hangingwall of a breach.
e Deepening of the sole thrust, forward thrust propagation and creation of a new duplex system with a piggyback basin located at the rear of the growing ridge.
In the lower right side of the picture, schematic representation of the flexure-hinge retreat, flexural deflection and flexural subsidence of the sinking lower plate.

In Sicily, the maximum rates of eustatic sea-level changes may equal the slip rates of the active thrusts and the rate of the flexure-hinge retreat. Consequently, tectonic cycles and eustatic cycles may be distinguished only by means of a careful basin analysis at the scale of the entire thrust belt-foredeep system considering that tectonic cycles coincide with important and sudden changes in the shape and size of the orogenic wedge and of the adjacent foredeep basin.

Generalizing the large variety of situations, the Plio-Pleistocene deposits in the Southern Apennines and Sicily are organized into 3rd-order sequences represented by cycles recording regularly recurrent tectonic events repeated in the same order. Higher-frequency eustatic cycles may be superimposed on the tectonic cycles (fig. 11). In the study region tectonic cycles have a periodicity of about 1.5 million years (figs. 4, 5 and 11). The duration of a tectonic cycle is not related to the absolute values of the single tectonic parametres (flexural deflection and flexure-hinge retreat of the lower plate, slip rate of the active thrusts) but to the entire path of the active thrust trajectories that play a recurrent leitmotif describing the "caterpillar-like" forward motion of the tectonic wedge of PATACCA & SCANDONE (2001). According to this model, every stage of forward nappe transport has been preceded and followed by a significant telescopic shortening of the structural edifice behind the nappe front. A significant forward displacement of the nappe front obviously occurred when the allochthonous sheets moved over a long thrust flat. An interruption of the nappe-front displacement took place when critical length was reached and important breaches cut across the tectonic wedge re-establishing favourable conditions for sliding. In this phase of the tectonic process, the kinematic evolution of the mountain chain was generally controlled by a backward (foreland-to-hinterland) migration of the active thrusts followed by a forward thrust propagation.

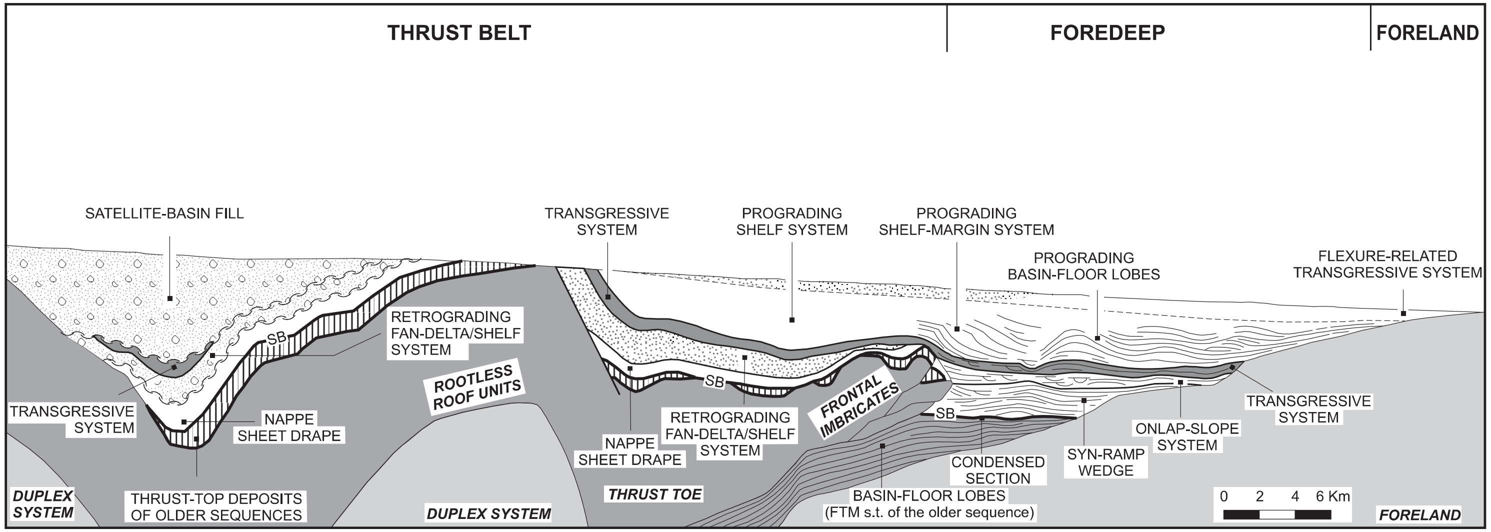
This caterpillar-like motion of the tectonic wedge allows the identification of well-defined tectonic cycles, each cycle starting with the activation of a long thrust flat playing the role of conveyor belt for the forward nappe transport and ending with the incorporation in the thrust belt of new tectonic slices detached from the foreland block. In the Southern Apennines and Sicily, every tectonic cycle includes four major steps that have been schematized in figure 18: 1) *hinterland-to-foreland transport of the allochthonous sheets over a long thrust flat*, figure 18a; 2) *development of the frontal ramp*, figure 18b; 3) *deactivation of the frontal ramp and foreland-to-hinterland migration of the active thrusts*, figure 18c and 4) *hinterland-to-foreland migration of the active-thrusts*, figures 18d and 18e. This mode of forward displacement of the tectonic wedge implies that tectonics acted as a continuous process and not as a series of "tectonic phases" interrupted by periods of tectonic quiescence. Figure 19 provides a synoptic representation of the conceptual model of a thrust-related depositional sequence describing the time-space migration of the active thrusts in a mountain chain and the related stratigraphic signatures in the thrust-top, foredeep and foreland deposits. The sedimentary features predicted by our tectonic/stratigraphic model cannot be fully described by a single diagram because of the numerous possible combinations of the major parametres with local variables (both geologic and climatic) that may influence sedimentary facies and architectures.

Hinterland-to-foreland transport of the allochthonous sheets over a long thrust flat

In this stage of the tectonic evolution of the thrust belt-foredeep system (fig. 18a), the migration of the equilibrium points on top of the allochthonous sheets is controlled by the rate of subsidence and the rate of forward nappe displacement. Both in the Southern Apennines and Sicily the corresponding systems tract (*active-thrust-flat systems tract*) is represented in the mountain chain by a drape of low-energy-shelf deposits (*nappe sheet drape)* unconformably overlying the advancing nappes. In the foredeep basin, the systems tract is represented by a *condensed section*, interpreted as the downdip termination of the previous shelf deposits. The base of the condensed section coincides with a major truncation surface that underlines in the whole basin the master sequence boundary. In the Southern Apennines, where the orogenic wedge moved over a 8-10° dipping thrust flat and where the vertical component of the slip rate (0.6-0.7 cm/y) largely exceeded the rate of flexural subsidence (about 1 mm/y), the open-shelf mudstones of the nappe sheet drape (3.70-3.35 Ma interval in fig. 4 and 1,83-1.57 Ma interval in fig. 5) gradually graded into inner-shelf sandstones. In this stage, sediment supply in the foredeep basin is minimum and sediment starvation is maximum.

Development of the frontal ramp

This change in the active-thrust trajectories (fig. 18b) does not produce remarkable facies variations in the sedimentary record on top of the nappes, apart those deriving from the possible local creation of small piggyback basins at the rear of the frontal ramp. The sedimentation is still represented by shallowing-upward low-energy-shelf deposits (*nappe sheet drape*, 3.35-3.30Ma interval in fig. 4 and 1.57-1.50 Ma interval in fig. 5). The persisting shallowing-upward trend is obviously related to the nappe motion over a gently dipping sole thrust at a velocity exceeding the subsidence rate. In the foredeep basin, on the contrary, the development of the frontal ramp is recorded by a dramatic change in the depositional features with the sudden accumulation of a thick and relatively confined clastic wedge characterized by prograding slope-fan systems in the footwall of the active ramp (*syn-ramp wedge*). Near the front of the allochthonous sheets, the syn-ramp wedge is basically composed of mass-flow deposits laid down from the uprising hangingwall block. Toward the basin, these more or less chaotic and quite massive deposits grade laterally



SYSTEMS TRACTS				THRUST BELT		FOREDEEP		FORELAND
THRUST-RELATED DEPOSITIONAL SEQUENCE	THRUST EMERGENCE BEHIND THE NAPPE FRONT	FORWARD THRUST MIGRATION SYSTEMS TRACT **FTM**		PIGGYBACK-BASIN FILL	PROGRADING SHELF SYSTEM	PROGRADING SHELF-MARGIN SYSTEM	PROGRADING BASIN-FLOOR LOBES	FLEXURE-RELATED TRANSGRESSIVE SYSTEM
		BACKWARD THRUST MIGRATION SYSTEMS TRACT **BTM**	late	TRANSGRESSIVE SYSTEM				NON DEPOSITION/ EXTREME STRATAL CONDENSATION
			early	RETROGRADING FAN-DELTA/SHELF SYSTEM		ONLAP-SLOPE SYSTEM		
	FORWARD NAPPE TRANSPORT	ACTIVE FRONTAL RAMP SYSTEMS TRACT **AFR**		NAPPE SHEET DRAPE		SYN-RAMP WEDGE		
		ACTIVE THRUST FLAT SYSTEMS TRACT **ATF**				CONDENSED SECTION		

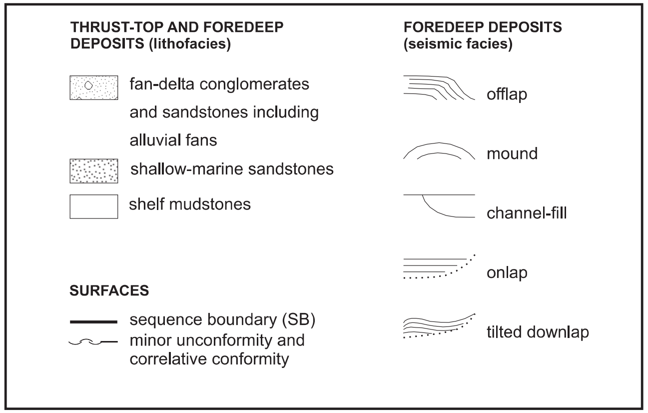


Fig. 19 - Conceptual model of a thrust-related depositional sequence describing the time-space propagation of the active thrusts in the mountain chain and the related key stratigraphic signatures in the coeval thrust-top, foredeep and foreland deposits (after PATACCA and SCANDONE 2001, with slight modifications). See explanation in the text.

into a channel-overbank system and into turbidite lobes fed also by longitudinal sediment dispersal. Spectacular examples of syn-ramp clastic wedges are available along the whole outer margin of the Southern Apennines (1.57-1.50 Ma interval of the Q_{1-2} depositional sequence of figures 7 and 8) and along the whole margin of the Gela nappe (1.42-0.96 Ma interval of the Q_{1-3} depositional sequence in figures 13 and 14). It is interesting to underline the remarkable differences in the size of the syn-ramp wedge in the Southern Apennines and Sicily, considerably smaller in Sicily, in agreement with the lower velocity of the flexure-hinge retreat of the foreland plate.

Deactivation of the frontal ramp and foreland-to-hinterland migration of the active thrusts

During this stage (fig. 18c), the sedimentation on top of the allochthonous sheets and in the foredeep basin is entirely controlled by a foreland-to-hinterland migration of the active thrusts (*backward-thrust-migration systems tract*) that may end with a generalized breaching of the duplex system. Because of the persisting flexural deflection of the lower plate, the portion of the tectonic wedge lying in the footwall of the active thrust may experience marine transgression. Maximum marine flooding is obviously reached in the final part of the systems tract when maximum out-of-sequence thrust propagation takes place. Thrust-top deposits referable to this systems tract are well represented by backstepping and deepening-upward fandelta/shelf deposits (*retrograding fandelta/shelf system*) overlain by more or less condensed muddy shelf deposits (*transgressive system*). In the Southern Apennines, this tectonic step is represented by the retrograding fandelta deposits and overlying shelfal mudstones of the 3.30-2.50 Ma interval of the P_{1-2} depositional sequence (figs. 4 and 5) and of the 1.50-0.92 Ma interval of the Q_{1-2} depositional sequence (fig. 5). In mainland Sicily, the backward-thrust-migration systems tract of the Q_{1-3} depositional sequence (0.96-0.83 Ma interval of fig. 11) is represented by the retrograding and shallowing-upward deposits of the Caltagirone Clay-San Michele di Ganzaria Sandstone couple. The shallowing-upward character of this systems tract may be confidently related to a local thickening and consequent uplift of the allochthonous sheets caused by an out-of-sequence breaching of the Gela nappe. In the foredeep basin, the backward-thrust-migration systems tract is seismically expressed, both in the Southern Apennines and Sicily, by a low-energy slope-fill margin (*onlap-slope system*) and by an overlying *transgressive system*. The slope facies, imaged by an onlap-fill configuration in the Southern Apennines (see fig. 8) and by a slope-front configuration in Sicily (see fig. 14) may grade basinward into minor mounded turbidite lobes and sheet turbidites. The onlap-slope system, marking the deactivation of the frontal ramp, represents a deposition under conditions of poor sediment supply only derived from the submarine erosion of the slope and of the outermost portion of the shelf. The overlying transgressive system testifies to the progressive flooding of the tectonic wedge involved in the flexural subsidence.

Hinterland-to-foreland migration of the active-thrusts

This tectonic stage is characterized by a hinterland-to-foreland migration of the active thrusts that follows the maximum marine flooding of the tectonic wedge, i.e. the maximum foreland-to-hinterland out-of-sequence thrusts propagation (fig. 18d and 18e). During this stage, (*forward-thrust-migration systems tract*) sedimentation on top of the allochthonous sheets and in the foredeep basin is generally coarser owing to an enhanced fluvial discharge related to an important relief rejuvenation. The strong acclivity had been principally produced in the final stage of the foreland-to-hinterland thrust migration when duplex breaching had caused a generalized uplift in the axial part of the mountain chain. The rates of the tectonic uplift (1.8-2.2 cm/y in the Southern Apennines and around 0.5 cm/y in Sicily) obviously correspond to the vertical component of the slip rate of ramps that cut across the tectonic edifice.

On top of the allochthonous sheets, the forward-thrust-migration systems tract is everywhere characterized by a fandelta/shelf system displaying an overall prograding geometry. The facies distribution and the internal stratal architecture of these deposits allow the identification of two different depositional settings, both closely controlled by the active-thrust trajectories: 1) wide stable shelves floored by the inactive thrust toe, characterized by well-developed shoal-water delta systems organized into coarsening-upward sequences (*prograding shelf system*) and 2) mobile piggyback basins characterized by a diachronous basal unconformity and by a widespread occurrence of growth strata featuring progressive angular unconformities in correspondence to the active outer margin of the basin (*piggyback-basin fill*). In some cases, the forward thrust propagation causes reactivation of the previously abandoned leading edge and breaching of the thrust toe (fig. 18d). In other cases, the deepening of the sole thrust and the propagation of the active thrusts beneath and beyond the previous leading edge causes the incorporation of new horses in the duplex system (fig. 18e). In both cases, a piggyback basin acting as a possible sedimentary trap develops in the hangingwall of the active thrust. The piggyback basin is obviously located in front of the active leading edge in the first case and at the rear of the active leading edge in the second case. An example of the first case (2.50-1.83 Ma interval of fig.4) is represented by the Pliocene deposits of the Ofanto synform that filled a piggyback basin developed in front of a growing antiformal stack (fig. 9). An example of the second case is represented by the Sinni Synthem in the Sant'Arcangelo depression (0.92-0.66 Ma interval in fig. 5) that filled a Pleistocene piggyback basin developed at the rear the growing Nocara Ridge. In Sicily, the forward-thrust migration systems tract is well represented by the shallowing-upward Capodarso calcarenites and Butera sandstones of the P_2-Q_1 depositional sequence (2.53-1.43 Ma interval in fig. 11). The spectacular growth strata present in the Capodarso calcarenites evidence deposition in a piggyback basin in the hangingwall of an active thrust. Unfortunately, the original thrust array has been obliterated by subsequent compressional tectonics, so that we do not know whether the leading edge of the duplex system active in that time was located in front of or (more probably) at the rear of the Caltanissetta-Assoro-Centuripe piggyback basins.

In the foredeep basin, *the forward-thrust-migration systems tract* is represented by a depositional offlapping slope indicative of a sustained sediment supply (2.13-1.83 and 0.92-0.66 Ma intervals in figs. 4 and 5, Southern Apennines; deposits younger that 0.83 Ma in figs. 11, 12 and 14, Sicily). These rapidly prograding slope deposits (*prograding shelf-margin system*) laterally evolve through a more or less prominent channel-fill complex, into a widespread system of basin-floor-lobe turbidites (*prograding basin-floor lobes*, fig. 8). This system records the maximum accumulation of turbidite deposits in a thrust-related sequence. In the Apennines, in particular, sandy turbidites may be volumetrically very important in forward-thrust-migrating systems tracts. Significant differences in volume and grain size of the sediment supply allow the differentiation of a mud-prone foredeep basin in Sicily and a sand-prone foredeep basin in the Apennines. The difference in the sediment discharge is likely related to the different shortening responsible for different tectonic uplift and different relief energy in the two regions.

ACKNOWLEDGEMENTS

British Gas-Rimi, Edison Gas and ENI are acknowledged for having allowed access to seismic lines and well logs not in the public domain. The authors are grateful to Barbara Taccini for the careful preparation of the illustrations.

REFERENCES

AMODIO-MORELLI L., BONARDI G., COLONNA V., DIETRICH D., GIUNTA G., IPPOLITO F., LIGUORI V., LORENZONI S., PAGLIONICO A., PERRONE V., PICCARRETA G., RUSSO M., SCANDONE P., ZANETTIN-LORENZONI E. & ZUPPETTA A. (1976) - L'Arco calabro-peloritano nell'orogene appenninico-maghrebide. Mem.Soc.Geol.Ital., 17, 1-60.

ANELLI L, MATTAVELLI L. & PIERI M. (1996) - *Structural-stratigraphic evolution of the petroleum systems of Italy*: In ZIEGLER P.A. & HORVAT F. Eds., Structure and Prospects of Alpine Basins and Forelands. Peri-Tethys Mem. 2, Mém. Muséum Nation. Histoire Natur. Paris, **170**, 455-483

ANTONELLI M., FRANCIOSI R., PEZZI G., QUERCI A., RONCO G.P. & VEZZANI F. (1988) - *Paleogeographic evolution and structural setting of the northern side of the Sicily Channel.* Mem. Soc. Geol. Ital., **41**, 141-157.

ARGNANI A. (1987) - *The Gela nappe: evidence of accretionary melange in the Maghrebian foredeep of Sicily*. Mem. Soc. Geol. Ital., **38**, 419-428.

ARGNANI, A., CORNINI S., TORELLI L. & ZITELLINI N. (1986) - *Neogene-Quaternary foredeep system in the Strait of Sicily*. Mem. Soc. Geol. Ital., **36**, 123-130.

ARGNANI, A., CORNINI S., TORELLI L. & ZITELLINI N. (1989) - *Diachronous foredeep-system in the Neogene-Quaternary of the Strait of Sicily.* Mem. Soc. Geol. Ital., **38**, 407-417.

ARUTA L., BUCCHERI G., GRECO A. & SPROVIERI R. (1972) - *Il Siciliano della foce del Belice (Sicilia meridionale).* Riv. Min. Sicil., **136-138**, 3-8.

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.

BELLO M., FRANCHINO A. & MERLINI S. (2000) *Structural model of Eastern Sicily.* Mem. Soc. Geol. Ital., **55**, 61-70.

BENEO E. (1957) - *Sull'olistostroma quaternario di Gela (Sicilia meridionale).* Boll. Serv. Geol. Ital., **79**, 5-15.

BERGGREN, W.A., HILGEN, F.J., LANGEREIS, C.G., KENT, D.V., OBRADOVICH, J.D., RAFFI, I., RAYMO, M.E. & SHACKLETON, N.J. (1995) - *Late Neogene chronology: new perspectives in high-resolution stratigraphy, in geochronology, time scales and global stratigraphic correlations: a unified temporal framework for an historical geology*. In Berggren W.A., Kent D.V., Aubry M.P. & Hardenbol J. Eds., Soc. Econ. Paleont. Mineral., Special Publ. **54**, 130-212.

BIANCHI F., CARBONE S., GRASSO M., INVERNIZZI G., LENTINI F., LONGARETTI G., MERLINI S., & MOSTARDINI F. (1987) - *Sicilia orientale: profilo geologico Nebrodi-Iblei.* Mem. Soc. Geol. Ital., **38**, 429-458.

BONARDI G., CAVAZZA W., PERRONE V. & ROSSI S. (1998) - *Calabria-Peloritani terrane and Northern Ionian Sea.* In VAI G.B. & MARTINI I.P. Eds., Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins, Kluwer Academic Publ., 287-306.

BROLSMA M.J. (1978) - *Quantitative foraminiferal analysis and environmental interpretation of the Pliocene and topmost Miocene on the south coast of Sicily.* Utrecht Micropaleont. Bull., **18**, 159 pp.

BUTLER R.W.H. & GRASSO M. (1993) - *Tectonic controls on base-level variations and depositional sequences within thrust-top and foredeep basins: examples from the Neogene thrust belt of central Sicily.* Basin Research, **5**, 137-151.

BUTLER R.W.H., GRASSO M. & LA MANNA F. (1992) - *Origin and deformation of the Neogene-Recent Maghrebian foredeep at the Gela Nappe, SE Sicily.* Journ. Geol. Soc. London, **149**, 547-556.

BUTLER R.W.H., GRASSO M. & LYCKORISH H. (1995) - *Plio-Quaternary megasequence geometry and its tectonic controls within the Maghrebian thrust belt of south-central Sicily.* Terra Nova, **7**, 171-178.

BUTLER R.W.H. & LICKORISH W.H. (1997) - *Using high resolution stratigraphy to date fold and thrust activity: examples from the Neogene of south-central Sicily*. Journ. Geol. Soc. London, **154**, 633-643.

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.

CARBONE S., GRASSO M. & LENTINI F., Eds. (1984) - *Carta geologica della Sicilia sud-orientale, 1:100.000.* Selca, Firenze.

CAREY S.W., 1958. *A tectonic approach to continental drift* In CAREY S.W., Convener, Continental drift: a symposium. Hobart, Univ. of Tasmania, Geol. Dept., 177-355.

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.

CASNEDI R. (1988a) - *La fossa bradanica: origine, sedimentazione e migrazione.* Mem. Soc. Geol. Ital., **41**, 439-448.

CASNEDI R. (1988b) - *Subsurface basin analysis of fault-controlled turbidite system in Bradano trough, Southern Adriatic foredeep, Italy*. AAPG Bull. **72**, 1370-1380.

CASTRADORI D. (1993) - *Calcareous nannofossil biostratigraphy and biochronology in eastern Mediterranean deep-sea cores.* Riv. Ital. Paleont. Stratigr., **99**, 107-126.

CATALANO R. (1997) - *An introduction to stratigraphy and structures of the Sicily chain.* In CATALANO R. Ed., Time scale and basin dynamics. Sicily, the adjacent Mediterranean and other natural laboratories - Field Workshop in Western Sicily (11-13 June 1997), Guidebook, 7-20.

CATALANO R., DI STEFANO E., INFUSO S., SULLI A., VAIL P.R. & VITALE F.P. (1997) - *Sequence and systems tracts calibrated by high-resolution bio-chronostratigraphy: the Central Mediterranean Plio-Pleistocene record*. In CATALANO R. Ed., Time scale and basin dynamics. Sicily, the adjacent Mediterranean and other natural laboratories - Field Workshop in Western Sicily (11-13 June 1997), Guidebook, 109-134.

CATALANO R., DI STEFANO E., LO CICERO G., INFUSO S., VAIL P.R. & VITALE F.P. (1993a) - *Basin analysis and sequence stratigraphy of the Plio-Pleistocene of Sicily.* In MAX M.D.& COLANTONI P. Eds., Geological development of the Sicilian-Tunisian Platform, Proc. Int. Sci. Meet. Univ. Urbino, Italy (4-6 Nov. 1992), Unesco Report in Marine Science, **58**, 99-104.

CATALANO R., DI STEFANO P., NIGRO F. & VITALE F.P. (1993b) - *Sicily mainland and its offshore: a structural comparison.* In MAX M.D. & COLANTONI P. Eds., Geological development of the Sicilian-Tunisian Platform, Proc .Int. Sci. Meet. Univ. Urbino, Italy (4-6 Nov. 1992), Unesco Report in Marine Sciencie, **58**, 19-24.

CATALANO R., DI STEFANO P., SULLI A. & VITALE F.P. (1996) - *Paleogeography and structure of the central Mediterranean: Sicily and its offshore area.* Tectonophysics, **260**, 291-323.

CATALANO R., FRANCHINO A., MERLINI S. & SULLI A. (2000) - *Central western Sicily structural setting interpreted from seismic reflection profiles.* Mem. Soc. Geol. Ital., **55**, 5-16.

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.

CENTAMORE E., CANTALAMESSA G., MICARELLI A., POTETTI M., RIDOLFI M., CRISTALLINI C. & MORELLI C. (1993) - *Contributo alla conoscenza dei depositi terrigeni neogenici di avanfossa del teramano (Abruzzo settentrionale).* Boll. Soc. Geol. Ital., **112**, 63-81.

CHANNELL J.E.T., DI STEFANO E. & SPROVIERI R. (1992) - *Calcareous plankton biostratigraphy, magnetostratigraphy and paleoclimatic history of the Plio-Pleistocene Monte San Nicola Section (Southern Sicily).* Boll. Soc .Paleont. Ital., **31**, 351-382.

CHANNELL J.E.T.& MARESCHAL JC (1989) - *Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian Rift.* In COWARD M.P. & DIETRICH D. Eds., Alpine tectonics. Geol. Soc. London Spec. Publ., **45**, 285-302.

CIARANFI, N., D'ALESSANDRO, A., LOIACONO, F. & MARINO, M. (1996a) - *A new stratigraphical section for the Marine Quaternary in Italy*. Paleopelagos, **6**, 361-370.

CIARANFI, N., MARINO, M., SABATO, L., D'ALESSANDRO, A. & DE ROSA, R. (1996 b) - *Studio geologico stratigrafico di una successione infra e mesopleistocenica nella parte sudoccidentale della Fossa Bradanica (Montalbano Ionico, Basilicata).* Boll Soc. Geol. Ital., **115**, 379-391.

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.

CITA M.B. & GARTNER S. (1973) - *IV. The stratotype Zanclean foraminiferal and nannofossil biostratigraphy.* Riv. Ital. Paleont. Stratigr., **79**, 503-558.

CNR-PROGETTO FINALIZZATO GEODINAMICA (1991) - *Synthetic structural-kinematic map of Italy. Structural Model of Italy, Sheet n. 5*. S.E.L.C.A., Firenze

COGGI L. (1968) - *Attività dell'AGIP e di altre società del gruppo ENI.* Enciclopedia del Petrolio e del Gas Naturale - Ed. Carlo Colombo, 514-537.

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.

DE KAENEL E., SIESSER W.G. & MURAT A. (1999) - *Pleistocene calcareous nannofossil stratigraphy and the western Mediterranean sapropels, sites 974 to 977 and 979.* In OMAS M.C., ZAHN R., KLAUS A. *et alii* Eds., Proc. ODP, Sci. Results., **161***:* College Station, TX (Ocean Drilling Program), 159-183.

DE METS C., GORDON R.G., ARGUS D.F., & STEIN S. (1990) - *Current plate motions.* Geophys. Journ. Int., **101**, 425-478.

DE VISSER J.P., EBBING J.H.J. GUDJONSSON L., HILGEN F.J., JORISSEN F.J., VERHALLEN P.J.J.M. & ZEVENBOOM D. (1989) - *The origin of rhythmic bedding in the Pliocene Trubi formation of Sicily, southern Italy.* Palaeogeogr. Palaeoclimatol. Palaeoecol., **69**, 45-66.

DI GERONIMO I & COSTA B. (1978) - *Il Pleistocene di Monte dell'Apa (Gela).* Riv. Ital. Paleont. Stratigr., **84**, 1121-1158.

DI GERONIMO I., GHISETTI F., LENTINI F., & VEZZANI L. (1978) - *Lineamenti neotettonici della Sicilia orientale*. Mem. Soc. Geol. Ital., **19**, 543-549.

DI GRANDE A., GRASSO M., LENTINI F. & SCAMARDA G. (1976) - *Facies e stratigrafia dei depositi pliocenici tra Leonforte e Centuripe (Sicilia centro-orientale).* Boll. Soc. Geol. Ital., **95**, 1319-1345.

DI STEFANO E. (1998) - *Calcareous nannofossil quantitative biostratigraphy of holes 969E and 963B (Eastern Mediterranean).* In ROBERTSON A.H.F., EMEIS, K.C., RICHTER C. & CAMERLENGHI A. EDS., Proc. ODP, Sci. Results, **160***:* College Station, TX (Ocean Drilling Program), 99-112.

DI STEFANO E., INFUSO S. & SCARANTINO S. (1993) - *Plio-Pleistocene sequence stratigraphy of South Western off-shore Sicily from well logs and seismic sections in a high resolution calcareous plankton biostratigraphic framework.* In MAX M.D. & COLANTONI P. Eds., Geological development of the Sicilian-Tunisian Platform, Proc. Int. Sci. Meet. Univ. Urbino, Italy (4-6 Nov. 1992), Unesco Report in Marine Science, **58**, 105-110.

DI STEFANO E., SPROVIERI R. & CARUSO A. (1993) - *High resolution biochronology in the Monte Narbone formation of the Capo Rossello section and the Mediterranean first occurrence of Globorotalia truncatulinoides.* Riv. Ital. Paleont. Stratigr., **99**, 357-370.

DI STEFANO E., SPROVIERI R. & SCARANTINO S. (1996) - *Chronology of biostratigraphic events at the base of the Pliocene.* Paleopelagos, **6**, 401-414.

DOGLIONI C. (1991) - *A proposal of kinematic modelling for W-dipping subductions - Possible applications to the Tyrrhenian-Apennine system*. Terra Nova, **3**, 423-434.

GRASSO M. (1999) - *Carta geologica del settore centro-meridionale dell'altopiano ibleo (provincia di Ragusa, Sicilia sud-orientale), 1:50.000.* Selca, Firenze.

GRASSO M., BUTLER R.W.H. & LA MANNA F. (1990) - *Thin skinned deformation and structural evolution in the Gela Nappe, SE Sicily*. Studi Geol.Camerti, Vol.spec. 1990, 9-17.

GRASSO M. & LENTINI F. (1982) - *Sedimentary and tectonic evolution of the eastern Hyblean Plateau (southeastern Sicily) during late Cretaceous to Quaternary times.* Paleogeogr. Paleoclimatol. Palaeoecol., **39**, 261-280.

GUERRERA F., COCCIONI R., CORRADINI D. & BERTOLDI R. (1984) - *Caratteristiche lito-sedimentologiche e micropaleontologiche (Foraminiferi, Dinoflagellati, Pollini e Spore) di successioni "Tripolacee" plioceniche del bacino di Caltanissetta.* Boll. Soc. Geol. Ital., **103**, 629-660.

HILGEN F.J. (1991) - *Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale*. Earth Planet. Sci. Lett., **104**, 226-244.

HILGEN F.J. & LANGEREIS C.G. (1993) - *A critical re-evaluation of the Miocene/Pliocene boundary as defined in the Mediterranean.* Earth Planet. Sci. Lett., **118**, 167-179

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.

HOLTON J. (1999) - *Four geologic settings dominate oil, gas fields of Italy, Sicily.* Oil & Gas Journ., Dec.1999, 81-84.

KELLER J., MINELLI G. & PIALLI P. (1995) - *Anatomy of late orogenic extension: the Northern Apennine case.* Tectonophysics, **238**, 275-294.

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.

LANGEREIS C.G. & HILGEN F.J. (1991) - *The Rossello composite: a Mediterranean and global reference section for the Early to early Late Pliocene*. Earth and Planet. Sci. Lett., **104**, 211-225.

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.

LICKORISH W.H. & BUTLER R.W.H. (1996) - *Fold amplification and parasequence stacking patterns in syntectonic shoreface carbonates*. Bull. Geol.Soc.Amer.*,* **108**, 966-977.

LICKORISH W.H., GRASSO M., BUTLER R.W.H., ARGNANI A. & MANISCALCO R. (1999) - *Structural styles and regional tectonic setting of "Gela Nappe" and frontal part of the Maghrebian thrust belt in Sicily.* Tectonics*,* **18**, 655-668.

MALINVERNO A. & RYAN W.B.F. (1986) - *Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere.* Tectonics, **5**, 227-245.

MARINO, M., (1996 a) - *Quantitative calcareous nannofossil biostratigraphy of the Lower-Middle Pleistocene, Montalbano Ionico section (Southern Italy).* Paleopelagos, **6**, 347-360.

MARINO, M. (1996 b) - *Calcareous nannofossil and foraminifera biostratigraphy of Pleistocene terrigenous sediments from Southern Italy*. Riv. Ital. Paleont. Stratigr., **102**, 119-130.

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.

MASSARI F., RIO D., SGAVETTI M., PROSSER G., D'ALESSANDRO A., ASIOLI A., CAPRARO L., FORNACIARI E. & TATEO F. (2002) - *Interplay between tectonics and glacio-eustasy: Pleistocene succession of the Crotone basin, Calabria (southern Italy).* Bull. Soc. Geol. Am., **114**, 1183-1209.

MATTAVELLI L. & NOVELLI L. (1990) - *Geochemistry and habitat of the oils in Italy.* Bull.Am.Assoc.Petroleum Geol., **74**, 1623-1639.

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

MAZZOLI S. & HELMAN M. (1994) - *Neogene patterns of relative plate motions for Africa-Europe: some implications for recent central Mediterranean tectonics.* Geol. Rundsch., **83**, 464-468.

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

MÖRNER N.A. (1996) - *Rapid changes in coasal sea level*. Journ. Coastal Res., **12**, 797-800.

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.

NIGRO F., & RENDA P. (2000) - *Un modello di evoluzione tettono-sedimentaria dell'avanfossa neogenica siciliana.* Boll. Soc. Geol. Ital., **119**, 667-686.

OGNIBEN L. (1969) - *Schema introduttivo alla geologia del confine calabro-lucano.* Mem. Soc. Geol. Ital., **8**, 453-763.

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.

PASINI, G. & COLALONGO, M.L. (1982) - *Recent research on the Vrica section (Calabria, Italy), the proposed Neogene/Quaternary boundary - Stratotype section.* XI INQUA Congr. (Moscow, Aug. 1982), Contr. to the Volume: "Final Report of the IGCP Proj.No.41 (Neogene/Quaternary Boundary)", 75 pp.

PASINI, G., & COLALONGO, M.L. (1994) - *Proposal for the erection of the Santernian/Emilian boundary-stratotype (lower Pleistocene) and new data on the Pliocene/Pleistocene boundary-stratotype*. Boll. Soc. Paleont. Ital., **33**, 101-120.

PATACCA E., SARTORI R. & SCANDONE P. (1990) - *Tyrrhenian basin and Apenninic arcs: kinematic relations since Late Tortonian times*. Mem. Soc. Geol. Ital., **45**, 425-451.

PATACCA E., SARTORI R. & SCANDONE P. (1993) - *Tyrrhenian basin and Apennines. Kinematic evolution and related dynamic constraints*. In BOSCHI E, MANTOVANI E. & MORELLI A. Eds., Recent Evolution and Seismicity of the Mediterranean Region, Kluwer Academic Publ., 161-171.

PATACCA E. & SCANDONE P. (1989) - *Post-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. (2004A) - *Geology of the Southern Apennines*. In MAZZOTTI A, PATACCA E & SCANDONE P Eds., The CROP 04 Transect - Southern Apennines", Boll. Soc. Geol. Ital., in press.

PATACCA E. & SCANDONE P. (2004B). *Geologic interpretation of the seismic line CROP 04 (Southern Apennines).* In MAZZOTTI A, PATACCA E & SCANDONE P Eds., The CROP 04 Transect - Southern Apennines", Boll. Soc. Geol. Ital., in press.

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., GIUNTA G. & LIGUORI V. (1979) *Mesozoic paleotectonic evolution of the Ragusa zone (Southeastern Sicily).* Geologica Rom., **18**, 331-369.

PIERI M. (2001) - *Italian petroleum geology*. In VAI G.B. & MARTINI I.P. Eds., Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publ., 533-549.

PIERI M. & MATTAVELLI L. (1986) - *Geological framework of Italian petroleum resources.* AAPG Bull. **70**, 103-130.

PIERI P., SABATO L., LOJACONO F. & MARINO M. (1994) - *Il bacino di piggyback di Sant'Arcangelo: evoluzione tettonico-sedimentaria*. Boll. Soc. Geol. Ital., **113**, 465-481.

RICHTER C., ROBERTS A.P., STONER J.S., BENNING L.D. & CHI C.T. (1998) - *Magnetostratigraphy of Pliocene-Pleistocene sediments from the eastern Mediterranean Sea*. In ROBERTSON A.H.F., EMEIS K.C., RICHTER C. & CAMERLENGHI A. EDS., Proc. ODP, Sci. Res., **160**: College Station, TX (Ocean Drilling Program), 61-73.

RIO D., CHANNEL J.E.T., BERTOLDI R., POLI M.S., VERGEZIO P.P., RAFFI I., SPROVIERI R. & THUNNEL R.C. (1997) – *Pliocene sapropels in the northern Adriatic sea: chronology and paleoenvironmental significance*. Paleogeogr., Paleoclimatol., Paleoecol., **135**, 1-25.

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.

RIO D., SPROVIERI R. & DI STEFANO E. (1994) - *The Gelasian stage: a proposal of a new chronostratigraphic unit of the Pliocene series.* Riv. Ital. Paleont. Stratigr., **100**, 103-124.

RIO D., SPROVIERI R. & RAFFI I. (1984) - *Calcareous plankton biostratigraphy and biochronology of the Pliocene-lower Pleistocene succession of the Capo Rossello area, Sicily*. Marine Micropaleont., **9**, 135-180.

RIO D., SPROVIERI R. & THUNELL R. (1991) - *Pliocene-lower Pleistocene chronostratigraphy: A re-evaluation of Mediterranean type sections*. Bull. Geol. Soc. Amer., **103**, 1049-1058.

ROCCO T. (1959) - *Gela in Sicilia. Un singolare campo petrolifero*. Riv. Min. Sicil., **58-59**, 167-188.

RODA C. (1965) - *La sezione stratigrafica pleistocenica di Niscemi (Caltanissetta).* Atti Accad. Gioenia Sci. Nat. Catania, s. 6, **17**, 37-62.

RODA C. (1967) - *Le formazioni del Miocene superiore e Pliocene inferiore e medio al M. Capodarso (Enna), con la stratigrafia del Sondaggio "Trabonella n. 1".* Atti Accad. Gioenia Sci. Nat. Catania, s. 6, **19**, 1-56.

RONCO G. P., PALOMBI E. & FOSSALUZZA S. (1990) - *The Vega oil field. A stratigraphic structural trap in the Iblean Foreland.* Mem. Soc. Geol. Ital., **45**, 777-782.

ROSSI S. & SARTORI R. (1981) - *A seismic reflection study of the external Calabrian Arc in the Northern Ionian Sea (Eastern Mediterranean).* Marine Geophys. Res., **4**, 403-426.

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

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.

ROYDEN L., PATACCA E. & SCANDONE P. (1987) - *Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust-belt and foredeep-basin evolution*. Geology, **15**, 714-717.

RUGGIERI G. & SPROVIERI R. (1975) - *La definizione dello stratotipo del Piano Siciliano e le sue conseguenze*. Riv. Min. Sicil., **26** (151-153), 1-7.

RUGGIERI G. & TORRE G. (1973) - *Geologia delle zone investite dal terremoto della Valle del Belice.* Riv. Min. Sicil., (139-141), 27-48.

SCANDONE P. (1982) - *Structure and evolution of the Calabrian Arc*. In MANTOVANI E. & SARTORI R. Eds., Structure, Evolution and Present dynamics of the Calabrian Arc. Earth Sci.Evol., **3**, 172-180.

SCHRAMM M.W. & LIVRAGA G. (1986) - *Vega field and the potential of Ragusa basin offshore Sicily.* In HALBOUTY M.T. Ed., Future Petroleum Provinces of the World, AAPG Mem., **40**, 559-566.

SELLA M., TURCI C. & RIVA A. (1988) - *Sintesi geopetrolifera della Fossa Bradanica (avanfossa della catena appenninica meridionale).* Mem. Soc. Geol. Ital., **41**, 87-107.

SESTINI G. & FLORES G. (1986) – *Petroleum potential of the thrust belt and foretroughs of Sicily.* In HALBOUTY MT. Ed., Future Petroleum Provinces of the World, AAPG Mem., **40**, 567-584.

SGARRELLA F., SPROVIERI R., DI STEFANO E. & CARUSO A. (1997) - *Paleoceanographic conditions at the base of the Pliocene in the Southern Mediterranean basin.* Riv. Ital. Paleont. Stratigr., **103**, 207-220.

SGARRELLA F., SPROVIERI R., DI STEFANO E., CARUSO A., SPROVIERI M. & BONADUCE G. (1999) - *The Capo Rossello bore-hole (Agrigento, Sicily) cyclostratigraphic and paleoceanographic reconstruction from quantitative analyses of the Zanclean foraminiferal assemblages*. Riv. Ital. Paleont. Stratigr., **105**, 303-322.

SHACKLETON, N.J., BALDAUF, J.G., FLORES, J.-A., IWAI, M., MOORE, T.C. JR., RAFFI, I. & VINCENT, E. (1995) - *Biostratigraphic summary for Leg 138.* In PISIAS N.G., MAYER L.A., JANECEK T.R., PALMER-JULSON A. & VAN ANDEL T.H. EDS., Proc. ODP, Sci. Results , **138**: College Station, TX (Ocean Drilling Program), 517-536.

SHIPBOARD SCIENTIFIC PARTY (1996A) - *Explanatory notes*. In OMAS M.C., ZAHN R., KLAUS A. *et alii* Eds., Proc. ODP, Sci. Results, **161***:* College Station, TX (Ocean Drilling Program), 21-49.

SHIPBOARD SCIENTIFIC PARTY (1996B) - *Site 963.* In EMEIS K.C., ROBERTSON A.H.F., RICHTER C. *et alii* Eds., Proc. ODP, Init. Repts., **160***:* College Station, TX (Ocean Drilling Program), 55-84.

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

SPROVIERI R. (1992) *Mediterranean Pliocene biochronology: an high resolution record based on quantitative planktonic foraminifera distribution.* Riv. Ital. Paleont. Stratigr., **98**, 61-100.

SPROVIERI, R. (1993) - *Pliocene-Early Pleistocene astronomically forced planktonic foraminifera abundance fluctuactions and chronology of mediterranean calcareous plankton bio-events*. Riv. Ital. Paleont. Stratigr., **99**, 371-414.

SPROVIERI R. & CUSENZA A. (1972a) - *La sezione di età siciliana della Valle del Belice (Trapani).* Rev.Españ.Micropaleont., **4**, 297-325.

SPROVIERI R. & CUSENZA A. (1972B) - *La sezione di età siciliana di Porto Palo (Trapani).* Riv. Min. Sicil., (136-138), 8 pp.

SPROVIERI R., DI STEFANO E. & SPROVIERI M. (1996) - *High-resolution chronology for late Miocene Mediterranean stratigraphic events*. Riv. Ital. Paleont. Stratigr., **102**, 77-104.

TRINCARDI F. & ARGNANI A. (1990) - *Gela submarine slide: a major basin-wide event in the Plio-Quaternary foredeep of Sicily*. Geo-Marine Lett., **10**, 13-21.

VERCELLINO J. & RIGO F. (1970) – *Geology and exploration of Sicily and adjacent areas*. In King R.E. Ed., Stratigraphic oil and gas fields, AAPG Mem., **16,** 388-399.

VITALE F. P. (1997A) - *The Belice and the Menfi basins: sequence stratigraphy and evolution during the Pliocene and the Early Pleistocene*. In CATALANO R. Ed., Time scale and basin dynamics. Sicily, the adjacent Mediterranean and other natural laboratories - Field Workshop in Western Sicily (11-13 June 1997), Guidebook, 48-58.

VITALE F.P. (1997B) - *Stacking pattern and tectonics: field evidences from Pliocene growth folds of Sicily (Central Mediterranean).* In CATALANO R. Ed., Time scale and basin dynamics. Sicily, the adjacent Mediterranean and other natural laboratories - Field Workshop in Western Sicily (11-13 June 1997), Guidebook, 135-155.

VITALE F.P. & SULLI A. (1997) - *The regional pattern of the Belice and Menfi basins: a deep geologic profile*. In CATALANO R. Ed., Time scale and basin dynamics. Sicily, the adjacent Mediterranean and other natural laboratories - Field Workshop in Western Sicily (11-13 June 1997), Guidebook, 59-69.

WEZEL F.C. (1963) - *Il Pliocene e Pleistocene di S. Michele di Ganzarìa (Catania).* Riv. Ital. Paleont. Stratigr., **70**, 307-380.

WORNARDT W.W. & VAIL P.R. (1991) - *Revision of the Plio-Pleistocene cycles and their application to sequence stratigraphy and shelf and slope sediments in the Gulf of Mexico.* Trans.Gulf Coast Assoc. Geol. Soc., **41**, 719-744.