Mem. Soc. Geol. It.,
45 (1990), 425-451, 5 ff., 6 tabb.

TYRRHENIAN BASIN AND APENNINIC ARCS: KINEMATIC RELATIONS SINCE LATE TORTONIAN TIMES (*)

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ABSTRACT

In the Tyrrhenian Sea and in the Apennines, tectonically-controlled depositional sequences developed since late Tortonian times inside half-graben depressions (syn-rift clastic wedges), inside basins located on top of thrust units undergoing tectonic transport (piggy-back basins), and in migrating foredeeps. The boundaries of these sequences appear as isochronous depositional surfaces regardless of the different structural settings; this allows to subdivide the considered time span into several intervals and to tentatively reconstruct, step by step, the kinematic relationships between the major extensional features in the source-areas (Tyrrhenian area) and the compressional ones in the sink-areas (Apennines). In order to evaluate the amount of shortening in the Apennines, a palinspastic reconstruction is proposed, which takes into account stratigraphy, geometry, and structural-paleogeographic location of the upper Tortonian-lower Pleistocene syntectonic sedimentation. The kinematic analysis evidentiates that two Apenninic arcs, northern and southern, developed with different deformational history and amount of shortening/rotations (stronger in the southern one). This evolution is paralleled by a bipartition of the Tyrrhenian Basin, in which the southern domain experienced stronger extension than the northern one, even with the generation of two small sectors floored by oceanic lithosphere.

In the Northern Apenninic Arc, the deformation mostly proceeded from W to E (or WSW-ENE) during the late Tortonian and Zanclean *p.p.*, and afterward fron SW to NE. In the Southern Apenninic Arc, the deformation proceeded roughly from W to E till late Pliocene-early Pleistocene times and subsequently from NW to SE. The divergence of the tectonic transport has been accomodated by complex transversal lineaments, the most important one being represented by the «Ortona-Roccamorfina Line» which separates the two present-day Apenninic Arcs. At least from early Pliocene times, the tectonic history has been further complicated by the occurrence of out-of-sequence arcuate features related to anticlockwise rotation of chain sectors, induced by triangular geometries of the coeval Tyrrhenian source areas.

The average deformation rate calculated for the whole considered time span along a W-E transect crossing the Central Tyrrhenian bathyal plain and the Southern Apennines is in the order of 5 cm/year both in the extensional areas and in the compressional ones. In the Southern Apennines this value has been obtained by evaluating the retreat of the foreland flexure (foredeep basin migration) and the thrust-front propagation in the mountain chain. Taking into account that higher values must have been reached in correspondence of the apex of the Southern Apenninic Arc (Calabrian Arc), we can deduce that the present-day seismogenic lithospheric slab beneath the South-Eastern Tyrrhenian Sea (length about 700 km), still experiencing passive subduction under the most deformed sector of the arc, is mostly related to the upper Tortonian-Recent deformational events of the system. The subduction rate has not been constant over the whole late Tortonian-Quaternary interval, since higher values have been estimated both in the extensional and compressional areas for Messinian times. The subducted lithosphere must be, at least in the deeper part of the slab, continental in nature, unless we assume that the thick Mesozoic platform carbonates of the Southern Apennines were deposited over an ancient oceanic crust.

KEY WORDS: *Tyrrhenian Sea, Apenninic Arcs, Neogene, Stratigraphic correlations, kinematic evolution.*

RIASSUNTO

Nel Mar Tirreno e negli Appennini si osservano, a partire dal Tortoniano superiore, successioni sedimentarie controllate dalla tettonica deposte in semigraben (cunei clastici sin-rift), in bacini al dorso di unità di catena sottoposte a trasporto orogenico (bacini piggy-back) e in bacini migranti di avanfossa.

I limiti di tali sequenze appaiono come superfici deposizionali isocrone, indipendentemente dalla loro collocazione strutturale. Ciò permette di suddividere il periodo temporale considerato in diversi intervalli e di ricostruire tentativamente, intervallo per intervallo, i rapporti cinematici fra aree in estensione (bacino tirrenico e suoi margini in terraferma) ed aree in compressione (Appennino). La valutazione dei raccorciamenti crostali in queste ultime aree è stata effettuata adottando una ricostruzione palinspastica che tiene conto della stratigrafia, della geometria e dell'ubicazione paleogeografico-strutturale delle succes-

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(*) Lavoro eseguito con contributi MPI 40% 1989 (resp. P. Scandone), MPI 40%-60% 1988-1989 (resp. R. Sartori).

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sioni sintettoniche deposte tra il Tortoniano superiore e il Pleistocene inferiore.

L'analisi cinematica mostra che la catena appenninica è formata da due grandi strutture arcuate, settentrionale e meridionale, che si sono sviluppate con diversi stili di deformazione e, soprattutto, con diverse entità di raccorciamento e di rotazione (molto più forti nell'arco meridionale). Questa diversa evoluzione è rispecchiata da una bipartizione del Bacino Tirrenico, il cui settore meridionale ha subìto una estensione di gran lunga maggiore di quello settentrionale, con la formazione di due piccole aree di litosfera oceanica. Nell'arco appenninico settentrionale la deformazione ha proceduto secondo una direzione prevalente W-E (o WSW-ENE) nel Tortoniano-Zancleano *p.p.* e secondo una direzione SW-NE nei tempi successivi. Nell'arco appenninico meridionale la progressione è stata prevalentemente da W verso E fino al Pliocene superiore-Pleistocene inferiore e da NW verso SE nei tempi più recenti. La divergenza fra questi versi di trasporto è compensata attraverso svincoli trasversali complessi, il più importante dei quali è rappresentato dalla «Linea Ortona-Roccamorfina» che separa i due archi appenninici maggiori con movimento trascorrente destro. La storia tettonica dell'area risulta ulteriormente complicata dallo sviluppo di strutture arcuate fuori sequenza, enucleate quantomeno a partire dal Pliocene inferiore, con rotazioni antiorarie di settori di catena da ricollegare forse a geometrie triangolari delle aree sorgente. La velocità di deformazione media del sistema per tutto il periodo considerato, calcolata lungo una sezione W-E passante per la piana batiale centro-tirrenica e l'Appennino meridionale, è dell'ordine di 5 cm/anno sia per le aree in estensione che per quelle in raccorciamento. Per queste ultime il valore di 5 cm/anno è stato ottenuto misurando la velocità di migrazione della flessura dell'avampaese (registrata dai vari depositi di avanfossa) e la velocità di migrazione dei fronti di compressione. Considerando che in corrispondenza dell'apice dell'arco appenninico meridionale (Arco Calabro) i valori di velocità devono essere stati sicuramente maggiori, si può affermare che gran parte dello *slab* litosferico sismogenico presente sotto il Tirreno sud-orientale (lunghezza circa 700 km), ancora in fase di subduzione passiva, sia da imputare agli eventi deformativi verificatisi tra il Tortoniano superiore e l'Attuale. La velocità di subduzione appare non essersi mantenuta costante nell'intero intervallo Tortoniano superiore-Attuale, dal momento che i valori di estensione e di raccorciamento calcolati per il Messiniano risultano sensibilmente più elevati di quelli calcolati per gli intervalli successivi. La litosfera subdotta deve essere, quantomeno nelle porzioni più profonde dello *slab*, di natura continentale, a meno di non voler ammettere che le potenti successioni carbonatiche di piattaforma dell'appennino meridionale si siano deposte su una crosta oceanica più antica del Trias superiore.

1. INTRODUCTION

In early Tortonian times, a roughly N-S trending mountain chain, consisting of Europe-verging and Africa-verging thrust units, extended between the Corsica-Sardinia block and the subducting western margin of the Adriatic Promontory. During the late Tortonian, severe extensional processes took place in the region and the previous collisional belt underwent extensive rifting and rapid tectonic subsidence (see, among several authors, KASTENS *et alii*, 1987, 1990 and references therein). N-S trending basinal areas, corresponding to the early Tyrrhenian Basin, developed between the eastern border of the Corsica-Sardinia block (transformed from an active plate-margin into a passive one) and the western border of a still active thrust belt. From late Tortonian times, extension in the Tyrrhenian region and compression in the Apennines have coexisted, with a progressive migration of the rift basin-thrust belt-foredeep system towards the present-day Padan-Adriatic-Ionian foreland.

Presently, the mountain chain depicts two major arcs (fig. 1): the Northern Apenninic Arc, which extends from Monferrato to the Latium-Abruzzi region, and the Southern Apenninic Arc which extends from the Abruzzi-Molise region to Sicily, through the Calabrian Arc. The two arcs merge along a transversal lineament known in the geological literature as the «Ortona-Roccamonfina Line» (LOCARDI, 1982; PATACCA & SCANDONE, 1989). The external portions of these arcs are marked by negative Bouguer gravity-anomalies whose

Fig. 1 - Structural sketch of the Tyrrhenian Sea and Apennines: 1) thrust sheets referable to the Tortonian mountain chain; 2-4) marine and continental deposits unconformably covering sunken sectors of the Apenninic chain dissected by the Tyrrhenian rifting: 2) upper Tortonian-Messinian *p.p.*; 3) Messinian *p.p.*-Piacenzian *p.p.*; 4) Piacenzian *p.p.*-Pleistocene; 5-7) terrigenous brackish-water and normal-marine deposits filling piggy-back-basins on top of the forward-migrating Apennine thrust sheets: 5) upper Tortonian-Messinian *p.p.*; 6) Messinian *p.p.*-Piacenzian *p.p.*; 7) Piacenzian *p.p.*-Pleistocene; 8) North-Tyrrhenian shallow plutonic bodies and minor volcanic rocks, upper Tortonian-Messinian *p.p.*; 9-10) extension-related volcanic and sub-volcanic rocks; 9) Messinian *p.p.*-Piacenzian *p.p.*; 10) Piacenzian *p.p.*-Quaternary; 11-12) subduction-related and high-K volcanic rocks: 11) Messinian *p.p.*-Piacenzian *p.p.*; 12) Piacenzian *p.p.*-Quaternary; 13-15) areas with accerted or hypothesized oceanic crust: 13) Messinian *p.p.*, 14) Zanclean *p.p.*-Piacenzian *p.p.*; 15) Piacenzian *p.p.*-Quaternary; 16) «cobblestone» area in the Ionian Sea; 17) surface and subsurface main thrust; 18) anticline axes; 19) syncline axes; 20) extensional listric fault; 21) strike-slip and transform faults; 22) base-of Pliocene isobaths (km); 23) front of the Apennine thrust belt.

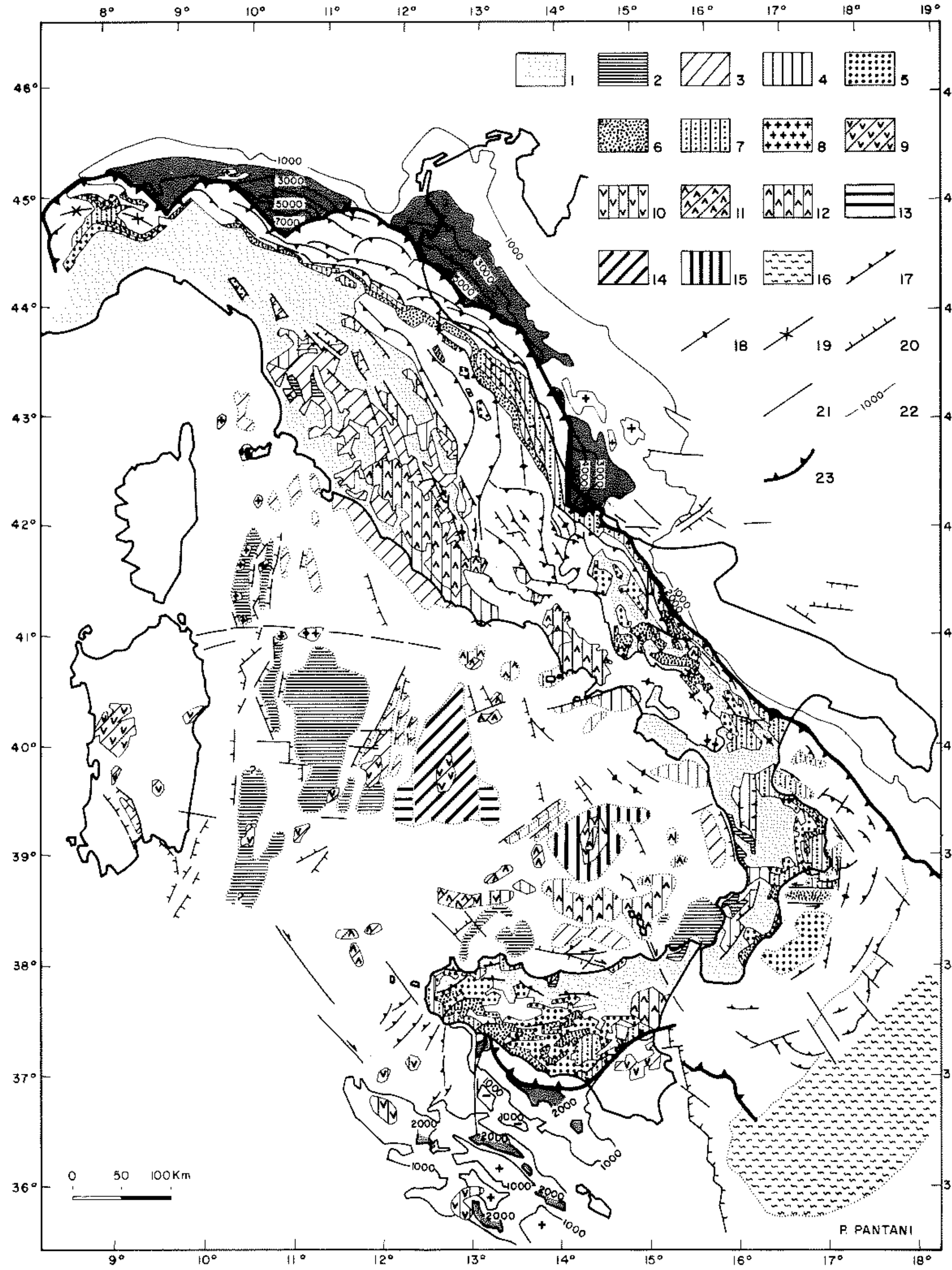
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Fig. 1

regional trend roughly follows the strike of the foreland flexure. The latter is regionally drawn by the deepening gradients of the base-of-Pliocene isobaths. In the Southern Tyrrhenian Sea, intermediate and deep-focus earthquakes witness the existence of a Benioff zone extending to a depth of 500 kilometres (see ANDERSON & JACKSON, 1987 and references therein).

The tectonic style of the southern arc is dominated by large-scale duplex systems (MOSTARDINI & MERLINI, 1986; PATACCA & SCANDONE, 1989) while in the northern arc the thrust propagation proceeded both by duplex structures (Northern Apennines) and (Central Apennines) by imbricate fans in piggy-back sequences (BALLY *et alii*, 1986). The tectonic structure is further complicated by out-of-sequence arcuate features, several tens of kilometers long (e.g. Olevano-Antrodoco Line and front of Sibillini Mountains, Gran Sasso-Genzana Arc, S. Biagio Saracinisco-Matese Line, Pliocene Ofanto basin), sometimes arranged at high angles with respect to the regional trend of the mountain chain (e.g. North-Gran Sasso frontal ramp).

The Tyrrhenian Basin can also be split into two domains, respectively N and S of a major lineament running W-E at some 41° of latitude (FINETTI & DEL BEN, 1986; WEZEL, 1985) and reaching estwards the Central Apennines. Since late Tortonian times, this lineament separated two domains with different extension rates. The Southern Tyrrhenian area was affected by severe rifting processes, up to the generation of two small basins floored by oceanic lithosphere. By contrast, the Northern Tyrrhenian area only experienced a moderate extension (SARTORI, 1989, 1990, with references).

This paper attempts a comparison of the evolutionary steps that generated the Tyrrhenian basin and the Apenninic chain, as recorded by major structural features and by tectonically-controlled sedimentary sequences. The aim is to define the kinematic contraints necessary for any evaluation of the geodynamic processes affecting the area.

2. METHODOLOGICAL APPROACH AND DEFINITION OF THE PRINCIPAL TECTONICALLY-CONTROLLED DEPOSITIONAL SEQUENCES

Our reconstruction of the time-space evolution of the Tyrrhenian basin-Apennine couple is based on a careful analysis of major structural features (listric faults in the extensional areas, thrust fronts in the compressional ones) and on the definition of several depositional sequences which appear to have been closely controlled, at the regional scale, by synsedimentary tectonics.

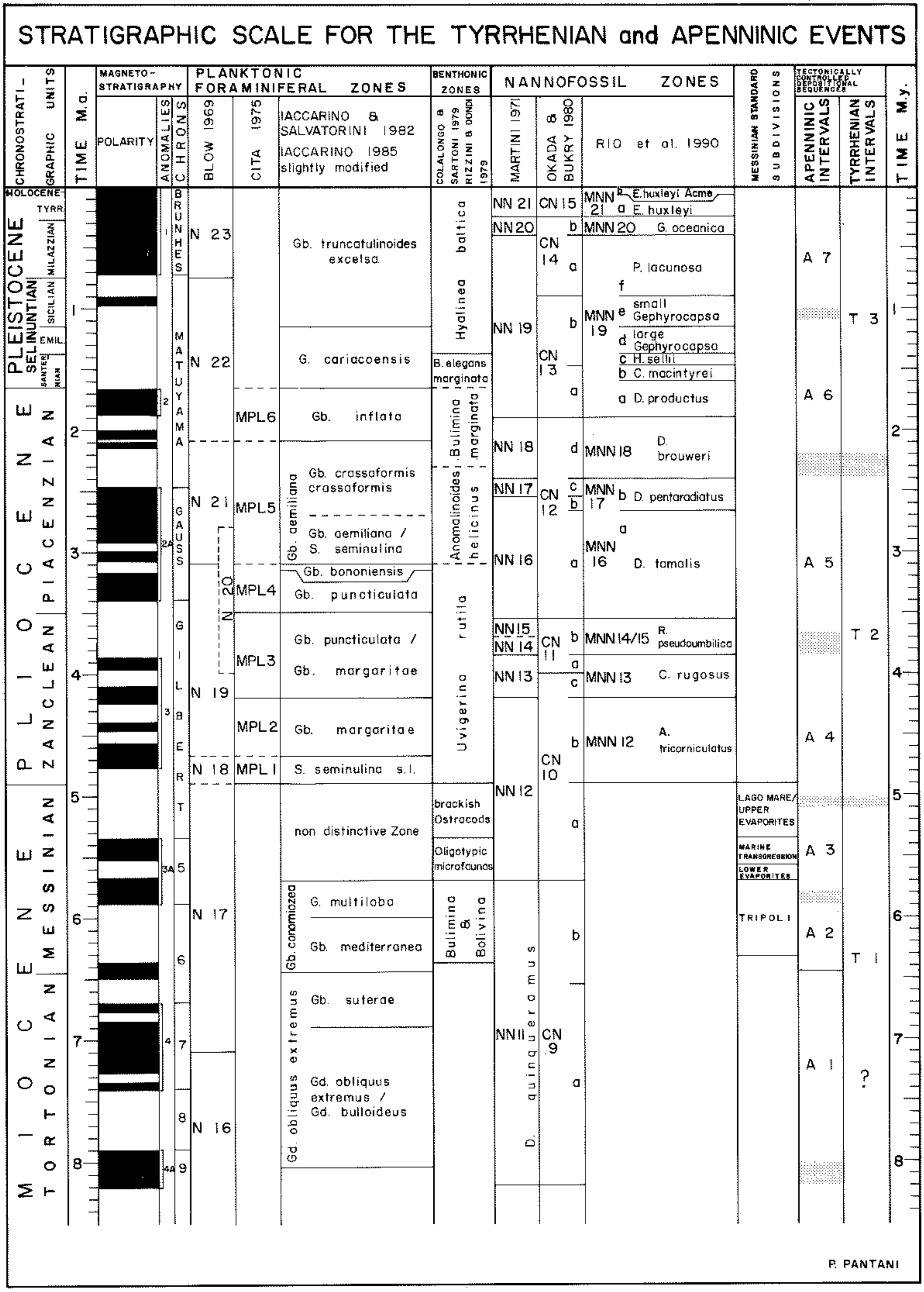
In the Tyrrhenian Sea, three discrete intervals of syn-rift deposition (making up clastic wedges in half-graben basins) and of oceanic expansion have been stratigraphically defined (T1-T3 in table 1) utilizing the drilling data of ODP Leg 107 and DSDP Legs 13 and 42, as well as all other available geological data summarized in SARTORI (1989). The areal distribution of the different episodes of extensional deformation (tectonic subsidence, spreading, magmatism) has been tentatively depicted by extrapolation of the sampling results via the dense network of reflection seismic profiles available in the area. The analysis was carried out either by the direct examination of the profiles or by critical review of the existing literature. The marine areas experiencing extension at different times, and the related tectonic structures, are approximately reported in the map of fig. 1. In some instances, structures producing tectonic subsidence in one interval have been rejuvenated during younger episodes. In such cases, only the oldest interval of synsedimentary tectonic activity has been indicated.

In the Apenninic chain, seven depositional intervals (A1-A7 in table 1) have been distinguished, which have recorded the time-space migration of the thrust belt-foredeep-foreland system from late Tortonian times. The time-scansion is based on:

- the age of the onset of the siliciclastic flysch deposition in the different foredeep domains and the age of the flexural sinking in the adjacent foreland segments. The flexural sinking is well recorded in carbonate ramps by condensed deposits (glauconite-rich sediments, bioturbated hemipelagic mudstones, black shales) indicating a sedimentation change from shallow-water to deeper-water conditions;
- the age of incorporation in the thrust belt of the inner portions of the eastward-migrating foredeep basins (occurrence of exotic huge slide-bodies and of chaotic mass-transported sediments in coarse-grained sandy

TABLE 1

Stratigraphic scale for the Tyrrhenian and Apenninic tectonic events.
(Modified after BERGGREN *et alii*, 1985; IACCARINO, 1985; RIO *et alii*, 1990 and VAI, 1988). The calibration of the late Miocene foraminiferal and nannofossil zones is mostly based on GLAÇON *et alii*, 1990. The calibration of the Messinian standard lithofacies is based on GERSONDE & SCHRADER, 1984; GLAÇON *et alii*, 1990 and MCKENZIE & OBERHÄNSLI, 1985, as well as on Shipboard Scientific Party, Site 654 in KASTENS *et alii*, 1987.



turbidites), as well as the time in which important shifts of foredeep depocentres took place (lateral progradation of coarsening-upward trends in siliciclastic flysch deposits);

– the age of start and end of the different sedimentary sequences which have been deposited on top of advancing thrust sheets, behind the frontal ramps (piggy-back basins).

The boundaries of the A1-A6 intervals follow isochrones which mark both the start of sedimentation in progressively younger piggy-back basins and the major steps of shift in the migrating foredeep basins. The base of the A7 interval, on the contrary, corresponds to the base of the Bradano sedimentary sequence (Montalbano clays, Monte Marano sandstones, Staturo Fm. and Irsina conglomerates) which unconformably overlies the front of the thrust-belt and conformably covers the eastern edge of a Piacenzian *p.p.*-lower Pleistocene *p.p.* clastic wedge corresponding to the youngest Apenninic foredeep. The base of the A7 interval, therefore, settles the age of the last orogenic transport towards the east and the end of the Apulia-foreland flexure retreat.

The geological data-base used for the time-space scansion of the Apennine tectonic evolution is not homogeneous. In the Southern Apenninic Arc and in the Latium-Abruzzi region, several new analytical data (PATACCA *et alii*, 1991a, b, c) allowed a redefinition of the tectonic events and a more detailed scansion of the timing of the deformation. In the greatest part of the northern arc, on the contrary, our analysis was mostly based on a critical review of the geological literature.

In the Tyrrhenian basin-Apennine couple, the most significant depositional sequences which clearly appear to have been closely controlled by tectonic activity may be referred to the following structural settings (see tables 2-4):

– extension areas. Syn-rift clastic wedges, well preserved in the Tyrrhenian area in half-graben basins bounded by listric faults. Sedimentary sequences referable to this tectonic environment crop out along the western margin of the Northern-Central Apennines and in the Calabria Coastal Chain. They may represent the conjugate, eastern margin of the Tyrrhenian Basin;

– mountain chain. Sedimentary sequences (mostly clastic bodies) deposited in piggy-back basins on top of advancing thrust-sheets. The base of such sequences is everywhere marked by unconformable contacts when they overlie roof units of a duplex system. In the areas where the thrust propagation proceeded by imbricate fans, on the contrary, deposits of a piggy-back basin located behind a frontal ramp may conformably follow the siliciclastic deposits of a previous foredeep basin. In such a case, shoaling-up trend of the sequence (see, e.g., the shallow «Ghioli di letto» deposits conformably overlying the turbiditic «Marnoso-arenacea» Fm. in Romagna) is the only element which may suggest a change of the tectonic environment. It is obvious, therefore, that piggy-back-basin deposits unconformably overlying roof-units of duplex systems are better recorders, helpful to filter the eustatic control from the tectonic one. In the Southern Apennines, the overall sedimentation in piggy-back basins (obviously controlled by the synform topography behind the frontal ramps) is characterized by general transgressive trends (shaleying-upward sequences) in the A1-A4 intervals; the regressive trend in the lower portion of the A3 interval (evaporitic limestone and evaporites overlying deep anoxic shales) reflects the well-known salinity crisis

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TABLES 2-4 – *Tectonic settings and related tectonically-controlled depositional sequences in the Tyrrhenian basin-Apennine thrust belt-foredeep system from late Tortonian to lower Pleistocene times.*

References representing the main source of data: ACCORDI *et alii*, 1988; AZZAROLI *et alii*, 1986; BALLY *et alii*, 1986; BERTOLDI, 1988; BOCCALETTI *et alii*, 1982; CAPOZZI, 1987; CASNEDI *et alii*, 1982; CASTELLARIN *et alii*, 1986; CENTAMORE & DEIANA, 1986; CIAMPO *et alii*, 1986; CNR Prog. Fin. Geod., 1989; CNR Prog. Fin. Geod., 1990; CREMONINI & RICCI LUCCHI, 1982; CRESCENTI, 1971, 1975; DALLAN, 1988; DI NOCERA *et alii*, 1974, 1979, 1981; ESU *et alii*, 1986; FREGNI *et alii*, 1983; GELATI *et alii*, 1987; IACCARINO & PAPANI, 1979; MOSTARDINI & MERLINI, 1986; OGNIBEN *et alii*, 1975; ORI *et alii*, 1986; PASQUARÈ *et alii*, *1985;* PATACCA *et alii*, 1991a, b, c; PIERI & GROPPI, 1981; RICCI LUCCHI, 1986; SARTORI, 1990; Univ. di Napoli «Federico II» Dip. Geof. Vulc. – Dip. Pal. – Dip. Sc. della Terra, 1989; VAI, 1988.

TABLE 2

LATE TORTONIAN-MESSINIAN p.p. (T1 = A1-A3)

EXTENSION AREAS	OCEANIC AREAS			Central Tyrrhenian Bathyal Plain (?) (Messinian p.p.)
	RIFT BASINS	NORTH-TYRRHENIAN AREA		continental deposits ("lignitifero"), sahelian marine deposits (Rosignano Limestone), evaporites and Pycnodonta clays of Southern Tuscany; Corsica Basin p.p., Montecristo Basin and Etruschi Trough of Tyrrhenian Sea
		SOUTH-TYRRHENIAN AREA		continental deposits, sahelian marine deposits and evaporites of Western Calabria and Northern Sicily; Tavolara Trough, Cornaglia Terrace, Cefalù Basin p.p. and Gioia Basin of Tyrrhenian Sea
MOUNTAIN CHAIN	PIGGY-BACK BASINS	NORTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEMS	marine terrigenous deposits (Sant'Agata Fossili and Termina marls), evaporitic limestones and evaporites of Langhe-Monferrato and Pavese-Emilia subapenninic hills
			ON IMBRICATE FANS IN PIGGY-BACK SEQUENCES	marine terrigenous deposits ("Ghioli di letto"), evaporites and brackish-water "Colombacci" Fm. p.p. of Romagna (Vena del Gesso); deep marine deposits ("Argille azzurre" of Urbania Basin), "Gessoso solfifera" Fm. and "Colombacci" Fm. of the Marche inner Basins (Urbania, Turrino, Serraspinosa, San Donato-Cantia, Camerino); evaporites of Aurunci Mts. (Penitro)
		SOUTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEMS	siliciclastic turbidites of the Gorgoglione Basin (upper Tortonian p.p.), siliciclastic turbidites of the San Bartolomeo Basin (uppermost Tortonian-lower Messinian), Altavilla sedimentary sequence (Tripoli, evaporitic limestones, evaporites and brackish-water deposits) of Southern Apennines; continental deposits (San Nicola conglomerates), sahelian marine deposits (Ponda clays) and evaporites of Eastern Calabria (Crotone Basin); deep marine deposits ("Globigerina" marls) and evaporites of Caltanissetta Trough (Central Sicily); Spartivento Basin (Ionian Sea)
	FRONTAL RAMPS	NORTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEMS	Ligurian nappes advancing from the "Marnoso-Arenacea" domain to the inner margin of the buried Emilia Folds (Rivergaro-Campore-Felino-Levizzano-Varignana)
			THRUST PROPAGATION MOSTLY BY IMBRICATE FANS IN PIGGY-BACK SEQUENCES	from the Umbria domain to the Santerno-Marzeno-Cingoli front (Romagna-Marche); from Lepini to Marsica (Central Apennine)
		SOUTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEMS	plastic nappes (Liguride, Sicilide and Sannio) advancing from the Alburno-Cervati to the Meta-Frosolone domains; Calabrian nappes overthrusting Ionian domains
FLEXURE ZONES	FOREDEEP BASINS	NORTHERN-APENNINIC ARC		Marnoso-Arenacea Fm. p.p.-Fusignano Fm p.p. of the buried Emilia and Romagna Folds; Marnoso-Arenacea Fm. p.p. of Romagna; (? upper Tortonian) Monte Vicino sandstones (Umbria), uppermost Tortonian-lower Messinian siliciclastic turbidites of the Marche "inner" Basins, and Messinian p.p. Laga Fm. of Northern-Central Apennine; siliciclastic flysch deposits of Latium-Abruzzi region (upper Tortonian in the Lepini (?) and Aurunci Mts., uppermost Tortonian and lower Messinian in the Aurunci, Simbruini and Marsica regions, Messinian p.p. in the Gran Sasso and Laga areas)
		SOUTHERN-APENNINIC ARC		Piaggine-Moleta-Pietraroja-Frosinone p.p. (upper Tortonian), Caiazzo-T. Torbido-Treste, Castelvetere-Vallone Forluso (uppermost Tortonian-lower Messinian), and Agnone - Olmi (Messinian p.p.) flysch deposits

TABLE 3

MESSINIAN p.p.-PIACENZIAN p.p. (T2 = A4-A5)

EXTENSION AREAS	OCEANIC AREAS			Central Tyrrhenian Bathyal Plain (Magnaghi-Vavilov Basin and Issel Basin)
	RIFT BASINS	NORTH-TYRRHENIAN AREA		Elba Basin and Giannutri Basin of Tyrrhenian Sea; Ruscinian p.p.-lower Villafranchian continental deposits of Northern Tuscany; brackish-water redeposited evaporites to normal marine deposits (uppermost Messinian-Zanclean p.p.) of Southern Tuscany; continental deposits (upper Turolian p.p.-Ruscinian p.p.) of Southern Tuscany (E of "Dorsale Medio-Toscana"); Zanclean p.p.-Piacenzian p.p. marine deposits of Southern Tuscany and Northern Latium; Ruscinian p.p.-lower Villafranchian of the Valdarno and Southwestern Umbria (Terni, Spoleto)
		SOUTH-TYRRHENIAN AREA		Western margin of the Central Tyrrhenian Bathyal Plain, Paola Basin and Orlando Basin of Tyrrhenian Sea
MOUNTAIN CHAIN	PIGGY-BACK BASINS	NORTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEM	brackish-water deposits (Cassano Spinola-Stirone conglomerates, Cortemaggiore sandstones) to normal marine deposits (uppermost Messinian-Zanclean p.p.); Zanclean p.p.-Piacenzian p.p. marine deposits of Langhe-Monferrato and Pavese-Emilia subapenninic hills (Asti, Bologna etc.); Zanclean p.p.-Piacenzian p.p. marine deposits of the Southern Marche-Northern Abruzzi region
			ON IMBRICATE FANS IN PIGGY-BACK SEQUENCES	brackish-water deposits ("Colombacci" Fm. p.p.) to normal marine deposits (uppermost Messinian-Zanclean p.p.); Zanclean p.p.-Piacenzian p.p. marine deposits of Romagna subapenninic hills; uppermost Messinian brackish-water deposits of the Marche inner Basins (Pietrarubbia-Turrino sandstones), Zanclean p.p.-Piacenzian p.p. marine deposits of Northern Marche
		SOUTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEM	brackish-water to normal marine deposits of the Braneta depositional sequence (uppermost Messinian-Zanclean p.p.); marine deposits of the Ariano sedimentary cycle (Zanclean p.p.-Piacenzian p.p. deposits of the Benevento, Ariano, Ofanto, Potenza, Calvello, etc. Basins); brackish water to normal marine deposits (uppermost Messinian-Piacenzian p.p.) of Eastern Calabria and Caltanissetta Trough
	FRONTAL RAMPS	NORTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEM	Ligurian nappes advancing from the inner margin of the buried Emilia Folds to the Romagna Folds (only in the Bologna-Varignana area); Villadegna-Tortoreto Lido thrust sheet overriding Maiella and more external unidentified domains (Marche-Abruzzi region)
			THRUST PROPAGATION MOSTLY BY IMBRICATE FANS IN PIGGY-BACK SEQUENCES	from the Santerno-Marzeno-Cingoli front to the Emilia-Romagna and Adriatic p.p. Folds; minor deformations in the Ferrara area; from Marsica to Maiella
		SOUTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEM	Sannio nappes advancing from the Meta-Frosolone domain to the Daunia domains; Molise nappes overriding the Scontrone-Porrara, Maiella and Casoli-Bomba domains; Calabrian nappes overthrusting Ionian domains
FLEXURE ZONES	FOREDEEP BASINS	NORTHERN-APENNINIC ARC		uppermost Messinian-Piacenzian p.p. portions of the buried Po-plain turbidites (Fusignano Fm p.p.-Porto Corsini Fm.-Porto Gaibaldi Fm p.p.); Villa Rofanello-La Queglia siliciclastic flysch deposits (uppermost Messinian-Zanclean p.p.); Maiella flysch deposits (Zanclean p.p.)
		SOUTHERN-APENNINIC ARC		Anversa-Castelnuovo flysch deposits (uppermost Messinian-(?) Zanclean p.p.) in the Scontrone-Porrara domain

TABLE 4

PIACENZIAN p.p.-QUATERNARY (T3 = A6-A7)

EXTENSION AREAS	OCEANIC AREAS			Marsili Basin of Tyrrhenian Sea
	RIFT BASINS	NORTH-TYRRHENIAN AREA		Viareggio Basin of Tyrrhenian Sea; lower Pleistocene marine deposits of the Southern Tuscany coastal plains; uppermost Piacenzian-lower Pleistocene marine to paralic deposits of Southern Valdichiana; upper Villafranchian continental deposits of intramontane Basins (Lunigiana-Garfagnana, Valdarno -Northern Val di Chiana, Mugello-Casentino, Val Tiberina, Rieti etc.)
		SOUTH-TYRRHENIAN AREA		continental and marine deposits of the Volturno, Salerno-Sele Basin and Sapri Basin; Crati and Mesima Basins of Western Calabria; Cefalù Basin p.p. of Tyrrhenian Sea
MOUNTAIN CHAIN	PIGGY-BACK BASINS	NORTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEM	marine and continental deposits of Asti Basin p.p., Pavese-Emilia and Southern Marche-Abruzzi subapenninic hills
			ON IMBRICATE FANS IN PIGGY-BACK SEQUENCES	marine to continental deposits (e.g. Faenza Basin) of the Emilia-Romagna, Ferrara and Adriatic Folds
		SOUTHERN-APENNINIC ARC	ON ROOF UNITS OF DUPLEX SYSTEM	marine to continental deposits of the Atessa sedimentary sequence (Sant'Arcangelo, Calvello and Potenza Basins p.p.); Sibari Basin; Crotone-Spartivento Basins p.p.; Piacenzian p.p.-Quaternary deposits of the Caltanissetta Trough
	FRONTAL RAMPS	NORTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEM	outer margin of Monferrato; Tortoreto Lido front (Southern Marche-Abruzzi)
			THRUST PROPAGATION MOSTLY BY IMBRICATE FANS IN PIGGY-BACK SEQUENCES	outer margin of the Emilia, Ferrara and Adriatic Folds
		SOUTHERN-APENNINIC ARC	THRUST PROPAGATION MOSTLY BY DUPLEX SYSTEM	buried outer margin of the Southern Apennine, external Calabrian arc, front of the Gela nappe
FLEXURE ZONES	FOREDEEP BASINS	NORTHERN-APENNINIC ARC		buried siliciclastic deposits of the Po-plain, out of Apenninic Arcs, partly overthrust by Monferrato-Emilia and Ferrara-Adriatic Folds (Porto Garibaldi Fm. p.p. and Asti sandstones p.p.)
		SOUTHERN-APENNINIC ARC		siliciclastic deposits tectonically covered by the outer margin of the mountain chain from Southern Abruzzi to Sicily

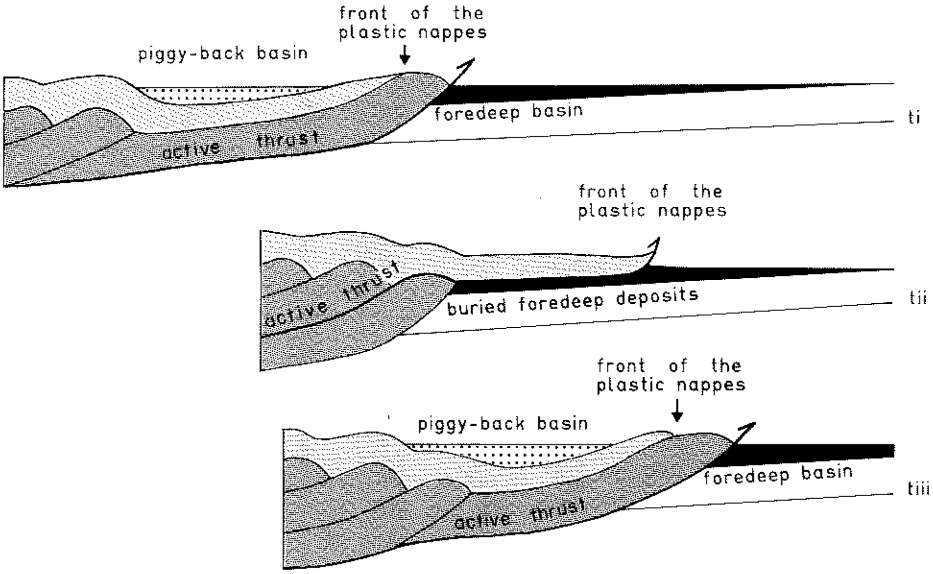

Fig. 2 - Simplified sketch describing foredeep migration, horse imbrication and plastic-nappe eastward motion in the Southern Apennines.

in the Mediterranean area. Conversely, the A5-A6 intervals, characterized by shelf to near-shore clastic sedimentation, show more frequently symmetrical vertical trends (fining upward sequences followed by coarsening upward sequences) possibly reflecting depositional cycles influenced by fluctuations of the sea-level correlable to the eustatic curves of HAQ *et alii* (1988);

– flexure zones. Clastic wedges deposited in active foredeep basins on top of sunken segments of the downward-bending foreland margin (flysch deposits). Usually, the flysch deposits conformably cover (hemi)pelagic sediments of previous foreland domains not yet reached by a volumetrically important siliciclastic supply. Nevertheless, in the innermost portions of the foredeep basins wildflysch deposits may unconformably overlie up-thrown blocks involved in the compressional deformation. In some cases, a retreat of the fault scarps is still recognizable, related to the development of overstep thrust sequences in the hanging wall behind the previous frontal ramp.

The described types of clastic wedges (syn-rift, piggy-back-basin and foredeep deposits) appear systematically arranged in such a way that in the same time interval a sequence pertaining to a certain structural setting has its coeval counterparts in the other two settings. This occurrence obviously implies that the extension in the Tyrrhenian area, the eastward migration of the foreland flexure with the consequent shift of the foredeep basins, and the progressive incorporation of these domains in the thrust belt represent different expressions of the same geodynamic process. In the compressional/flexural areas of the Southern Apennines, a peculiar kinematic mechanism responsible both for the foredeep migration and the duplex propagation has been recognized, which differs somewhat from more classical mechanisms well described in the geological literature (see e.g. BOYER & ELLIOT, 1982).

According to such a mechanism (see fig. 2) a foredeep basin develops at a time t_i east of frontal ramp which represents the emergence of an active thrust surface coinciding with the sole thrust. A piggy-back-basin is emplaced on top of the plastic nappes (e.g. Liguride, Sicilide, Sannio nappes) behind the frontal ramp. In the time t_{ii}, the previous frontal ramp is temporarily abandoned and an out-of-sequence active thrust produces the eastward transport of the plastic nappes, as well as the truncation of the sedimentation in the piggy-back-basin and the tectonic burial of the foredeep clastic wedge. In the time t_{iii}, the eastward propagation of the flat-ramp system east of the front of the plastic nappes produces a new frontal ramp and the generation of a piggy-back-basin/foredeep-basin new couple. After a certain time, also the t_{iii} frontal ramp will be abandoned while the previous t_{ii} frontal ramp will be reactivated by out-of-sequence thrust propagation. These relations are particularly well documented for late Tortonian-Messinian times (A2-A3 intervals), in which the higher resolution of the integrated (foraminifer and nannofossil) biostratigraphy together with the widespread occurrence of several regional key-beds («tripoli», evaporites, post-evaporite tuffite horizon, etc.) allowed us a detailed reconstruction of the tectonic events.

3. TIME-SPACE EVOLUTION OF THE TYRRHENIAN BASIN AND APENNINES

In this chapter, the main steps of the Tyrrhenian-basin/Apennine-chain geological evolution will be briefly summarized. The time intervals chosen for the description of the tectonic history follow the scansion of the Tyrrhenian areas in order to keep the least common denominator for extensional, compressional and flexural settings. Fig. 1 schematically shows the present-day structure of the region, which obviously includes the entire deformation from late Tortonian times and the initial structural pattern before the early Tyrrhenian rift. First of all, we need to establish the initial conditions, mostly related to the Corsica-Sardinia counterclockwise rotation. Fig. 3 is an attempt to restore palinspastic relationship between the Corsica-Sardinia block and the African Promontory after the Corsica-Sardinia rotation and before the early Tyrrhenian rift, that is in the late Tortonian (about 8 MY ago). In this time, an eastward-verging mountain chain separated the Corsica-Sardinia block from the Apenninic domains non yet reached by the compression front. The position of the present-day foreland has been obtained by admitting a certain amount of counterclockwise rotation of the Adriatic Promontory with respect to the Africa pole during the Europe-Africa convergence in the last nine million years (LOWRIE, 1985). A sink-sink transform fault had to connect the southern edge of the eastward-downgoing European lithosphere and the northern margin of the westward-downgoing Adriatic lithosphere (see LAUBSCHER, 1988) at least from late Oligocene times. North of this shear zone, the convergence rate between the two continental masses during lower-middle Miocene times was equalized by the rate of flexure retreat in the European lithosphere. In the south, on the contrary, the rate of flexure retreat in the Adriatic-Ionian lithosphere largely exceeded the convergence rate, allowing the opening of the Western Mediterranean Basin («roll-back» mechanism of MALINVERNO & RYAN 1986). The triangular shape of this basin suggests that the flexural retreat had to increase from north to south.

3.1. LATE TORTONIAN-MESSINIAN P.P. (T1 = A1-A3 INTERVALS OF TABLE 1)

Severe rifting occurred in the Northern Tyrrhenian area (see fig. 1 and table 2) and in the western part of the Southern Tyrrhenian Sea, as well as in the Gioia basin off Calabria (part of the conjugate, eastern margin of the Tyrrhenian basin). In Southern Tuscany, the early rift deposits are represented by the so-called «Lignitifero» whose sequence clearly displays up-section a transition from fluvio-lacustrine to paralic environments. The «Sahelian» transgression in this area («Rosignano Limestone») evidences that marine conditions were reached in the western part of the Tyrrhenian basin during early Messinian times (1). Southwards, sim-

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(1) Structural investigations carried out in South-Western Tuscany on post-Tortonian deposits (interpreted in this paper as syn-rift clastic wedges) have

ilar conditions are recognizable in the Calabria Coastal Chain and in Northern Sicily, where uppermost Tortonian (?) continental conglomerates and sands grade upwards to open-marine lower Messinian deposits. After the «Sahelian» transgression and before the development of the «Lago-Mare» facies the Messinian sequences appear everywhere to have been closely controlled by the climatic changes responsible for the salinity crisis in the entire Mediterranean region. In the South-Central Tyrrhenian Sea, oceanic crust possibly emplaced in limited portions of the basin.

In the same time-interval, a drastic shift of the foredeep basins is clearly recognizable in the whole Apenninic chain. In the Northern-Central Apennines the foredeep migrated from Umbria to Romagna («Marnoso-Arenacea Romagnola») via Monte Vicino sandstones, and finally reached the Marche domain (Laga Fm., *p.p.*) via the siliciclastic flysch deposits of the Marche «inner» basins (Urbania-Serraspinosa *p.p.* and Camerino sandstones, uppermost Tortonian-lowermost Messinian). In the Latium-Abruzzi region (transect 1 in fig. 3 and tables 5-6) the foredeep shifted eastwards from an unidentified domain (possibly including the Lepini mountains) to the Gran Sasso-Genzana domain via Aurunci, Simbruini and Marsica. The time-space migration of the foredeep basin in this region is well evidenced by the occurrence of:

- coarse grained siliciclastic flysch deposits (Torrice Flysch, uppermost Tortonian-Messinian) conformably overlying siliciclastic distal turbidites (Frosinone *p.p.* Flysch, upper Tortonian NN11a) in the Ernici-Aurunci domain;
- siliciclastic flysch deposits (lower Messinian) stratigraphically overlying *Orbulina* limestones and marls (uppermost Tortonian NN11b) in the Marsica-Meta domain;
- siliciclastic flysch deposits (Laga Flysch, Messinian) stratigraphically overlying Pteropod marls (lower Messinian) in the Gran Sasso-Genzana domain.

Intermediate steps of the foredeep migration in the A2 interval are well evidenced by the occurrence of progressively younger multistorey bodies of massive sandy turbidites («proximal turbidites», S_{1-3} sequences of LOWE, 1982) moving from the western to the eastern domains. The common presence of huge blocks of shallow-water carbonates, as well as carbonate-debrite and calciturbidite layers in the siliciclastic deposits of this interval (e.g. Rocca d'Evandro in the Aurunci area, Val Roveto) indicate the proximity of active thrust fronts. The breccia beds (car-

Fig. 3 - Palinspastic sketch of the Apenninic domains in late Tortonian times: 1) Padan-Adriatic lithosphere involved in the deformation related to the Africa-Europe convergence; 2) Tortonian mountain chain and tentative palinspastic relocation of the Calabrian Arc; 3) paleogeographic domains characterized by Mesozoic shallow-water carbonate platforms; 4) inactive front of the Europe-verging mountain chain; 5) active front of the upper Tortonian mountain chain; 6) outer fronts of the thrust systems in the Alps and in the Apennines; 7) transects 1-3 of tables 5-6. The Insubric line is merely a geographic reference-element.

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evidenced the existence of tectonic features related both to compressional (horizontal σ_1) and extensional (vertical σ_1) stress-fields. Compression (mostly evidenced by transpressive features) and extension seem to have been alternatively active from Messinian to Quaternary times (BOCCALETTI *et alii*, 1987; CERRINA FERONI *et alii*, 1983, 1989; MARTELLI *et alii*, 1989; PERTUSATI *et alii*, 1978, 1980; PLESI & CERRINA FERONI, 1979). According to these Authors, the compression responsible for the Apennine shortening did not cease in South-Western Tuscany in the upper Tortonian-Messinian, as usually accepted in the geological literature after TREVISAN (1952), since in this area compressional events would have alternated with extensional ones up to Quaternary times.

The available data are not sufficient, in our opinion, to solve this puzzling problem (compressional structures exist, on the other hand, also along the Tyrrhenian margin of the Southern Apennines, see fig. 1), and they do not allow to elaborate a reliable mechanical model. Nevertheless, we wish to underline that first-order regional features clearly indicate that South-Western Tuscany underwent severe rifting in late Tortonian times and the extensional tectonics migrated towards the present-day orographic divide of the Apenninic chain simultaneously with the shift of the thrust belt-foredeep system towards the present-day Padan-Adriatic foreland. It is hard to believe, following such a picture, that a compression related to the Apennine shortening persisted up to Quaternary times in the westernmost sectors of an eastward-migrating rift-system. We suggest that other kinematic mechanisms should be explored, considering the possible existence of source-source and source-sink transfer-faults in the Tyrrhenian-Apennine system and taking into account the sinistral shear between the Adriatic domains and the Corsica-Sardinia block produced by the post-Tortonian Europe-Africa convergence (see DEWEY *et alii*, 1973, 1989).

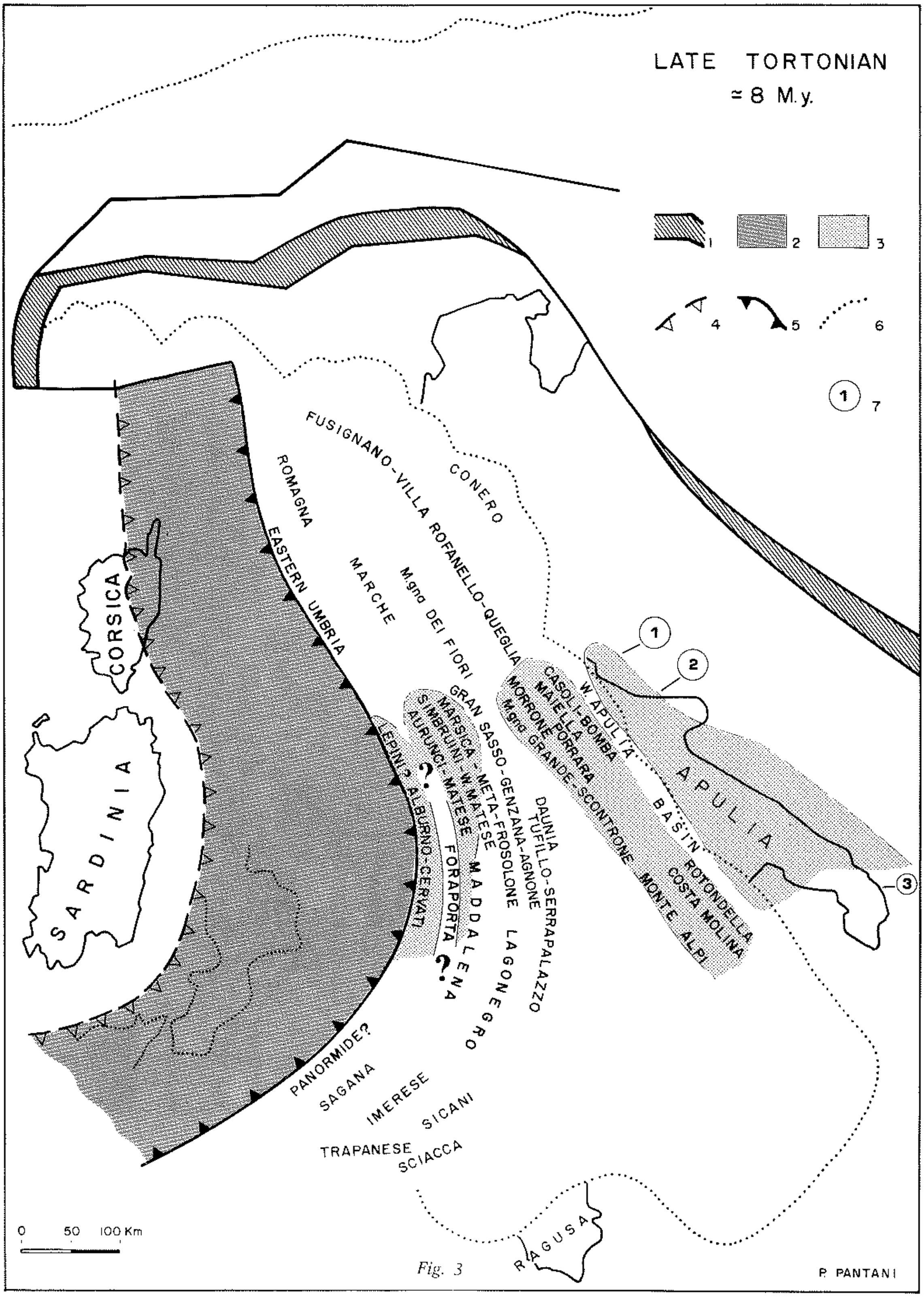

Fig. 3

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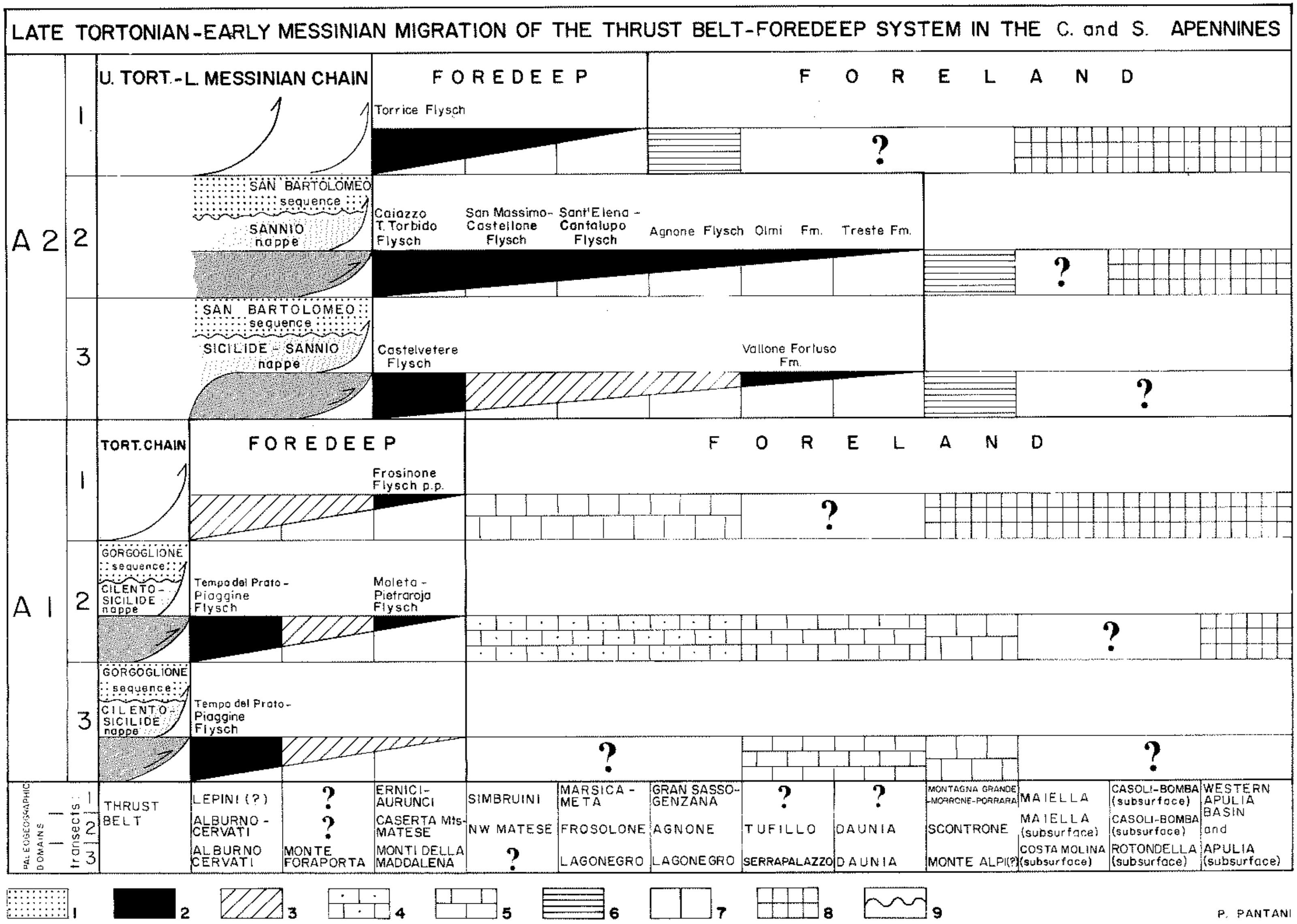
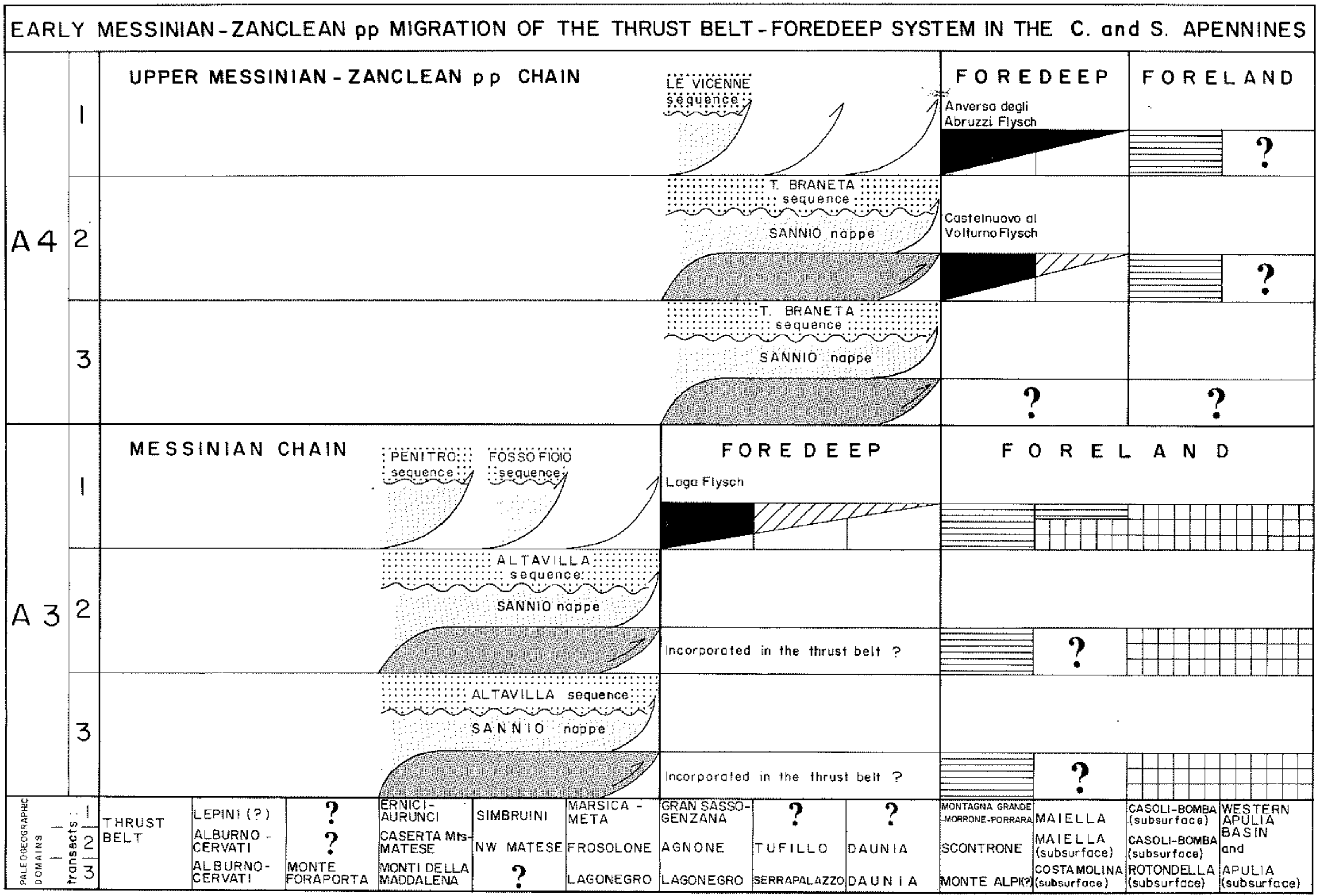
TABLES 5-6

Time-space migration of the thrust belt-foredeep system in the Southern Apennines from late Tortonian to Early Messinian and from late Messinian to Zanclean p.p. times.





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1) Sedimentary sequences deposited on top of advancing thrust sheets (piggy-back basins) and continental/paralic deposits unconformably overlying the mountain chain; 2) foredeep basins (proximal and distal siliciclastic turbidites); 3) inferred foredeep basins; 4) foreland basinal domains with minor siliciclastic input; 5) foreland basinal domains characterized by carbonate resediments; 6) muddy slopes to deep ramps («marne a Pteropodi», «tripoli»); 7) deep carbonate ramps («Orbulina limestones and marls», «Cerrogna»); 8) shallow carbonate ramps and (A3 interval) evaporites; 9) angular unconformity and regional disconformity.

bonate debrites usually interfingering with the siliciclastic turbidites which form the bulk of the foredeep deposits) locally unconformably overlie the Mesozoic carbonates (e.g. Renga breccias of Simbruini Mountains, see DEVOTO, 1967), suggesting overstep thrust propagation in the Apennine outer margin and consequent westward retreat of the active fault-scarps.

In the Southern Apennines (transects 2-3 in fig. 3 and tables 5-6), the foredeep basin shifted in the A1-A2 intervals from the Alburno-Cervati to the Daunia domains via Matese, Frosolone and Agnone domains (in the north) and via Monti della Maddalena, Lagonegro and Serra Palazzo domains (in the south). The shift is well documented in correspondence of the transect 2 of fig. 3 by the occurrence of two eastward-prograded major clastic wedges. The first wedge is represented by the upper Tortonian Piaggine-Tempa del Prato and Moleta-Pietraroja flysch deposits which filled a trough extended from the Alburno-Cervati to the Matese domains. The second wedge, uppermost Tortonian-lower Messinian in age, prograded over the Moleta-Pietraroja distal siliciclastic turbidites and extended from the Caserta-Matese domain (whose internal parts had been reached by the compressional deformation) to the Daunia domain. The different portions of this large clastic wedge are represented by the Caiazzo-Torrente Torbido Flysch (Caserta mountains and Matese), San Massimo-Castellone Flysch (North-Western Matese), Cantalupo-Sant'Elena Flysch (Frosolone), Agnone Flysch (Agnone), Olmi Fm. (Tufillo) and Treste Fm. (Daunia). The latter, consisting of thin and very-fine-grained siliciclastic turbidites (2) conformably overlying uppermost Tortonian hemipelagic marly limestones and marls, represents the eastwards pinch-out of the foredeep basin in the A2 interval (*G. multiloba* zone). In the Campania-Basilicata Apenninic segment (see transect 2 of fig. 3 and table 5), the second clastic wedge is represented only by the Castelvetere Flysch (southern equivalent of the Caiazzo-Torrente Torbido Flysch) and by the Vallone Forluso Fm. (southern equivalent of the Olmi Fm.). The western portions of these clastic wedges are characterized by massive or crudely bedded coarse-grained sandstones and granule conglomerates deposited by high-density turbidity currents. Huge carbonate blocks and thinning-out breccia layers (supplied from active carbonate fault-scarps) near the base of the sequence and olistostromes (derived from the advancing nappes) in the upper part are common features.

The eastward shift of the foredeep basins was accompanied by a parallel migration of the compression fronts in the mountain chain. In the Northern-Central Apennines the compression migrated from the Umbria domain to the Santerno-Marzeno-Cingoli front. North of the Sillaro River, marine deposits (Sant'Agata Fossili and Termina marls), as well as evaporitic limestones and evaporites, were deposited in piggy-back basins on top of the advancing Ligurian nappes. In Romagna (Vena del Gesso), the sudden change from the lower Messinian part of the deep-water «Marnoso-Arenacea» Fm. to the shallower «Ghioli di letto» Fm. and, finally, to evaporites and to the «Colombacci» clays may be interpreted as the result of a tectonic reversal produced by the eastward propagation of the flat-ramp system and by the consequent incorporation of the previous foredeep basin in the thrust belt. The same interpretation can justify the deposition of the «Gessoso-Solfifera» Fm. and of the «Colombacci» clays of the Marche inner basins (Urbania, Turrino, Serraspinosa, San Donato-Cantia and Camerino) which stratigraphically overlie siliciclastic flysch deposits (Urbania, Serraspinosa *p.p.* and Camerino sandstones). We are conscious that the sedimentation change may have been influenced by the large sea-level drop related to the Messinian evaporative episode, but we observe that such variation did not significantly modify the depositional features in more external sectors of the foredeep basin (Laga) where deep-water turbidites were deposited before, during and after the salinity crisis.

In the Latium-Abruzzi region (see transect 1 of fig. 3 and tables 5-6) the compression proceeded from the Lepini Mountains to

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(2) These distal siliciclastic turbidites are in turn stratigraphically overlain by «tripoli», evaporitic limestones and evaporites. We have no elements to discriminate whether this sudden depositional change was controlled by eustatic variations of the sea-level or it was produced by structural inversions related to a progression of the compression front (see also the Romagna and Marche domains in the same time interval).

Marsica, via Simbruini, and possibly reached the Gran Sasso-Genzana domain at the end of the A3 interval (see GHISETTI & VEZZANI, 1988). The time in which the Simbruini mountains were incorporated in the thrust belt is well fixed by the age of the Renga breccias (lowermost Messinian, PATACCA *et alii*, 1991b; SANTO & SGROSSO, 1988) and by the age of continental deposits (lower Messinian, DEVOTO, 1969) unconformably overlying both the Mesozoic carbonates and the Renga breccias. The incorporation of the Marsica domain in the Messinian mountain chain is proved by the occurrence of continental deposits, unconformably overlying Mesozoic carbonates, which yelded a Paratethysian ostracod fauna characteristic of mesohaline environments (DEVOTO, 1969). In the Southern Apennine duplex system (see transects 2-3 of fig. 3 and tables 5-6), the Liguride, Sicilide and Sannio nappes moved from the inner margin of the Alburno-Cervati domain to the Frosolone domain, covering progressively younger foredeep deposits.

On top of these advancing plastic nappes, piggy-back basins developed behind the frontal ramps. The corresponding deposits are represented by the upper Tortonian Gorgoglione Fm., by the lower Messinian San Bartolomeo sequence and by the Messinian Altavilla sequence. Immediately after the deposition of the Altavilla sedimentary sequence, the Sannio nappe overrode the Agnone domain, as well as (probably only in southern areas) the Tufillo-Serra Palazzo and the Daunia domains. At the A3/A4 boundary, the frontal ramps reached the eastern margin of the Molise basin, incorporating in the thrust belt the deposits of the Agnone-Lagonegro, Tufillo-Serra Palazzo and Daunia domains. In the Calabrian Arc (Crotone and Spartivento basins) and in Sicily (Caltanissetta Trough) piggy-back basinal deposits and evaporites are widespread, but the compression fronts are still unidentified either because they are deeply buried beneath the roof-thrust of the duplex system (Calabria and Eastern Sicily) or (Western Sicily) because the available data do not allow their precise location.

3.2a. LATE MESSINIAN-PIACENZIAN P.P. (T2 = A4-A5 INTERVALS OF TABLE 1)

Starting from the picture of fig. 4, a new system of eastward-propagating extensional faults dissected the eastern portion of the previously rifted Northern Tyrrhenian basin and the western margin of the Apenninic chain. In Southern Tuscany (fig. 1 and table 3), thick clastic wedges accumulated in narrow depressions whose elongation changed in the time from N-S to NW-SE, bounded by listric master faults along the eastern margins and by antithetic faults along the western ones. Two depositional intervals may be recognized in this time span, both closely controlled by synsedimentary tectonics. The first interval is represented by uppermost Messinian «Lago-Mare» terrigenous deposits and re-deposited evaporites, followed by Zanclean marine clays (MPL 1-MPL3 *p.p.* zones). The second interval is represented by Zanclean-Piacenzian marine deposits (MPL3 *p.p.*-MPL5 *p.p.* zones) organized into upward-coarsening regressive sequences. The marine deposits progressively grade eastwards into continental/paralic sediments (upper Turolian deposits of Baccinello V3 near Grosseto, Ruscinian deposits of Casino and Val di Pugna near Siena, lower Villafranchian deposits of Valdarno and Spoleto). During Zanclean-Piacenzian times, Northern Tuscany too underwent moderate extension and Ruscinian *p.p.*-lower Villafranchian basins developed north of the Arno plain (Lucca basin, Garfagnana, Lunigiana). In the Southern Tyrrhenian area, widespread rift processes took place east of the Central Fault, which probably led to the opening of the central bathyal plain (Magnaghi-Vavilov and Issel basins). The lower portion of the thick clastic wedge of the Paola basin could represent the conjugate eastern margin of the lower Pliocene rift basin before the emplacing of the central-plain oceanic crust.

The Tyrrhenian extension was accompanied by an eastward migration of the Apennine thrust fronts and by a parallel shift of the foredeep basins. Starting from the upper Messinian, foredeep siliciclastic deposits are usually not exposed at the surface (only in the Marche-Abruzzi region upper Messinian-Zanclean flysch deposits crop out), and the available information mostly derives from published results of oil exploration (see AGIP, 1982; BALDUZZI *et alii*, 1982a, b; BALLY *et alii*, 1986; CASNEDI, 1983; CASNEDI *et alii*, 1981, 1982; CRESCENTI *et alii*, 1980; DONDI *et alii*, 1982; PIERI & GROPPI, 1981). In spite of the rich subsurface information, some segments of the Apenninic foredeep are still poorly known, so that it is really hard to try a satisfactory reconstruction of the thrust belt-foredeep time-space migration.

In the Northern-Central Apennines, the shortening produced the present-day Emilia and Romagna folds, as well as a part of the Adriatic folds. In the same time interval, the Ferrara fold-system too underwent minor deformation. Foredeep basinal deposits in this area are represented, in subsurface, by the Fusignano and Porto Corsini formations, as well as by some portions of the Porto Garibaldi Formation (AGIP, 1982; DONDI *et alii*, 1982). In the Po plain, available geological sections based on seismic data (see PIERI & GROPPI, 1981) show clastic wedges deposited in former foredeep basins overlain by clastic wedges deposited in piggy-back basins behind active ramps. These sections clearly describe how foredeep basinal areas were progressively incorporated in the thrust belt.

In the mountain chain, piggy-back basin deposits crop out, unconformably overlying the Ligurian nappes (north of the Sillaro River) or the previously deformed Romagna and Marche thrust sheets (VAI, 1988). As in the rift basins of the inner margin of the Apennines, also in the piggy-back sequences of the mountain chain two depositional sequences may be recognized, separated by regional disconformities and locally by angular unconformities. The lower sequence (uppermost Messinian-Zanclean *p.p.*) is represented by continental and brackish-water deposits (Cassano Spinola and Stirone conglomerates, «Colombacci» Fm. *p.p.*, Pietrarubbia-Turrino sandstones etc.) conformably overlain by open marine Zanclean sediments. The upper sequence (Zanclean *p.p.*-Piacenzian *p.p.*) is represented by marine deposits widespread along the entire Apenninic margin from the Asti basin to the Pescara area. In the Marche-Abruzzi region the upper sequence, more than 3000 metres thick, unconformably overlies the siliciclastic turbidites of the La Queglia flysch (Cellino Fm. in CASNEDI, 1983). The latter represents the eastward progradation (after the deposition of the upper Messinian tuffite bed) of the Laga foredeep basin, incorporated in the thrust belt during the Zanclean (MPL3 zone) and presently forming (see also BALLY *et alii*, 1986) the upper unit of a duplex system (Villadegna-Tortoreto Lido thrust sheet). We presume that the Piacenzian foredeep deposits, virtually lacking in the Marche-Abruzzi region, have been tectonically covered by this large thrust sheet.

In the Abruzzi-Molise area, new stratigraphic investigation (PATACCA *et alii*, 1991b) allowed us a detailed reconstruction of the time-space migration of the foredeep basin in late Messinian-early Pliocene times (see transects 1-2 in fig. 3 and interval A4 in table 6). During the late Messinian, the foredeep depocentre reached the Scontrone-Porrara and the Montagna Grande paleogeographic domains, as it is testified by the occurrence of wildflysch deposits (Castelnuovo al Volturno Flysch) in the south-western areas and of sandy turbiditic sequences (Porrara and La Queglia Flysch) in the north-eastern ones. The wildflysch deposits (transect 2) include huge blocks and olistostromes derived from the advancing Molise nappes (3) whereas the more distal sandy turbidites only include coarse debrites rich in displaced evaporites and evaporitic limestones (Anversa degli Abruzzi and Castel di Sangro areas, transect 1). The siliciclastic flysch deposits conformably overlie deep-ramp hemipelagic sediments of previous foreland domains which had undergone flexural subsidence starting from late Tortonian times. Near the Mes-

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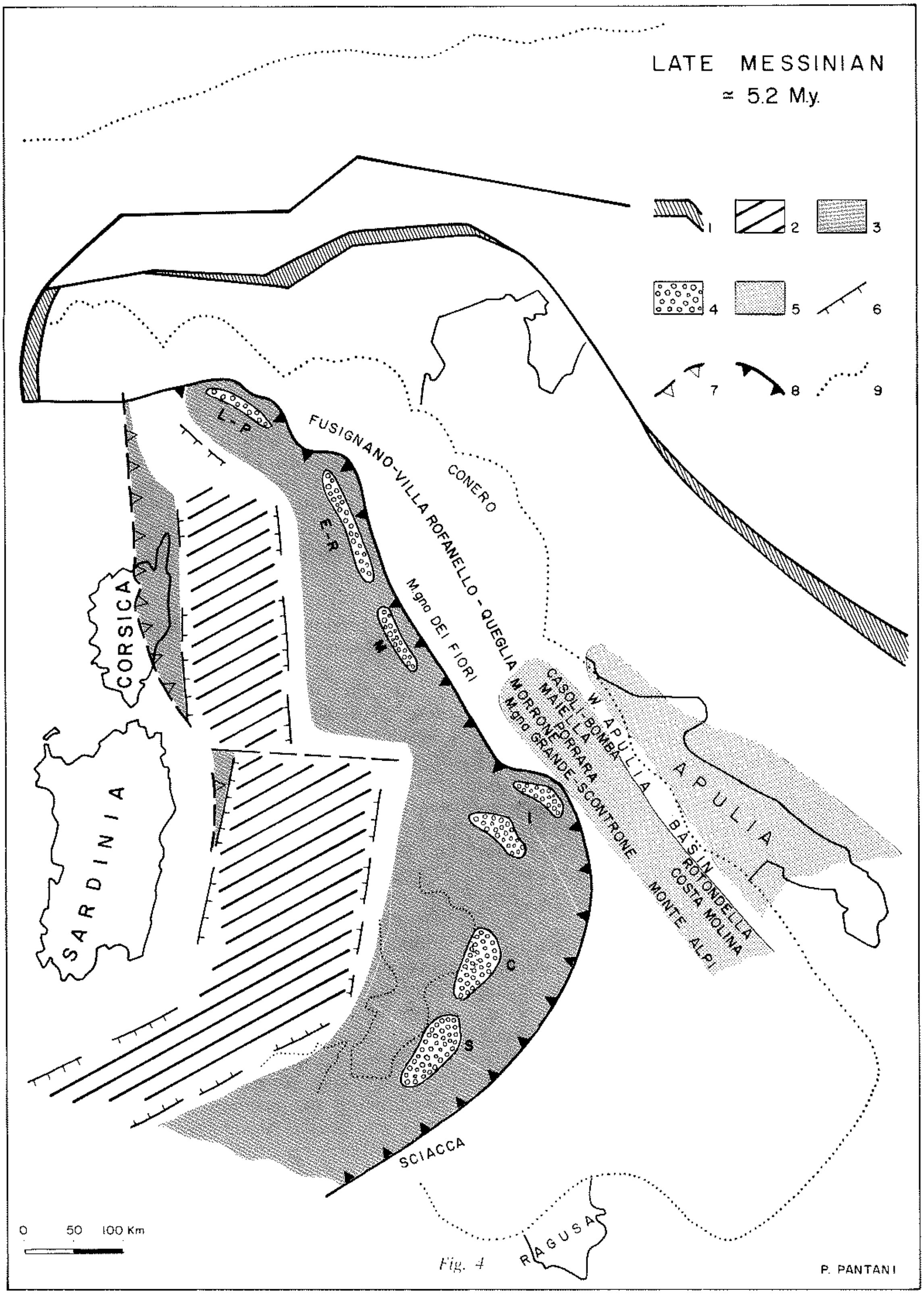
(3) The Molise nappes have derived from the Frosolone, Agnone, Tufillo and Daunia domains.

Fig. 4 - Palinspastic sketch of the Tyrrhenian basin-Apennine thrust belt-foreland system in late Messinian times: 1) Padan-Adriatic lithosphere involved in the deformation related to the Africa-Europe convergence; (2) Tyrrhenian areas affected by rift processes; 3) late Messinian mountain chain. Along the eastern margin of the Corsica-Sardinia block, remnants of the pre Upper Tortonian chain; 4) palinspastic relocation of the principal piggy-back basins in the A3 interval. From N to S: Langhe-Pavese (L-P), Emilia-Romagna (E-R), Marche (M), Irpinia (I), Crotone (C), Spartivento (S); 5) paleogeographic domains characterized by Mesozoic shallow-water carbonate platform; 6) listric faults; 7) inactive front of the Europe-verging mountain chain; 8) active front of the upper Messinian mountain chain; 9) outer fronts of the thrust systems in the Alps and in the Apennines. The Insubric line is merely a geographic reference-element.


LATE MESSINIAN
≈ 5.2 My.
1
2
3
4
5
6
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9
L-P
E-R
M
I
C
S
FUSIGNANO-VILLA ROFANELLO-QUEGLIA
CONERO
M.gno DEI FIORI
CASOLI-BOMBA
MAIELLA
PORRARA
MORRONE
M.gno GRANDE-SCONTRONE
W APULIA BASIN
APULIA
ROTONDELLA
COSTA MOLINA
MONTE ALPI
CORSICA
SARDINIA
SCIACCA
RAGUSA
0 50 100 Km
P. PANTANI

Fig. 4

sinian-Pliocene boundary, foredeep basinal conditions were reached also in the Maiella domain which had experienced flexural subsidence after the salinity crisis. The present-day Maiella unit tectonically overlies the buried Casoli and Bomba carbonate thrust-units (see MOSTARDINI & MERLINI, 1986). The upper part of the sequence in these units consists of Zanclean *p.p.*-Piacenzian *p.p.* (MPL2-MPL4 zones) hemipelagic marls and clays (see CASNEDI *et alii*, 1981) likely deposited on a foreland muddy ramp. These Pliocene deposits conformably overlie Mesozoic-Tertiary carbonates, as well as Messinian evaporites. No evidence of a foredeep basin in this time interval is available both in the Central and Southern Apennines, in spite of the widespread occurrence of piggy-back-basin deposits. We hypothesize that the Zanclean *p.p.*-Piacenzian *p.p.* foredeep basin had to be located between the early frontal thrust of the Maiella unit and the Casoli-Bomba domain, and it was subsequently buried beneath the Maiella carbonates during the upper Pliocene-lower Pleistocene compression. The absence of large portions of Pliocene foredeep deposits makes difficult a detailed reconstruction of the thrust propagation in this region after Zanclean times. A rather good scansion is available for the upper Messinian-Zanclean interval, when the thrust propagation brought to the transport of the Scontrone-Porrara and La Queglia units over the inner margin of the Maiella domain (MPL3 zone). South of the Montagna della Maiella emergence, The Molise nappes overrode the Scontrone-Porrara belt and finally covered the Maiella domain (MPL3 zones), transported by the advancing Scontrone-Porrara thrust sheets.

In the Southern Apennines, few scattered autcrops of uppermost Messinian-lower Pliocene deposits unconformably overlying the Sannio nappe (Braneta sedimentary sequence, see CIAMPO *et alii*, 1986) have been interpreted as relics of broader clastic bodies filling piggy-back-basins. Zanclean *p.p.*-Piacenzian *p.p.* (MPL3 *p.p.*-MPL5 zones) piggy-back-basin deposits are widespread in the Southern Apennines (e.g. Benevento, Ariano, Ofanto, Potenza and Calvello basins), everywhere represented by near-shore to shallow-shelf clastic sediments unconformably overlying roof-units of the duplex system. Larger sedimentary bodies (uppermost Messinian-Zanclean *p.p.* and Zanclean *p.p.*-Piacenzian *p.p.*) referable to two distinct piggy-back basin sequences are preserved also in the Calabrian Arc (Crotone basin *p.p.*, Spartivento basin *p.p.*) and in Sicily (Caltanissetta Trough).

During the upper Messinian-Piacenzian interval, large-scale arcuate features (e.g. «Ancona-Anzio» system and Gran Sasso-Genzana arc) developed in the Apenninic chain, related to out-of-sequence thrust processes. The chronology of this out-of-sequence deformation is still poorly defined. Nevertheless, it is probable that the Gran Sasso-Genzana arc and the subsequent Sibillini front/Olevano-Antrodoco Line system developed towards the end of the upper Messinian-Zanclean interval. The development of these arcuate structures requires considerable amounts of counterclockwise rotations of the thrust units, in a good accordance with the triangular shape of the Zanclean source-areas both in the Northern and Southern Tyrrhenian basin.

3.3. PIACENZIAN P.P.-QUATERNARY (T3 = A6-A7 INTERVALS OF TABLE 1)

In the North-Tyrrhenian extensional areas (see fig. 1 and table 4), a north-eastward propagation of the rift system is documented by a severe tectonic activity in the intramontane basins all along the internal margin of the Northern-Central Apennines, from Lunigiana to Valtiberina and to the Rieti basin via Valdarno-Valdichiana and Mugello-Casentino. In the same time interval, previously block-faulted areas were reactivated and underwent new tectonic subsidence (e.g. Viareggio basin, Southern Tuscany-Northern Latium coastal plains). In the Southern Tyrrhenian Sea, a new rifting event occurred south-east of the Central bathyal plain, followed by the generation of the rombohedral Marsili basin. The Calabrian Arc migrated south-eastwards, piggy-back transporting the previously rifted basins of Gioia and Paola. Along the inner margin of the southern apenninic arc, a new block-faulting accompanied by high-rate subsidence produced the Volturno, Salerno-Sele, Sapri, Crati and Mesima basins, as well as the re-activation of previously rifted areas in the North-Sicily off-shore (e.g. Cefalù basin).

As in the previous intervals, the migration of the Tyrrhenian extension was accompanied by a retreat of the foreland flexure and by a parallel migration of the thrust belt-foredeep system. Most of the foredeep basins developed in this time interval have been tectonically covered by the frontal thrusts of the Apenninic chain. In the Northern Apennines, the foredeep deposits are represented by a large portion of the Porto Garibaldi and Asti formations drilled beyond the front of the buried Emilia, Ferrara and Adriatic folds. In the Southern Marche-Abruzzi region, upper Pliocene/lower Pleistocene foredeep deposits are directly overlain by the Villadegna-Tortoreto Lido thrust sheet.

Piggy-back basins widespread from Piedmont to Northern Abruzzi (Asti basin, Faenza basin, South-Marche basin etc.) roughly follow more or less pronounced synforms which were developing behind the frontal ramps. Out-of-sequence thrust fronts are well documented in the Emilia (behind the Parma-Brè buried folds) and Romagna regions, all along the northern foot of the Apennine mountains (see CASTELLARIN *et alii*, 1986; PIERI & GROPPI, 1981; VAI, 1988).

In the Southern Apenninic arc, Piacenzian *p.p.*-lower Pleistocene *p.p.* foredeep deposits are well known in subsurface from Abruzzi-Molise to the Taranto Gulf (BALDUZZI *et alii*, 1982a, b; CASNEDI *et alii*, 1981, 1982). These deposits stratigraphically overlie the carbonates (or the Messinian evaporites) of the Apulia-Platform/Western-Apulia-Basin domains (see MOSTARDINI & MERLINI, 1986) and are in turn tectonically covered by the roof units of the southern-arc duplex system. Piacenzian *p.p.*-lower Pleistocene deposits (Atessa sequence) unconformably resting on top of the roof units obviously represent remnants of piggy-back basins. The latter are mostly preserved in the southern sectors of the arc (e.g. Sant'Arcangelo, Crotone and Spartivento basins *p.p.*, Caltanissetta Through *p.p.*). Out-of-sequence structures developed also in the southern arc, the most important ones being represented by a system of imbricates widely developed along the outer margin of the Campania-Lucania Apennines from the Vulture region to the Stigliano area.

The overall available geological information clearly shows that a significant clockwise rotation of the slip vectors must have occurred in the Southern Apenninic Arc during the Piacenzian-lower Pleistocene interval, whilst a persistence of a SW-NE direction of the orogenic transport is recognizable in the Northern Apenninic Arc. We do not known the precise moment in which this direction change occurred and the available data do not allow to recognize whether the rotation of the slip vectors was gradual or not. It is sure, in any case, that during the early Pleistocene the Apulia foreland segment ceased flexural subsidence and the previous foredeep basin was filled by allochthonous sheets and by post-orogenic sediments (Bradano cycle). The occurence of *Hyalinea baltica* beneath the allochthonous sheets (BALDUZZI *et alii*, 1982a) and of *G. truncatulinoides excelsa* in the post-orogenic deposits allows to fix this important change in the geodynamic behaviour around the Emilian-Sicilian boundary. Moreover, the previously subsiding foredeep area underwent rapid uplift, so that fluvial conglomerates which represent the top of the Bradano cycle (Irsina Conglomerate) were displaced up to about 400 metres above s.l. along the western margin of the Murge region and up to 800-900 metres along the outer margin of the Apennines. Conversely, flexure retreat and orogenic transport continued in the Calabrian Arc, following NW-SE slip vectors. The differential motion of this orogenic segment suggests the existence of an important system of sinistral transfer-faults between the Apennines and Calabria corresponding in the depth to a lithospheric free boundary *sensu* ROYDEN *et alii* (1987). Significant sinistral strike-slip motions, active in post-Sicilian times, have been recently recognized in the Southern Apennines (TURCO & MALITO, 1988).

4. DISCUSSION AND CONCLUSIONS

The step by step comparison in evolution between the Tyrrhenian Sea and the Apennines allows to point out a number of kinematic constraints for the area.

A) *Geometry and relationships between source and accumulation areas.*

The coincidence of extension in the Tyrrhenian domain (including the rifted zones of the internal Apennines) with crustal shortening in the mountain chain and foreland flexuration in the sink areas points to a unique genetic mechanism for the observed processes. Their spatial-temporal distribution indicates that:

– the differentiation of the two Apenninic arcs from a previous more linear mountain chain, accompanied by different amounts of shortening and rotations, started with late Tortonian times. This differentiation was paralleled by a bipartition of the Tyrrhenian extensional areas, in which extension was much stronger south of the 41° N Lineament where two small domains floored by oceanic lithosphere were generated;

– the amounts of shortening in the thrust belt and of flexure retreat in the foreland areas appear quite larger in the Southern Apenninic Arc than in the Northern one. Coupling this observation with the bipartition of the Tyrrhenian domain, and assuming that in the investigated region the foreland flexuration is a surficial expression of the downward-bending of a lithospheric slab under passive subduction, we must conclude that the 41° N Lineament separated areas with different lithospheric retreat when the vergence of the orogenic transport was roughly eastwards both in the Northern and Southern Apennines. Therefore it corresponds to a major lithospheric discontinuity. In early Pliocene times, however, this general process combined with the enucleation of large-scale arcuate features representing out-of-sequence deformations related to differential anticlockwise rotations of chain segments. This non-cylindrical propagation of the thrust fronts may be probably referred to the triangular geometry of the Central Tyrrhenian area, where oceanic lithosphere was emplacing during the same time interval south of 41° N, as well as to the triangular geometry of the rifted northern Tyrrhenian area;

– in the Northern Apenninic Arc, at least from Emilia to Marche, the vergence of the tectonic transport during Piacenzian-Quaternary times was rather constant, and related to a progressive rift migration in the internal areas. In the southern arc, instead, starting from the upper Piacenzian/lower Pleistocene, the vergence appears to have turned from a roughly eastward direction to a roughly southeastward direction, inducing a prevalence of transpressional-transtensional deformations in the Southern Apennines. This new pattern seems again connected with a change in the South-Tyrrhenian source area, where emplacement of oceanic lithosphere shifted from the central bathyal plain to the Marsili Basin, back of the Calabrian Arc. This new basin has a rombohedral shape indicating a local extension oriented NW-SE. With Pleistocene, a strong divergence in tectonic transport seems then to be established between the two Apenninic arcs. This divergence should be accommodated by new tectonic lineaments, which must play the role of major lithospheric discontinuities. The «Ortona-Roccamorfina Line», characterized by dextral strike-slip motion with a compressional component is here interpreted as the surface expression of a lithospheric tear fault (southern free boundary of the sunken Adriatic lithosphere beneath the Northern Apenninic Arc).

B) *Deformational rates.*

We have tried to estimate the deformational rates for the Tyrrhenian-Apennine system in two independent ways, namely measuring extensional rates in the Tyrrhenian areas and rates of foredeep migration (time-space migration of the flysch deposits in the different paleogeographic domains), as well as rates of the compression-front propagation in the Southern Apennines. The pictures we obtained are quite comparable with the two approaches, and indicate a mean value in the order of 5 cm/year from late Tortonian to early Pleistocene times in the Southern Apennines. Slightly higher value (6 cm/year or some more) can be estimated for the extension behind the Calabrian segment of the southern arc. Moreover, our step-by-step analysis allows a calculation of such rates for different time intervals. Although in a preliminary stage, this analysis seems to indicate that deformational rates were not constant, at least in the southern arc-Southern Tyrrhenian couple. The maximum speed, up to 8 cm/year seems to have occurred essentially during Messinian times, while Pliocene rate values appear to be comparatively lower.

C) *Additional constraints for the subduction process.*

According to the previous figures and to the paleogeographic reconstructions reported in figs. 2 and 3, and assuming that all proces-

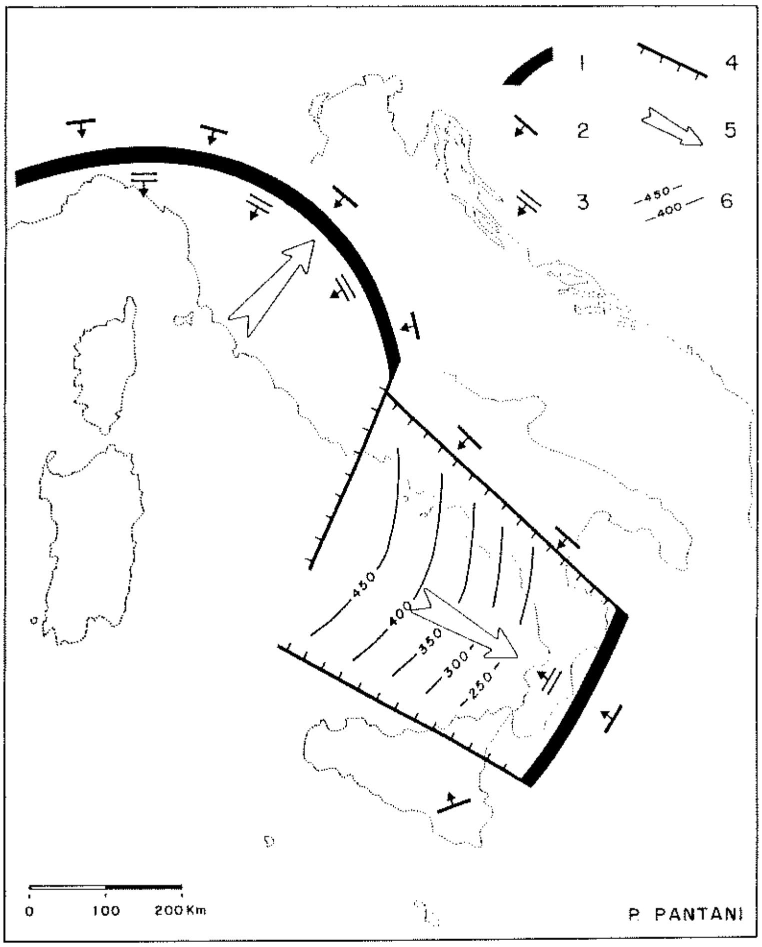

Fig. 5 - Kinematic relationships between the Northern and the Southern Apenninic arcs in post-Sicilian times showing the differential flexure retreat and sinking of the Padan-Adriatic-Ionian lithosphere: 1) lithosphere flexure zone; 2) dip of the foreland lithosphere evidenced by the gradient of the base-of-Pliocene isobaths; 3) dip of the passively-sinking lithosphere; 4) lithosphere tears bounding slabs with different dips and different rates of flexure retreat; 5) slip vectors of the orogenic transport; 6) isobaths of the Benioff zone in the Southern Tyrrhenian area (From PATACCA & SCANDONE 1989 with slight modificatios).

ses we described were related to a passive sinking of the foreland lithosphere (that is without any significant convergence between the Padan-Adriatic-Ionian foreland and the Corsica-Sardinia block), we arrive at the following considerations:

– *Quaternary subduction configuration.* Fig. 5 schematically shows the possible interpretation of the present-day «Ortona-Roccamonfina-Line» as the surface expression of a lithospheric tear fault playing the role of free boundary of the Northern Apenninic Arc. The inferred free boundaries of the southern-arc passively-subducting foreland lithosphere are also represented, together with the sense of the Quaternary orogenic transport. According to such a picture, two lithospheric slabs should underlie the northern and southern arcs. Geophysical data suggest the existence of deep-seated lithospheric roots in the northern arc (DELLA VEDOVA *et alii*, 1991), but no direct evidences are supplied by deep-focus earthquakes. A well defined Benioff zone is evident only in the Southern Tyrrhenian Sea where the earthquake hypocentre depths reach about 500 kilometres. Nevertheless, passive subduction processes must be inferred also beneath the Northern Apenninic Arc, although the sinking rate should be much smaller (around 1.5-2 cm/year) than in the southern arc (more than 6 cm/year);

– *nature of the subducting seismogenetic slab.* Late Tortonian-Messinian lithospheric bending and passive sinking in the southern arc involved paleogeographic domain characterized by extensive and thick carbonate platforms. This would suggest that the lithosphere was continental in character (although possibly thinned), unless we assume that the carbonate platforms developed as oceanic morphostructures. However, no evidence for an oceanic substratum is available. We do not exclude that part of the seismogenic slab may be oceanic in nature, as some characteristics of the Northern Ionian Sea would suggest. Nevertheless, it is worth mentioning that in this case subduction of a continental lithosphere had to occur before the subduction of an oceanic one. This appears somewhat conflicting with the obtained rates of foreland flexure retreat, higher in the early time intervals, since a continental lithosphere should downbend with more difficulty because of its higher buoyancy;

– *age of the subducting slab*. If we take into account the amount of extension envisageable behind the Calabrian apex of the Southern Apenninic Arc (more than 6 cm/year for at least 8 MA) and compare it with the lenght of the slab presently undergoing subduction beneath Calabria (some 700 km), we are forced to think that about 70% of the slab represents subduction that occurred since the onset of the Tyrrhenian rift. In other words, the bulk of the seismogenetic slab does not represent a relic of the lithosphere which had subducted beneath the Sardinia calc-alkaline arc during late Oligocene-middle Miocene times but it represents the original substratum of the post-Tortonian thrust sheets stacked in the present-day Southern Apenninic Arc.

Manoscritto pervenuto il 13 febbraio 1991.
Testo approvato per la stampa il 3 giugno 1991.
Ultime bozze restituite il 26 ottobre 1992.

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