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Oligocene migration path for Apulia macromammals: the Central-Adriatic bridge

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ABSTRACT

In the second half of the past century two important Tertiary land-vertebrate fossil sites were discovered in Southern Italy, the first located in Western Gargano near Apricena and the second situated in Abruzzi in the outskirts of Scontrone. The vertebrate fossil assemblages of the two sites, which are characterized by the same remarkable endemic attributes, include small and large land mammals, a lutrine carnivore, testudines, crocodiles and birds of prey. The Scontrone bonebeds have a Tortonian age. The Gargano fossil vertebrates, which are contained in karstic fissure fillings, have been attributed to a time interval spanning from the Tortonian to the Messinian-early Pliocene, but their exact age remains still undefined. The characters of the faunal assemblage of both sites, showing no affinity with West-European or African Neogene faunas, suggest a possible provenance from the Balkan region.

This paper is aimed at providing information on the migration path followed by the forerunners of the Gargano and Scontrone land mammals when they spread over Apulia. Our results are mostly based on the seismostratigraphic analysis of more than 6000 kilometers of reflection seismic profiles from the Adriatic offshore, tied to several tens of deep wells. The conclusion of this study is that, moving from the Balkan region, the terrestrial vertebrates crossed the present Central Adriatic Sea during the Oligocene (most likely around the early/late Oligocene boundary, i.e. around 29-30 Ma), when a severe sea-level fall exposed a landbridge connecting Dalmatia and Gargano via the Tremiti Islands.

The seismostratigraphic investigation clearly indicates that the Dalmatia-Gargano landbridge was set up owing to three favourable circumstances:

– the growth of prominent structural highs in the Central Adriatic area, mostly related to salt tectonics, which interrupted the continuity of the middle Liassic basinal domain. Vertical movements peaked between the late Liassic and the early Cretaceous, but the tectonics has continued, though less intense, until the Quaternary;

– the occurrence of an important sea-level fall around the end of the early Paleocene, which caused in the whole Central Adriatic area a generalized absence of lower Paleocene deposits, as well as a widespread seaward progradation of upper Paleocene/Eocene shallow-marine carbonates over older deeper-marine deposits. Consequently, a wide shallow-water plateau spread between Gargano and the Dalmatian Islands, separating a Northern Adriatic Basin from a Southern Adriatic Basin;

– the occurrence, finally, of a further particularly strong sea-level fall in Oligocene times (likely coincident with the well-known mid-Oligocene global sea-level fall), which caused a generalized exposure of the Central Adriatic area.

The results of this study suggest a possible common origin of the giant insectivore *Deinogalerix*, recovered both at Scontrone and Gargano, and mainland counterparts distributed in the Balkan region during the second half of the Oligocene.

Key words: *Scontrone, Gargano, Dalmatia, Apennines, Central Adriatic stratigraphic architecture, land vertebrates, Oligocene paleogeography, Miocene paleogeography, seismic interpretation.*

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RIASSUNTO

Una via di migrazione oligocenica per i macromammiferi miocenici dell'Apulia: il ponte continentale centro-Adriatico.

Nella seconda metà del secolo scorso furono scoperti in Italia meridionale due importanti giacimenti terziari a vertebrati, il primo nel Gargano presso Apricena e il secondo in Abruzzo presso Scontrone. L'associazione faunistica dei due siti è identica, con notevoli caratteri di endemismo, e include grandi e piccoli mammiferi terrestri, lontre, cheloni, coccodrilli e uccelli predatori. Il giacimento fossilifero di Scontrone ha un'età tortoniana. L'età dei fossili del Gargano, tutti contenuti in riempimenti di cavità carsiche, è ancora mal definita e in letteratura varia dal Tortoniano al Messiniano/Pliocene inferiore. I caratteri di ambedue le associazioni a vertebrati suggeriscono una provenienza dall'area balcanica.

Questo lavoro ha lo scopo di fornire informazioni sulla probabile via seguita dai progenitori dei vertebrati di Scontrone e del Gargano per raggiungere la Piattaforma Apula. I risultati sono basati sull'analisi sismostratigrafica di oltre 6000 chilometri di profili sismici a riflessione in mare tarati su una sessantina di pozzi per ricerca di idrocarburi. I risultati di questo studio dimostrano che, muovendosi dall'area balcanica, questi vertebrati terrestri attraversarono l'Adriatico centrale durante l'Oligocene, molto verosimilmente intorno al limite Oligocene inferiore/Oligocene superiore (29-30 milioni di anni fa), quando un severo abbassamento del livello del mare a scala globale causò l'esposizione subaerea della regione e permise l'instaurarsi di una via di comunicazione tra la Dalmazia e il Gargano attraverso le Isole Tremiti. L'analisi dettagliata di profili sismici in Adriatico mostra che questa via di immigrazione fu determinata dal concorso di tre circostanze favorevoli:

– formazione nell'Adriatico centrale di alti strutturali, soprattutto legati ad una tettonica salina, i quali interruppero la continuità delle aree bacinali impostatesi alla fine del Lias inferiore. Questa tettonica fu particolarmente attiva tra il Lias superiore e il Cretacico inferiore, ma i movimenti hanno persistito, sia pur con intensità minore, fino al Quaternario;

– importante abbassamento del livello del mare intorno alla fine del Paleocene inferiore che determinò nell'Adriatico centrale un'assenza quasi generalizzata di depositi del Paleocene inferiore ed un'estesa progradazione di depositi carbonatici di mare basso del Paleocene superiore/Eocene al di sopra di depositi cretacei di mare più profondo. Come conseguenza, un vasto plateau di mare basso si instaurò tra il Gargano e le isole della Dalmazia separando un bacino nord-adriatico da un bacino sud-adriatico;

– nuovo e più importante abbassamento del livello del mare durante l'Oligocene (molto verosimilmente coincidente con l'abbassamento del livello del mare verificatosi a scala globale intorno al limite Oligocene inferiore-Oligocene superiore, più drastico di quello paleocenico). Questo evento, forse sommato ad altri eventi minori all'inizio e alla fine dell'Oligocene, causò una generalizzata esposizione subaerea del plateau centro-Adriatico e la creazione di un ponte tra la Dalmazia e il Gargano attraverso il quale migrarono i vertebrati terrestri.

I risultati di questo studio suggeriscono anche una possibile origine comune dell'insettivoro gigante *Deinogalerix*, ritrovato sia in Abruzzo sia nel Gargano, e di alcuni insettivori distribuiti nella regione balcanica nella seconda metà dell'Oligocene.

Termini chiave: *Scontrone, Gargano, Dalmazia, Appennino, architettura stratigrafica dell'Adriatico centrale, vertebrati terrestri, paleogeografia oligocenica, paleogeografia miocenica, interpretazione sismica.*

1. INTRODUCTION

In the second half of the past century two important Tertiary land-vertebrate fossil sites were discovered in Southern Italy. The first was found in Western Gargano between Apricena and Poggio Imperiale. The fossil remains, which are included in continental karstic fissure fillings («terra-rossa»), have been attributed to the early Tortonian (Vallesian-Turolian boundary) by FREUDENTHAL (1971, 1976), while DE GIULI & TORRE (1984) and DE GIULI *et alii* (1985 a,b,c; 1986 a,b) dated them to the latest Miocene/earliest Pliocene. The karstic system, which consists of a complex and multistorey network of sedimentary dykes, affects the top of Jurassic-Cretaceous carbonates of the Apulia Platform and is buried under middle-upper Miocene and locally Pliocene shallow-water calcarenites. Because the karstic fissures have long acted as sediment traps and successive generations of filling deposits represent palimpsests or «overlays» of accumulation events, the homogeneity of the fauna they contain must be questioned. Hence, the exact chronological position of the Gargano vertebrate remains within a generic middle-upper Miocene and earliest Pliocene time span is still very unclear. The second fossil site is Scontrone in Abruzzi. It consists of bone-bearing coastal-flat carbonates of ascertained Tortonian age (Scontrone Member of the *Lithothamnium* Limestone Formation, PATACCA *et alii* in press). The associated faunal remains include small and large land mammals, a lutrine carnivore, testudines and crocodiles. The same taxa, but somewhat more advanced, occur in Gargano. Moreover, the faunas from both localities show identical endemic characters. The specimens are now preserved in different institutions, both in Italy (Centro di Documentazione Paleontologico at Scontrone, Dipartimento di Scienze della Terra of the University of Rome «La Sapienza», Dipartimento di Scienze della Terra of the University of Florence) and in Holland (Nationaal Natuurhistorische Museum-Naturalis in Leiden).

Major goals of our study were: 1) to find out where did the Scontrone-Gargano land vertebrate ancestors come from; 2) when did they colonize the area, and 3) which migration route did they follow.

2. THE SCONTRONE-GARGANO VERTEBRATES: SOURCE AREA OF THE ANCESTORS AND AGE OF THE APULIA COLONIZATION

Both paleontological evidence and regional palinspastic restorations prove that the Scontrone and Gargano fossil sites belonged to the same paleobiogeographic province. The shared endemic characters of both faunas clearly attest to their common origin as well as to their prolonged isolation while geological evidence shows that in Mesozoic and Tertiary times Scontrone and Gargano belonged to a vast and isolated shallow-water paleogeographic domain known in the literature as the Apulia Platform.

Remarkable differences exist between the Scontrone-Gargano fossil assemblage and the probably coeval late Miocene vertebrate faunas recovered at Baccinello in Southern Tuscany (see AZZAROLI & GUAZZONE, 1980; AZZAROLI *et alii*, 1986). The characters of the Tuscan faunas, which are embedded in continental deposits lying in unconformity on top of the emerging Apennine chain, point to an indisputable West-European provenance of the vertebrate forerunners (ROOK *et alii,* 2006). Fig. 1 shows a paleogeographic reconstruction of the Apennine-Apulia region in early Tortonian times with the relocation of the Baccinello, Scontrone and Gargano fossil sites. The early Tortonian is when the oldest populations of Scontrone and Baccinello disseminated and the Gargano faunas had necessarily already spread out into the region. The differences between the Baccinello and Scontrone-Gargano fossil vertebrates are justified by the obvious natural barriers existing between the Apennine mountain chain and the Scontrone-Gargano foreland. The palinspastic restoration proposed in fig. 1 shows that a foredeep basin developed without interruptions all along the front of the eastward-propagating Apennine thrust belt separated the Tortonian mountain chain from the Apulia foreland. This prominent feature, which persisted from Oligocene times on, had to represent an insuperable barrier for land mammal migration and faunal homogenization.

Extensive paleontological research has been carried out on the Scontrone and Gargano vertebrate populations (BALLMANN, 1973, 1976; BUTLER, 1980; DE GIULI & TORRE, 1984; DE GIULI *et alii,* 1985 a,b,c, 1986 a,b; FREUDENTHAL, 1971, 1972, 1973, 1976; LEINDERS, 1983; MAZZA, 1986, 1987; MAZZA *et alii,* 1995; RUSTIONI *et alii,* 1992; MAZZA & RUSTIONI, 1996). Typical components of this unique terrestrial community are the Hoplitomerycids (fig. 2), bizarre ruminants with an archaic mixture of cervid-, giraffid- and bovid-like features, most informative from both the paleoecological and paleogeographical viewpoints. In fact, by diversifying into a variety of forms, from small, sturdy and massively built ones up to larger and more slender representatives, the Hoplitomerycids indicate the existence of an array of ecologic niches, and thus indirectly prove that the Scontrone-Gargano bioprovince developed in a morphologically complex setting under various environmental conditions. But they tell us more than this. Despite being so different proportionally, the various Hoplitomerycids show remarkably homeomorphic traits, denoting their stemming from a single ancestral stock. A few attempts have already been made to find the potential ancestors of the Scontrone-Gargano continental taxa; however, the hypotheses are hardly destined to reap success because of the fauna's high degree of endemization. It is certainly not accidental that most studies eventually point to a Central/Eastern European origin of the analyzed taxa. The Hoplitomerycids show dental affinities with the Central European Eocene choeropotamids and dacrytherids, with which they might be remotely linked. As concerns *Deinogalerix*, BUTLER (1980) considered its derivation from the Central European *Parasorex* and *Schizogalerix* unlikely, while VAN DEN HOEK OSTENDE (2001) elected *Parasorex* its most probable ancestor. VAN DEN HOEK OSTENDE based his opinion on the closer dental similarity of *Parasorex* to *Deinogalerix*, although *Schizogalerix* would be a much closer neighbour to the Scontrone-Gargano genus than was *Parasorex*. The *Deinogalerix* find from Scontrone can shed new light on the phylogeny of these particular Galericines, as it seems to open two possible alternatives: a phyletic succession of *Schizogalerix*, *Parasorex* and *Deinogalerix*, or a dicotomical derivation of *Schizogalerix* and *Deinogalerix* from *Parasorex*. Refer-

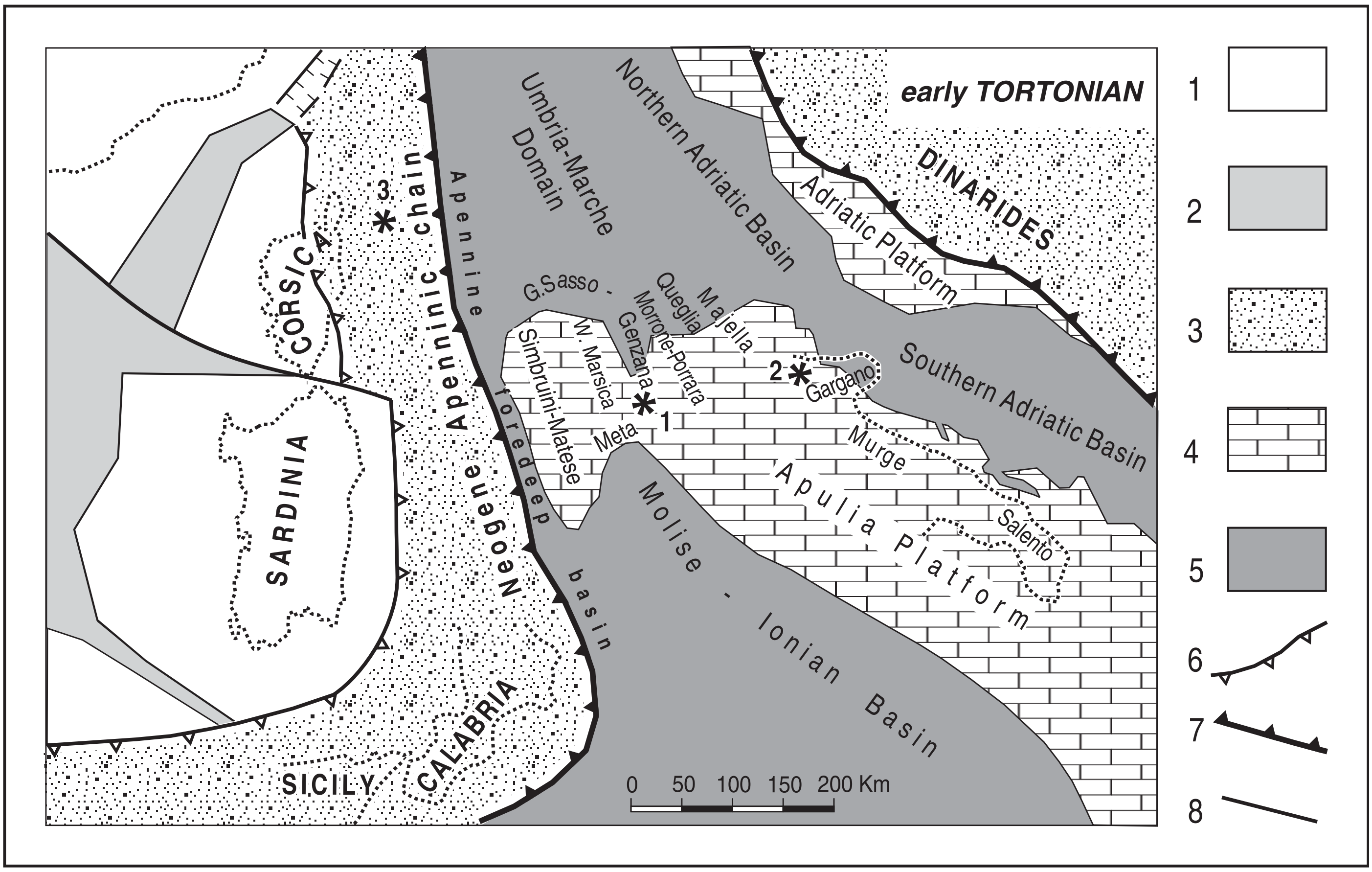

Fig. 1 - Palinspastic restoration of the Apennine-Adriatic domains in early Tortonian times. Asterisks indicate the location of the Scontrone (1), Gargano (2) and Baccinello (3) fossil sites. The picture shows that when the Scontrone bonebed was accumulated the Apulia Platform formed, together with the other carbonate-platform domains of the Central Apennines (Simbruini-Matese and Western Marsica), a physiographic high surrounded by deeper marine areas and separated from the Apennine mountain chain by a continuous foredeep basin: 1) Areas of the European hinterland floored by continental crust; 2) Areas of the European hinterland floored by oceanic or thinned continental crust; 3) Thrust belts; 4) Subaerial and shallow-water areas of the Adriatic-Ionian foreland; 5) Deep-water domains in the Adriatic-Ionian foreland and foredeep basin at the front of the Neogene Apennine chain; 6) Inactive front of the Europe-verging thrust system; 7) Active front of the Africa-verging thrust system in the Apennines and Dinarides; 8) Major strike-slip faults.
– Ricostruzione palinspastica dei domini appenninico-adriatici nel Tortoniano inferiore. Gli asterischi indicano la posizione dei giacimenti fossiliferi di Scontrone (1), del Gargano (2) e di Baccinello (3). La figura mostra che nel tempo in cui si depositò il livello ricco a vertebrati di Scontrone la Piattaforma Apula formava, assieme ad altre aree di piattaforma di mare basso dell'Appennino Centrale (Simbruini-Matese e Marsica Occidentale), un alto morfologico circondato da acque profonde. Questo alto morfologico era separato dalla catena appenninica da un bacino d'avanfossa: 1) Aree del retropaese europeo a crosta continentale; 2) Aree del retropaese europeo a crosta oceanica o crosta continentale assottigliata; 3) Catene montuose; 4) Aree emerse ed aree di mare basso dell'avampaese adriatico-ionico; 5) Aree di mare profondo dell'avampaese adriatico-ionico e bacino di avanfossa al fronte della catena appenninica neogenica; 6) Fronte inattivo del sistema di catena Europa-vergente; 7) Fronte attivo del sistema di catena Africa-vergente nell'Appennino e nelle Dinaridi; 8) Principali faglie trascorrenti.

ring to *Prolagus* from Gargano, the two endemic species *P. apricenicus* and *P. imperialis* have likely derived from a *P. oeningensis* side stock detached from the population that was migrating from Central Europe towards Turkey through the Balkans (Mazza, 1986, 1987). Lastly, a possible origin of the Gargano glirids from Eastern European or Anatolian stocks is suggested by the conclusions of a PhD study recently carried out at University of Florence (Rinaldi, 2006).

The characters of the Scontrone-Gargano land communities indicate a paleobiogeographic province isolated from the nearest mainland for a considerable lapse of time, but there is no paleontological basis to calculate the duration of the isolation and therefore to establish the age of the first colonization. De Giuli *et alii* (1986 a,b) supposed the early Miocene and the middle Miocene p.p. as the most favourable period for the establishment of a hypothetical archipelago in the Apulo-Dalmatic region determining speciative radiation phenomena during mammal migration from the Balkan region. However, if we analyze the stratigraphic record of the Apulia Platform and of the Adriatic region starting from the early Tortonian (age of the older fossil remains) and go back through Tertiary times, the only possible time interval in which land mammal migration took place is in the Oligocene, most likely around the Rupelian/Chattian boundary (ca 29-30 Ma) when a major sea level fall known at the global scale (see i.e. Schlanger & Premoli Silva, 1986; Haq *et alii,* 1988; Lincoln & Schlanger, 1991; Miller *et alii,* 2005) caused the emergence of the Apulia Platform and of the greatest part of the Central Adriatic region. The effect of this event, probably combined with the effects of other minor sea-level drops in the earliest and latest Oligocene, is testified by an impor-

Fig. 2 - Imaginative reconstruction of the *Hoplitomeryx* habitat in a picture by S. Maugeri. (Courtesy of Centro di Documentazione Paleontologico of Scontrone).
– *Fantasiosa ricostruzione dell'habitat di* Hoplitomeryx *in un disegno di S. Maugeri (Centro di Documentazione Paleontologico of Scontrone).*

tant unconformity widespread on a regional scale, which has been detected in the Apulia Platform as in the other Mesozoic-Tertiary carbonate platforms incorporated in the Apennine chain. In the platforms of Central-Southern Italy, middle-upper Miocene and locally upper Oligocene-lower Miocene carbonate ramp deposits lie directly upon truncated Cretaceous or upper Paleocene-Eocene shallow-water limestones.

A detailed seismostratigraphic investigation of the Adriatic offshore shows that the Oligocene sea level fall exposed a set of coalescent structural highs created by Jurassic-lower Cretaceous salt tectonics which established a bridge in the Central Adriatic area connecting Dalmatia and Gargano via the Tremiti Islands. The bridge was likely an uninterrupted land path rimmed by islands separated by narrow straits.

3. GEOLOGICAL OUTLINES OF THE ADRIATIC REGION

Because the Gargano and Scontrone land mammals probably came in from the Balkans, our investigation was

Fig. 3 - Tectonic lineaments of the peri-Adriatic region with the distribution of the platforms and basins in the foreland areas and the distinction between platform-derived and basin-derived tectonic units in the Apennines and Dinarides. Asterisks indicate the Scontrone (1) and Gargano (2) fossil sites. Main bibliographic sources: AUBOUIN *et alii* (1960, 1970); PAPA (1970); DIMITRIEVIĆ (1982); CATI *et alii* (1987); DÈ DOMINICIS & MAZZOLDI (1987); RADOIČIĆ (1987); DOULCET *et alii* (1990); CNR-PROGETTO FINALIZZATO GEODINAMICA (1991); AIELLO & DE ALTERIIS (1991); ARGNANI *et alii* (1996); RADOIČIĆ & D'ARGENIO (1999); NIEUWLAND *et alii* (2001); VELAJ (2001); GRANDIĆ *et alii* (2002); MERLINI *et alii* (2002); TARI (2002): 1) Major subaerial Quaternary volcanoes; 2) Undifferentiated internal units of the Apennines, Calabrian Arc and Dinarides-Hellenides; 3) External units of the Apennines, Sicilian Maghrebides and Dinarides-Hellenides chiefly represented by Mesozoic-Tertiary basinal and pelagic carbonate sequences; 4) External units of the Apennines-Sicilian Maghrebides and Dinarides-Hellenides chiefly represented by Mesozoic-Tertiary shallow-water carbonate sequences; 5) Foreland areas characterized by thick Mesozoic-Tertiary shallow-water carbonate sequences; 6) Foreland areas characterized by Mesozoic-Tertiary basinal and pelagic carbonate sequences; 7) Front of the Sicilian Maghrebides, Apennines, Alps, Southern Alps and Dinarides-Hellenides; 8) Major thrusts; 9) Normal faults; 10) High-angle faults, mostly strike-slip faults; 11) Anticline axis; 12) Syncline axis.
– *Lineamenti tettonici principali della regione centro-mediterranea e distribuzione delle unità di piattaforma e di bacino nelle aree di avampaese e nelle aree di catena. Gli asterischi 1 e 2 indicano rispettivamente i giacimenti fossiliferi di Scontrone e del Gargano. Fonti bibliografiche principali: AUBOUIN* et alii *(1960, 1970); PAPA (1970); DIMITRIEVIĆ (1982); CATI* et alii *(1987); DÈ DOMINICIS & MAZZOLDI (1987); RADOIČIĆ (1987); DOULCET* et alii *(1990); CNR-PROGETTO FINALIZZATO GEODINAMICA (1991); AIELLO & DE ALTERIIS (1992); ARGNANI* et alii *(1996); RADOIČIĆ & D'ARGENIO (1999); NIEUWLAND* et alii *(2001); VELAJ (2001); GRANDIĆ* et alii *(2002); MERLINI* et alii *(2002); TARI (2002): 1) Principali vulcani quaternari subaerei; 2) Unità interne indifferenziate dell'Appennino, dell'Arco Calabro e delle Dinaridi-Ellenidi; 3) Unità esterne dell'Appennino, delle Maghrebidi Siciliane e delle Dinaridi-Ellenidi rappresentate prevalentemente da successioni mesozoico-terziarie di bacino o di alto strutturale pelagico; 4) Unità esterne dell'Appennino, delle Maghrebidi Siciliane e delle Dinaridi-Ellenidi rappresentate prevalentemente da successioni calcaree mesozoico-terziarie di carbonati di mare basso; 5) Aree di avampaese caratterizzate da potenti successioni carbonatiche mesozoico-terziarie di mare basso; 6) Aree di avampaese caratterizzate da successioni calcaree mesozoico-terziarie di bacino o di alto strutturale pelagico; 7) Fronte delle Maghrebidi Siciliane, dell'Appennino, delle Alpi, del Sudalpino e delle Dinaridi-Ellenidi; 8) Principali faglie inverse e sovrascorrimenti; 9) Faglie dirette; 10) Faglie ad alto angolo, principalmente faglie trascorrenti; 11) Asse di anticlinale; 12) Asse di sinclinale.*

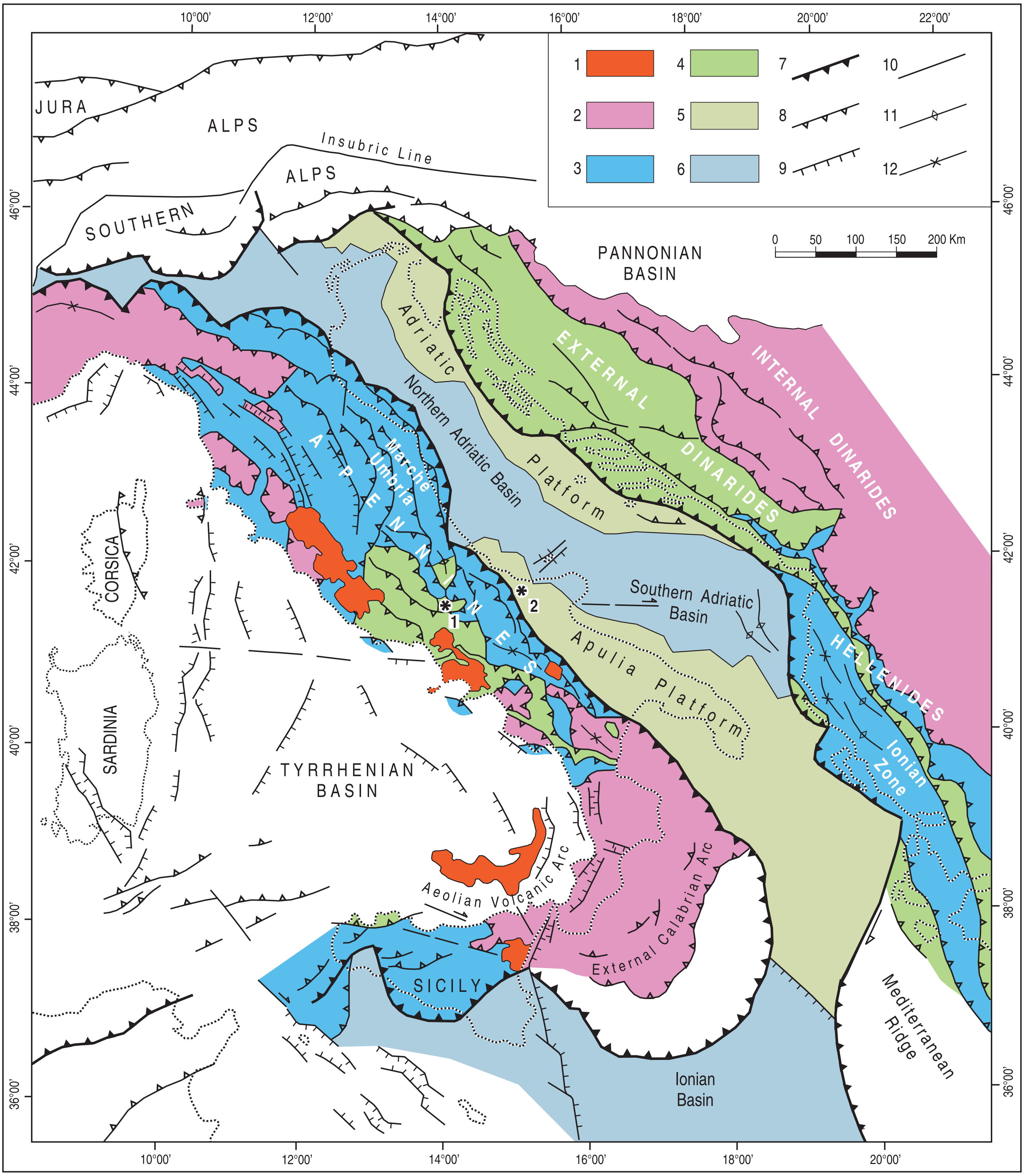
JURA
ALPS
Insubric Line
ALPS
SOUTHERN
PANNONIAN
BASIN
Adriatic
Northern Adriatic Basin
Platform
EXTERNAL
DINARIDES
INTERNAL
DINARIDES
A P E N N I N E S
Marche Umbria
CORSICA
SARDINIA
TYRRHENIAN
BASIN
Southern Adriatic
Basin
Apulia Platform
HELLENIDES
Ionian
Zone
Aeolian Volcanic Arc
External Calabrian Arc
SICILY
Ionian
Basin
Mediterranean
Ridge
0 50 100 150 200 Km
1 2 3 4 5 6 7 8 9 10 11 12
10°00' 12°00' 14°00' 16°00' 18°00' 20°00' 22°00'
46°00' 44°00' 42°00' 40°00' 38°00' 36°00'

Fig. 3.

focused on the whole peri-Adriatic region, to find the potential routes followed by the migrating mammal communities. At first, we have distinguished shallow-marine areas from deeper-marine ones. The structural map of fig. 3 shows the spatial distribution of the platform and basins in the undeformed (or slightly deformed) foreland areas, as well as the distribution of the platform-derived and basin-derived tectonic units in the Apennine, Dinaride and Hellenide thrust belts. Excluding the deep-marine seaways of Lagonegro in the Apennines and of Budva-Pindos in the Dinarides-Hellenides, which are both related to middle Triassic tectonics, the bulk of the Bahamian-type platform-and-basin systems in the peri-Adriatic region were set up as a consequence of a lower Jurassic extensional tectonics, which dissected an original upper Triassic-lower Liassic shallow epeiric area. Presently, three major stratigraphic-structural elements can be distinguished in the Adriatic area: the Adriatic Platform, the Adriatic Basin (which includes a Northern Adriatic Basin and a Southern Adriatic Basin) and the Apulia Platform.

The Adriatic Platform (CATI *et alii,* 1987; CASERO *et alii,* 1990; VLAHOVIĆ *et alii,* 2005 and references therein) extends from Istria to Southern Dalmatia. It consists of a thick pile (about 6000 m) of Triassic evaporites followed by shallow-water carbonates ranging in age from the late Triassic to the Eocene. The carbonates grade upward into Eocene siliciclastic flysch deposits. Unconformable Oligocene continental deposits, which post-date the main compressional deformation of the External Dinarides, crop out in the Croatia mainland (Promina Beds, see DIETRICH, 1944; CNR-PROGETTO FINALIZZATO GEODINAMICA, 1991; MRINJEK, 1993 a,b).

The Northern and Southern Adriatic Basins, which have been extensively explored for hydrocarbon research and have been drilled by several tens of deep wells, are represented by Mesozoic-Paleogene sedimentary sequences similar to those characterizing the Umbria-Marche region in the Apennines and the Ionian Zone in the Hellenides (see, among many others, BONARELLI, 1901; CRESTA *et alii,* 1989; PASSERI, 1994 for the Umbria-Marche stratigraphic sequence and AUBOUIN & NDOJAJ, 1964; AUBOUIN *et alii,* 1970 for the Ionian Zone in the Hellenides). The Adriatic Basin sequence consists of Triassic dolomites and evaporites (Burano Formation), lower Liassic shallow-water limestones (Calcare Massiccio Formation) and middle Liassic to Cretaceous deeper-marine carbonates showing significant lateral variations in facies and thickness. These deeper-water deposits are followed by shallower Paleocene-Miocene carbonate-ramp deposits and finally by the Messinian evaporites of the Gessoso-Solfifera Formation. In the Northern Adriatic basin the Plio-Pleistocene is represented by an overall shallowing-up sequence of siliciclastic deposits, which conformably overlie the carbonate succession. In the Southern Adriatic Basin the siliciclastic input began in the Oligocene with the development of a foredeep basin in the Ionian Zone of the Hellenides.

The Apulia Platform, like the Adriatic Platform, includes a thick pile of upper Triassic dolomites and evaporites followed by upper Triassic-upper Cretaceous shallow-water carbonates (CIARANFI *et alii,* 1988). The few deepest wells that have crossed the Triassic evaporites have reached a Paleozoic-lower Triassic terrigenous-carbonate mixed sequence, which has been penetrated for as much as 900 meters. The architecture of the margin of the Apulia Platform and of the adjacent slope is spectacularly exposed in the Gargano and Salento regions (see among many others MARTINIS & PAVAN, 1967; MASSE & LUPERTO SINNI, 1987; BOSELLINI *et alii,* 1993; BOSELLINI & PARENTE, 1994; MORSILLI & BOSELLINI, 1997; BOSELLINI *et alii,* 1999 a,b; BORGOMANO, 2000; GRAZIANO, 2000, 2001). The geometry of the sedimentary bodies that form the platform-to-basin system and the overall depositional architecture of the transitional zone between the platform margin and the basin, which have been recognized on land, are also traceable in several offshore seismic profiles (see DE ALTERIIS & AIELLO, 1993).

The present geographic configuration of the Adriatic region might suggest a possible entry of the Gargano-Scontrone vertebrates from Albania via the Apulia Platform. However, during the Oligocene, i.e. when the Scontrone-Gargano vertebrates spread into Apulia, the segment of Hellenic chain presently facing on to the Southern Adriatic Sea in front of the Salento Peninsula (Ionian Zone in fig. 3) was represented by a wide foredeep basin (see PAPA, 1970; NIEUWLAND *et alii,* 2001; VELAJ, 2001), which certainly constituted an insuperable barrier for land mammal migration. The other possible immigration way for the faunas was thus to be sought in the Central Adriatic region, in particular where the Adriatic Platform and the Apulia Platform face each other and the basinal corridor between the Balkans and Southern Italy reaches the minimum width. More than 6000 kilometers of offshore seismic profiles and about 60 composite logs of exploratory wells have been analyzed in order to investigate this area. In addition, over 300 logs of wells drilled in mainland Italy have been carefully examined to better constrain the paleogeographic reconstruction of the Apulia Platform during the Paleogene and the Miocene. The latter include only wells that have reached the Apulia Platform beneath the Plio-Pleistocene deposits of the foreland/foredeep basin or beneath the allochthonous sheets of the Apennine mountain chain. Fig. 4 shows the grid of the interpreted seismic lines together with the location of the wells that have reached the top of the carbonates in the Apulia Platform or the pre-Pliocene deposits in the Adriatic basinal areas. Thanks to the very gentle tectonic deformation of the Adriatic foreland, which does not demand any structural smoothing, the base map of fig. 4 has been directly associated with a paleogeographic map showing the reconstructed distribution of the basins and of the shallow areas that underwent subaerial exposure around the end of the early Oligocene. Information from wells located in internal sectors of the Apennine thrust belt, which are constituted of tectonic units that have undergone severe telescopic shortening (filled dots in fig. 4), refers to areas that a palinspastic restoration would relocate several kilometers southwest from their present-day position. The paleogeographic map of fig. 4 combines the results of our seismic investigation on the Adriatic offshore and the scattered stratigraphic information derived from the wells that have reached the Apulia Platform onshore, as well as the geological information on Croatia-Montenegro (onshore and offshore) that can be found in the available literature (see, among many others, CNR-PROGETTO FINALIZZATO GEODINAMICA, 1991; RADOIČIĆ & D'ARGENIO, 1999; GRANDIĆ *et alii,* 2002 and references therein). The map indicates

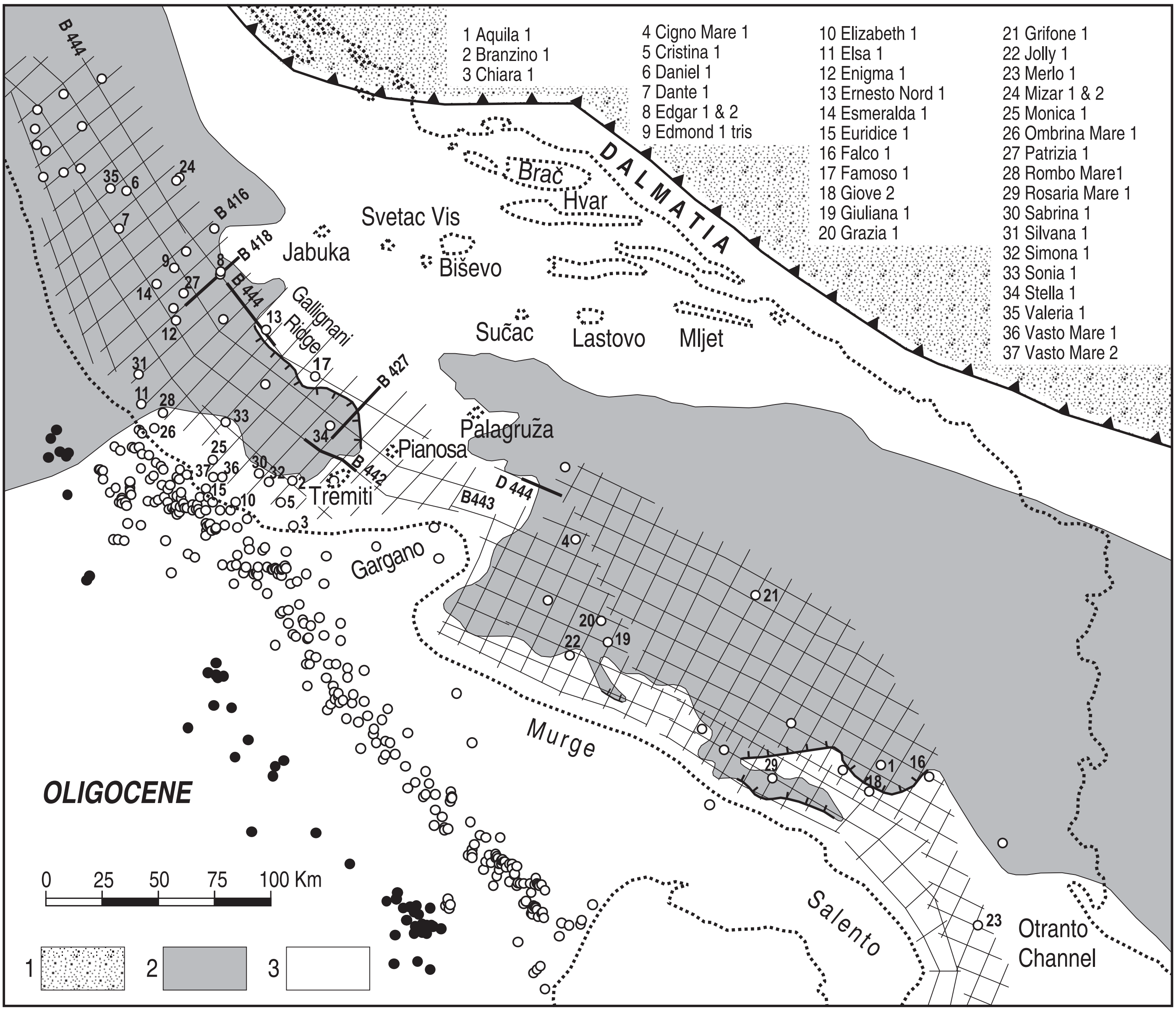

Fig. 4 - Paleogeographic reconstruction of the Central Adriatic region around the end of the early Oligocene. The picture shows the Dalmatia-Gargano landbridge dividing the Adriatic Basin into two portions, the Northern and Southern Adriatic Basins, both characterized, at the time, by the deposition of the hemipelagic Scaglia Cinerea Formation. The landbridge comprised the Dalmatia Islands, the Tremiti Islands, the Pianosa-Palagruža Plateau and a NW-SE structural high explored by the Ernesto N1 and Famoso 1 wells known as Ernesto-Famoso High or Gallignani Ridge. The picture also shows the grid of the seismic lines and the location of the wells examined in this study. Wells with Arabic numerals are quoted in the text. Heavy lines mark the portions of interpreted seismic lines given in figs. 6, 8 and 9. See discussion in the text: 1) External Dinarides; 2) Basinal areas (coinciding with the areal distribution of the Oligocene Scaglia Cinerea Formation); 3) Areas characterized by sedimentary gaps and subaerial exposure during the most of the Oligocene.
– Ricostruzione paleogeografica della regione centro-adriatica verso la fine dell'Oligocene. La figura mostra il ponte Dalmazia-Gargano che divideva il Bacino Adriatico in due parti, il Bacino Adriatico Settentrionale e il Bacino Adriatico Meridionale, entrambi caratterizzati in quel tempo dai depositi emipelagici della Scaglia Cinerea. Il ponte includeva le isole della Dalmazia, le Tremiti, il Plateau Pianosa-Palagruža e un alto strutturale orientato NW-SE perforato dai pozzi Ernesto N1 e Famoso 1, noto come Alto Ernesto-Famoso o Dorsale Gallignani. La figura mostra anche la traccia dei profili sismici e la posizione dei pozzi esaminati in questo studio. I pozzi numerati sono quelli citati nel testo. Le linee più spesse indicano le parti di profili sismici illustrati nelle figg. 6, 8 e 9. Si veda la discussione nel testo: 1) Dinaridi Esterne; 2) Aree bacinali (coincidenti con le aree nelle quali è presente la Scaglia Cinerea); 3) Aree caratterizzate da esposizione subaerea durante la gran parte dell'Oligocene.

that around the end of the early Oligocene, as a consequence of the dramatic mid-Oligocene global sea-level fall, a part of the Central Adriatic area surfaced, joining the Apulia Platform to a large part of the Dalmatia offshore, and thus creating a path for the migration of land mammals from the Balkan mainland to Gargano via Palagruža, Pianosa and the Tremiti islands. This corridor was completely flooded during the Langhian and the Apulia Platform stood completely isolated until the Messinian salinity crisis when an even more dramatic sea-level fall favoured another wave of mammal migration from the Balkans.

The birth of an Oligocene landbridge across the Central Adriatic region was a fortuitous event determined by the combined effect of three favourable circumstances:

– the presence in the Central Adriatic area of structural highs produced by a Jurassic-early Cretaceous salt-related tectonic activity. These structural highs interrupted the continuity of the basinal corridor between the Adriatic and the Apulia Platforms;

– the occurrence of a first severe sea-level fall likely at the end of the early Paleocene. As a consequence of this event, late Paleocene/Eocene shallow-water limestones spread over most of the Central Adriatic structural highs on top of deeper-marine deposits (e.g. Eocene shallow-water carbonates in the line B-427 in fig. 6 and in the lines B-442 and B-444 in fig. 9). Consequently, a wide shallow-water plateau formed between the Gargano Promontory and the Dalmatian islands. In the Apulia Platform and marginal areas, the mid-Paleocene falling event is testified by a generalized virtual absence of lower Paleocene deposits and by a prominent erosional truncation at the top of the Cretaceous carbonates, which are directly overlain by transgressive middle-upper Eocene shallow-water deposits;

– the occurrence of a second, particularly severe sea-level drop during the Oligocene, most likely matched with the mid-Oligocene sea-level fall around 29-30 Ma. This event caused the temporary emergence of the previous shallow-water areas and a widespread subaerial exposure of the Apulia Platform.

4. THE OLIGOCENE PATHWAY ACROSS THE CENTRAL ADRIATIC SEA

The profile in fig. 5, which contains names and synonyms of the major lithostratigraphic units distinguished in the study area, outlines the stratigraphic architecture of the Central Adriatic region NW of the Gargano Promontory from the late Triassic to the late Miocene. The profile, the greatest part of which derives from the interpretation of a merged seismic line running partly on land and partly offshore, describes the relationships between the shallow-water deposits of the Apulia Platform and the deeper-water deposits of the Northern Adriatic Basin along a section linking the platform margin and the southern termination of the basin through the Central Adriatic area. The figure synthesizes also the stratal architecture of the single units and sketches the role of the Jurassic extensional faults in the creation of the Bahamian-type platform-and-basin system, as well as the role of the salt tectonics (particularly active between the middle/upper Liassic and the early Cretaceous) in the construction of the Central Adriatic structural highs. The Tortonian age of the vertebrate fossil association of Scontrone and the long-ranging Tortonian to Messinian/early Pliocene age attributed to the Gargano fauna prompted us to focus on the stratigraphic investigation on the entire Oligocene-Miocene intervals of the Apulia and Adriatic sequences.

Several geological sections and many well logs document the Oligocene exposure of the Apulia Platform. In this region, the temporal gap related to the mid-Oligocene emergence was surely enhanced by the previous mid-Paleocene falling event and by a pre-Oligocene regional tilting of the platform carbonates towards the SW with associated erosion which caused the exposure of the lower Cretaceous portion of the carbonate sequence in the whole region NW of the Gargano Promontory. In Western Gargano, transgressive middle-upper Miocene shallow-ramp limestones (Apricena Calcarenite, see fig. 5) lie with angular unconformity over lower Cretaceous platform-interior carbonates (Bari Limestone) with interposed «terra-rossa» soils (see, among others, D'Alessandro *et alii,* 1979). In the Adriatic offshore (e.g. wells Ombrina Mare 1, Rombo Mare 1, Sonia 1, Monica 1, Vasto Mare 1 and 2, Euridice 1, Elizabeth 1, Sabrina 1, Simona 1, Cristina 1 and Chiara 1 NW of the Gargano Promontory, as well as Jolly 1 SE of Gargano, see fig. 4), upper Oligocene-lower Miocene or middle/upper Miocene transgressive deposits (called in commercial wells San Ferdinando, Bolognano, Bisciaro-equivalent and Schlier-equivalent formations) lie directly upon lower Cretaceous shallow-platform carbonates (Cupello Limestone in commercial wells), which can be correlated with the Bari Limestone of the Apulia mainland. In the Salento Peninsula, where the hiatus is less extensive than in Gargano (see fig. 5), upper Oligocene shallow-water limestones (Castro Limestone and Porto Badisco Calcarenite, likely separated by an internal unconformity) lie with angular unconformity over Cretaceous and Eocene shallow-ramp carbonates (uppermost Cretaceous Ciolo Limestone, middle Eocene Torre Tiggiano Limestone and upper Eocene Torre Specchialaguardia Limestone, Parente, 1994; Bosellini *et alii,* 1999a and references therein). In the southwestern part of the Salento Peninsula, upper Oligocene continental deposits (Galatone Formation), followed disconformably by uppermost-Oligocene/lower Miocene shallow-water biocalcarenites (Lecce Formation), lie in weak angular unconformity over upper Cretaceous rudistid limestones (Altamura Limestone) with intervening thin layers of «terra-rossa» and other paleosols (Margiotta & Negri, 2004; Margiotta & Ricchetti, 2002). In the offshore of Murge and Salento, a few wells (Falco 1, Rosaria Mare 1 and Merlo 1) have encountered the upper Cretaceous Altamura Limestone beneath upper Oligocene-Miocene ramp carbonates. The shallow-platform Altamura Limestone is locally followed (i.e. Rosaria Mare 1 and Merlo 1) by uppermost Cretaceous deeper-ramp bioclastic limestones (Scaglia Fm and Monte Acuto Fm in well-logs), which correspond onshore to the Caranna Limestone of Murge and to the upper portion of the Caramanica Limestone and equivalent Monte Acuto Fm of Gargano (Luperto Sinni & Borgomano, 1989, 1994; Bosellini *et alii,* 1999b). Only at the margin of the platform, nummulitid-bearing limestones attributed to the upper Paleocene-Eocene (Peschici Fm in Branzino 1 NW of Gargano) or to the middle Eocene (Torre Tiggiano Limestone in Giove 2 SE of Gargano) have been found sandwiched between upper Cretaceous shallow-water limestones and transgressive upper Oligocene-Miocene shallow-ramp carbonates correlative with the Porto Badisco Calcarenite plus Pietra Leccese Formation. A pre-Miocene subaerial exposure is documented also in more internal (western) portions of the Apulia Platform. In the subsurface of Val d'Agri, for instance (see southernmost cluster of filled dots in fig. 4), several wells for oil research have crossed middle-upper Miocene deposits (referable to the Pietra Leccese Fm) on top of uppermost Cretaceous or Paleocene-Eocene ramp carbonates with an intervening horizon of «terra rossa»

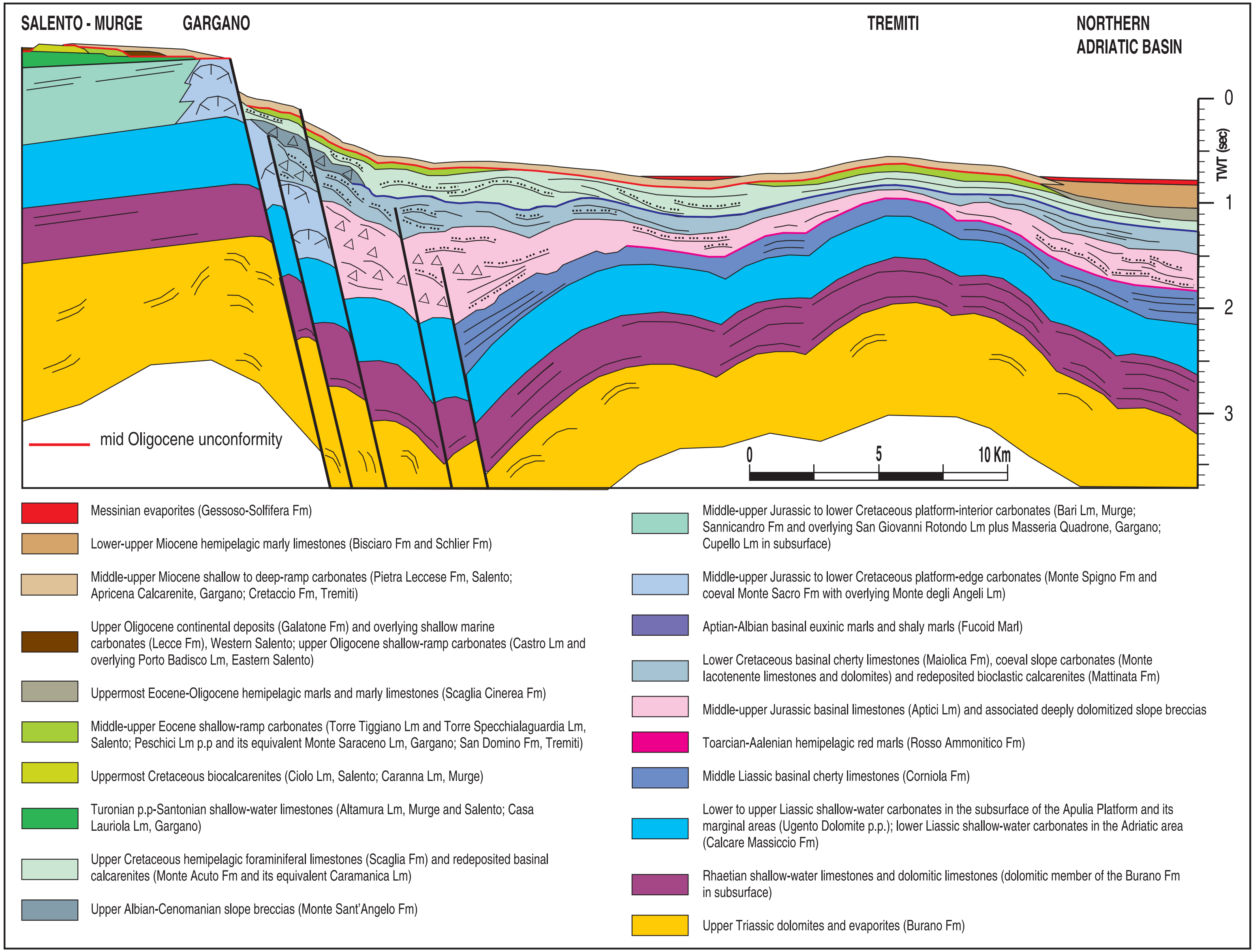

Fig. 5 - Depositional architecture of the Apulia Platform-Adriatic Basin system largely based on the seismostratigraphic interpretation of an onshore-offshore merged line cutting across the margin of the Apulia Platform, the Central Adriatic Swell and the southern margin of the Northern Adriatic Basin. The profile evidences the backstep of the Jurassic-Neogene extensional faulting responsible for the onset of the platform-basin system in the area and illustrates the Jurassic-lower Cretaceous salt tectonics responsible for the growth of the Central Adriatic Swell. The paleofault limiting the syntectonic wedge of the Aptici Limestone has been reactivated in post-Jurassic times. The figure includes also a summary of the lithostratigraphic units distinguished in the area.

– Architettura deposizionale del sistema Piattaforma Apula-Bacino Adriatico largamente basata sull'interpretazione sismostratigrafica di una linea sismica composita terra-mare che attraversa il margine della Piattaforma Apula, l'alto strutturale dell'Adriatico Centrale e il margine meridionale nel Bacino Nord-Adriatico. Il profilo evidenzia l'arretramento della tettonica estensionale giurassica responsabile dell'instaurarsi del sistema piattaforma-bacino e illustra la tettonica salina del Giurassico-Cretacico inferiore responsabile del sollevamento dell'Adriatico Centrale. Si noti la riattivazione in tempi post-giurassici della paleofaglia che limita il cuneo sedimentario dei Calcari ad Aptici. La figura fornisce anche una breve descrizione delle unità litostratigrafiche distinte nell'area.

deposits. In the westernmost wells of the Apulia Platform, lower Messinian shallow-ramp carbonates directly overlie deeply karstified lower Cretaceous platform carbonates referable to the Bari Limestone.

In the Adriatic Basin, lithology, age and depositional architecture of the sedimentary sequence are known thanks to the extensive petroleum exploration. In this region, a wide grid of reflection seismic profiles and several tens of well logs are available in the public domain. All the lithostratigraphic units making up the dominantly basinal sequence are expressed by quite characteristic seismofacies which can be easily identified and mapped through the entire study area. The stratigraphic sequence, moving downsection, consists of:

– shallowing upward Plio-Pleistocene siliciclastic deposits, which end with middle-upper Pleistocene sands organized in prograding clinoforms. The basal hemipelagic shaly deposits are characterized by an overall reflection-free facies with a continuous strong reflector which corresponds to a middle Pliocene tuffite horizon;

– Messinian evaporites (Gessoso-Solfifera Formation), featured in the seismic profiles by a very strong couplet of reflectors;

– lower to upper Miocene well-bedded hemipelagic marls and marly limestones (including the middle-upper Miocene Schlier Formation and the lower Miocene Bisciaro Formation) expressed by continuous, even parallel reflectors;

– uppermost Eocene-Oligocene hemipelagic marls (Scaglia Cinerea Formation, sometimes indicated in the composite logs as the marly member of the Scaglia Fm and attributed to the Oligocene). In the seismic profiles, the Scaglia Cinerea Fm is typically expressed by a reflection-free seismic unit;

– upper Cretaceous-upper Eocene basinal cherty limestones rich in planktonic foraminifers (Scaglia Formation, indicated in some composite logs as the calcareous member of the Scaglia Formation). These well-bedded limestones, seismically imaged by medium-frequency, rather continuous strong reflectors, form a seismic unit frequently bounded upwards by a bumped surface. This irregular surface follows convex-up mounded reflectors indicative of local prominent depositional lobes;

– Aptian-Albian dark-gray marls and shaly marls (Fucoid Marl). This interval, usually a few tens of meters thick and characterized by rather high values of the GR curve in correspondence to several repeated anoxic events, is evidenced in seismic profiles by a couplet of very strong, continuous reflectors making-up a widespread, very useful key horizon in the whole Adriatic area;

– lower Cretaceous bedded cherty limestones (Maiolica Formation), commonly imaged by a substantially reflection-free seismic unit or locally by high-frequency even parallel reflectors characterized by low/medium amplitude and high continuity;

– middle-upper Jurassic basinal cherty limestones (Aptici Limestone), a well-reflective seismic unit usually expressed by discontinuous, frequently mounded high/medium-amplitude and medium-frequency reflectors;

– lower Jurassic (Toarcian-Aalenian) red marls (Rosso Ammonitico Formation), a unit only a few tens of meters thick expressed in seismic profiles by a quite continuous reflector locally representing a very useful key horizon;

– middle Liassic bedded cherty limestones (Corniola Formation) imaged by low-frequency, quite continuous even parallel reflectors;

– lower Liassic shallow-water limestones (Calcare Massiccio Formation), which form a quite isopachous seismic unit characterized by discontinuous reflectors with local hummocky continuity and variable amplitude and frequency. The contact between the Corniola Fm and the Calcare Massiccio Fm corresponds to an abrupt change of facies from a reflective seismic unit to a very poorly reflective one;

– Rhaetian shallow-water limestones and dolomitic limestones (well-bedded lagoon deposits), the top of which is marked by a quite continuous reflector. This unit, usually indicated in the composite logs as the dolomitic member of the Burano Formation, is imaged by continuous parallel reflectors with high amplitude and low frequency;

– Triassic dolomites and evaporites (Burano Formation) seismically represented by a broad, reflection-free unit showing locally low-frequency discontinuous and contorted strong reflectors.

The picking of the most prominent reflectors representing key horizons and the mapping of the aforementioned seismic units over most of the Adriatic Basin allowed us to reconstruct the geometry of the lithostratigraphic units and the effects of the synsedimentary tectonics. In addition, the integrated seismic data and stratigraphic information provided by the composite logs (ages and fossil contents) made it possible to date the unconformity surfaces and to identify the depositional environments of the single units, as well as to recognize the effects of the eustatic sea-level changes and the effects of the synsedimentary tectonics.

Considering the age of the land vertebrates, also in the Adriatic region the attention has been focused on the Oligo-Miocene portion of the sedimentary sequence, and in particular on the presence or absence of the hemipelagic deposits of the Scaglia Cinerea Formation. In the well logs, these deposits are attributed usually to the Oligocene and only in some cases to the late Eocene-Oligocene; in biostratigraphically well-tied surface sections, the age of the Scaglia Cinerea Fm ranges from the uppermost part of the late Eocene (COCCIONI *et alii*, 1988) to the lowermost part of the early Miocene (MONTANARI *et alii*, 1991). The Scaglia Cinerea Fm is developed NW of the Tremiti Islands over the whole Northern Adriatic Basin, with thicknesses ranging from a few tens of meters (e.g. Silvana 1) to some hundreds of meters (e.g. Esmeralda 1, Valeria 1, Patrizia 1 and Edmond 1Tris in fig. 4). In the Southern Adriatic Basin, the Mesozoic-Tertiary sedimentary sequence has been crossed by a limited number of wells, which have encountered a succession of depositional units analogous to those present in the north but with thicker Scaglia Cinerea, Bisciaro and Schlier deposits (e.g. in Aquila 1 and Grazia 1 where the Oligo-Miocene sedimentary sequence may exceed one thousand metres). These deposits, and most of all the Bisciaro Fm, contain variable amounts of sandy siliciclastic material, derived from the Albanian sector of the rising External Dinarides. In the Northern Adriatic Basin, boreholes on isolated structural highs (e.g. Daniel 1 and Edgar 1 and 2) have not found Oligocene deposits (see Line B-418 in fig. 6 and correlation between Patrizia 1 and Edgar 2 in

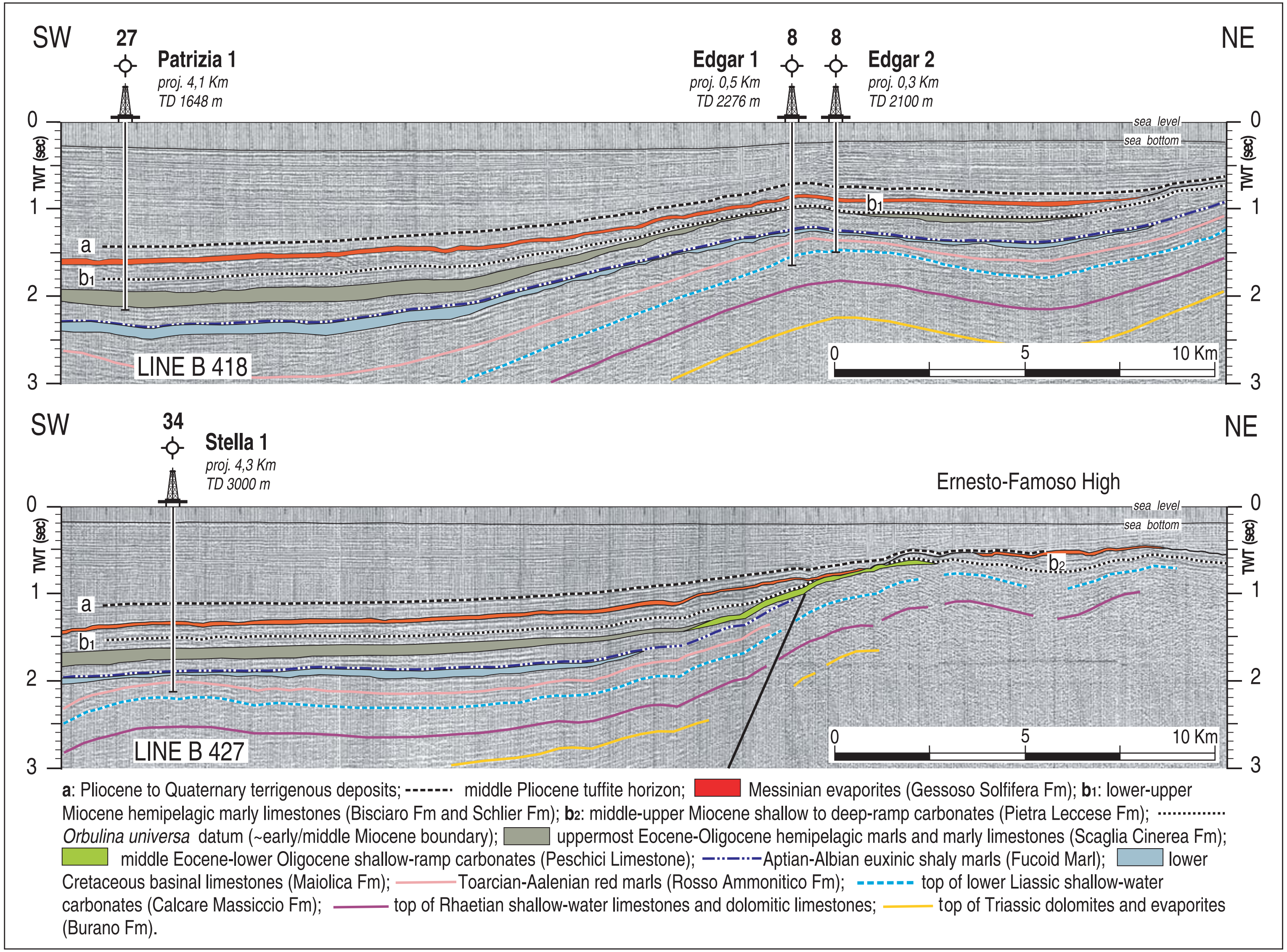

Fig. 6 - Interpreted reflection seismic profiles (location in fig. 4) showing the tapering of the Scaglia Cinerea Fm towards the Ernesto-Famoso High and the extreme condensation and sediment starvation of the uppermost Eocene-Oligocene deposits on top of the Edgar pelagic swell (Line B-418). The southwestward development of the Scaglia Cinerea Fm in more complete sections marks the transition towards the Northern Adriatic Basin. An evident disconformity occurs at the base of the middle-upper Miocene carbonates (b_2) on the Ernesto-Famoso High (Line B-427). The erosional gap associated with this disconformity may locally encompass the late Cretaceous, the entire Paleogene and the early Miocene. An older disconformity surface marks the base of the Peschici Limestone in correspondence to the southwestern margin of the Ernesto-Famoso High. The reflectors and units highlighted in the figure were used to reconstruct the growth history of this prominent positive structure.

– Profili sismici interpretati (v. ubicazione fig. 4) che evidenziano la distribuzione della Scaglia Cinerea, la condensazione di questi depositi sull'alto sottomarino di Edgar (Linea B-418) e la transizione tra il Bacino nord-Adriatico e l'alto di Ernesto-Famoso (Linea B-427). Nel profilo B-427 è evidente la disconformità alla base dei carbonati miocenici di mare basso (b_2) trasgressivi sull'alto strutturale. La lacuna associata a questa disconformità può ricoprire il Cretacico superiore, l'intero Paleogene e una parte del Miocene inferiore. Una superficie di disconformità più vecchia marca la base dei Calcari di Peschici in corrispondenza del margine sud-occidentale dell'alto di Ernesto-Famoso. I riflettori e i corpi evidenziati a colore hanno permesso di ricostruire la storia di crescita di questo importante alto strutturale.

fig. 7). In these structural highs the Miocene hemipelagic deposits of the Bisciaro and Schlier formations directly overlie the middle Eocene portion of the basinal Scaglia Formation. This type of unconformity, base-concordant with the underlying reflectors (see fig. 6), suggests that the absence of Oligocene deposits in these isolated highs is a consequence of non-deposition by sediment starvation during the growth of the positive structures. In the well Dante 1, which is not far from Daniel 1 (see fig. 4), the shallow-water deposits of the Gessoso-Solfifera Fm lie directly over the upper Eocene portion of the basinal Scaglia Fm suggesting thus the existence of small islands in Oligocene-middle Miocene times. These few small islands, in any case, did not form an archipelago in some way connected with the Adriatic Platform.

In the Southern Adriatic Basin, DÈ DOMINICIS & MAZZOLDI (1987) and MORELLI (2002) have interpreted a strong, irregular reflector observed at the base of the Scaglia Cinerea Formation as an unconformity. The uneven surface at the base of the Oligocene hemipelagic marly deposits of the Scaglia Cinerea Fm, which corresponds in exploratory wells to a quite prolonged temporal gap (e.g. Oligocene marly deposits over upper Cretaceous basinal limestones, see Cigno Mare 1, Grifone 1, Grazia 1 and Giuliana 1), is actually related to the existence of mounded lobe deposits in the upper Cretaceous portion of the Scaglia Fm on top of which local sediment starvation occurred (see an example on the Line D-444 in fig. 9). In conclusion, during the Paleogene and Miocene up to the Messinian salinity crisis both the Northern and Southern Adriatic Basins were deep-marine areas punctuated by local submarine highs and perhaps, only in the northern basin, also by small islands. Such a configuration constituted a natural barrier that prevented any possibility of land mammal migration to the Abruzzi-Apulia domain from the Balkan mainland.

NW of Pianosa and SW of the Jabuka-Palagruža alignment, a prominent positive structure known as Ernesto-Famoso High or Gallignani Ridge (see RIDENTE & TRINCARDI, 2006 and references therein) extends for 90-100 kilometres with a NW-SE direction. This important physiographic feature, explored by the wells Ernesto Nord 1 and Famoso 1, joins with the SW-NE striking positive structure of the Tremiti Islands between Pianosa and Palagruža. Selected seismic profiles (Line B-427 in fig. 6 and Line B-444 in fig. 8, see location in fig. 4) show the facies relationships between the North-Adriatic basinal areas and the Ernesto-Famoso High with the onlap of the Scaglia Cinerea Fm on the flanks of the relief. On top of the positive structure, middle-upper Miocene deepening-up shallow carbonate ramp deposits (Pietra Leccese Fm, b_2 in the profiles of figs. 6 and 8) unconformably overlie upper Eocene-lower Oligocene shallow-water limestones characterized by a benthic-foraminifer association including *Chapmanina, Victoriella, Discocyclina* and *Nummulites vascus* (Peschici Limestone in Famoso 1). In the composite log of Famoso 1 the middle-upper Miocene limestones of the Pietra Leccese Fm (Schlier Fm in the well description) are clearly recognizable by the characteristic very-high response of the GR curve due to the abundance of phosphates and other dispersed organic matter (teeth and bones of fishes, coprolites etc.). The same organic content characterizes also the equivalent of the Pietra Leccese Fm that crops out in the Tremiti Islands (see fig. 5). The latter consists of a lower/middle to upper Miocene deepening-up sequence of shallow-water limestones grading upwards into open-ramp marls and marly limestones (Cretaccio Formation in CREMONINI *et alii,* 1971). These deposits unconformably overlie middle Eocene shallow-water calcarenites rich in larger foraminifers (upper portion of the of San Domino Formation of CREMONINI *et alii,* 1971, equivalent to the Eocene portion of the Peschici Limestone in Famoso 1) with an intervening discontinuous thin layer of «terra-rossa» filling karstic fissures (see also SERVIZIO GEOLOGICO D'ITALIA, 1971; PAMPALONI, 1989; FORESI *et alii,* 2002). The temporal gap recognized in the Tremiti Islands can be wider on the Ernesto-Famoso High, where upper Eocene limestones are locally unconformably overlain by a few tens of meters of upper Tortonian dark-gray marls followed by the evaporites of the Gessoso-Solfifera Fm (see Ernesto Nord 1 in fig. 8 and Line B-427 in fig. 6).

Salt tectonics, with halokinetic mechanisms possibly activated by faults (strike-slip faults and normal faults) has certainly contributed to the uplift of the Ernesto-Famoso High and, more in general, to the growth and coalescence of isolated submarine highs, which allowed shallow-water sedimentation in the Central Adriatic area in the Eocene. Salt-related structures are well known in the Croatian offshore (see GRANDIĆ *et alii,* 2002), in the Italian territorial waters (see DÈ DOMINICIS & MAZZOLDI, 1987; DE ALTERIIS, 1995), as well as in the Apulia mainland (COTECCHIA & CANITANO, 1955; MARTINIS & PIERI, 1963). A striking diapiric structure in the Adriatic offshore has been drilled by Mizar 2 (TD 1962 m), which penetrated 1438 meters of Triassic evaporites directly overlain by Plio-Pleistocene deposits. In contrast, the well Mizar 1 (TD 4000 m), which is located only 2 kilometers from Mizar 2, crossed a complete sedimentary sequence from the Messinian Gessoso-Solfifera Fm down to the middle Liassic basinal carbonates of the Corniola Formation. The interpreted seismic lines B-418 and B-427 in fig. 6 and B-444 in fig. 8 show the complex growth history of the Ernesto-Famoso High and of the contiguous Edgar submarine high between the middle/late Liassic and the middle Pliocene. The basinal deposits between the top of the Calcare Massiccio Fm and the Fucoid Marl, which converge towards the NE in fig. 6 and towards the SE in fig. 8, evidence an overall progressive thinning by condensation and sediment starvation of the middle/upper Liassic-lower Cretaceous deposits due to mighty impulses of uplift. The upward decrease in the deformation of the basinal deposits overlying the Fucoid Marl shows that the phases of uplift turned weaker through time. A gentle deformation affects also the overlying Plio-Pleistocene siliciclastic deposits. The subtle channels at the top of the Scaglia Cinerea Fm recognizable on the Line B 418 just on the right of Patrizia 1 have been related to erosional processes connected with the mid-Oligocene global sea-level fall. In Patrizia 1 the age of the Scaglia Cinerea Fm spans from the latemost Eocene (*Globorotalia cerroazulensis* Zone) to the early Oligocene (*Globorotalia ampliapertura* Zone and *Globorotalia opima* Zone). The major disconformity at the base of the middle-upper Miocene ramp-carbonates b_2 on top of the Ernesto-Famoso High (lines B-427 in fig. 6 and B-444 in fig. 8) is the result of the combined effects of the tectonic uplift and of the eustatic sea-level falls. The synsedimentary growth of the Ernesto-Famoso structure is documented, as in the case

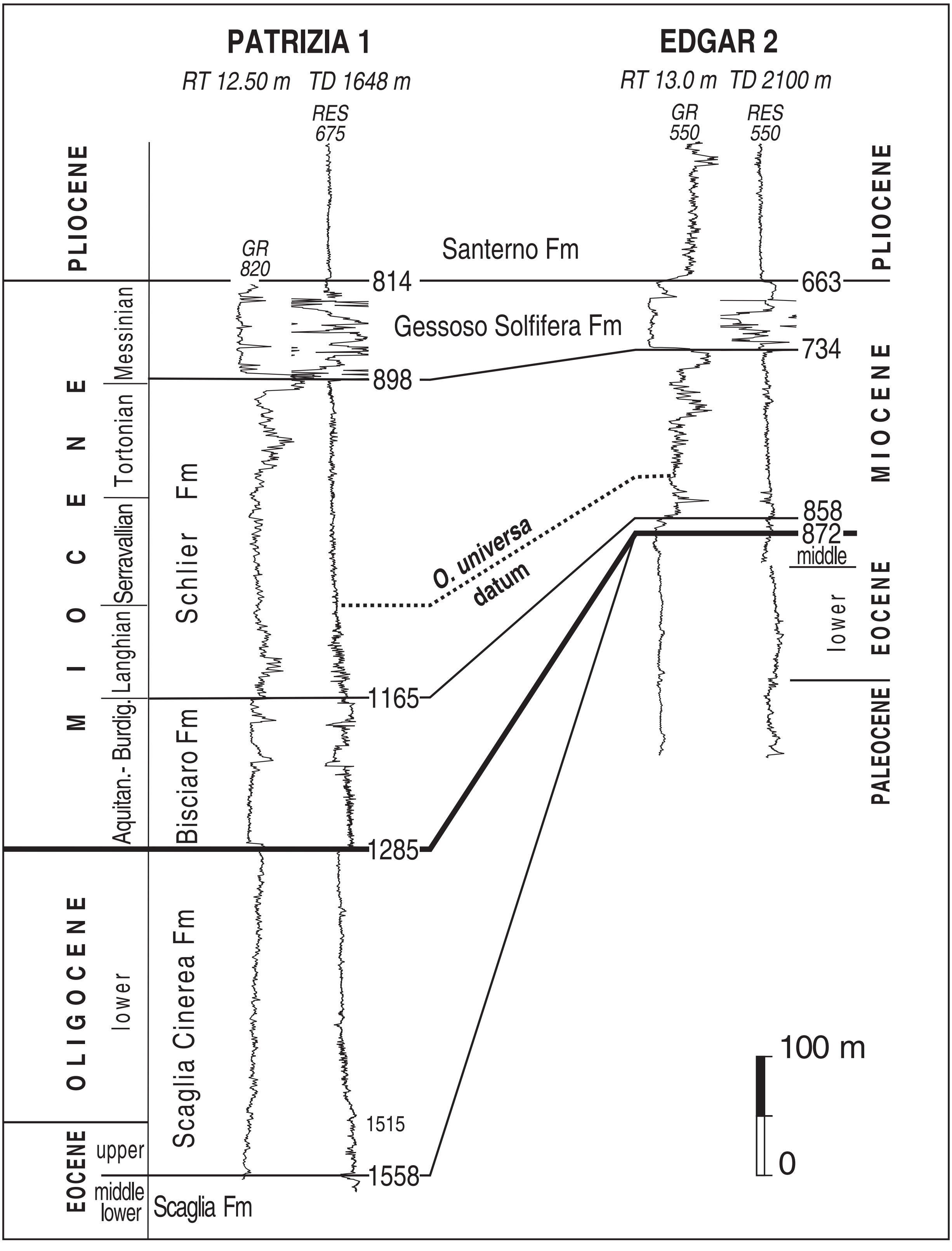

Fig. 7 - Well-log correlation of the Eocene to Miocene portion of the sequence crossed by the well Patrizia 1 with the coeval terms encountered by Edgar 2 (location in fig. 4). Owing to the detailed biostratigraphic information available in the composite log, these wells have been useful for calibrating the seismic lines in the Central Adriatic area. The condensation of the Miocene deposits and the absence of the Scaglia Cinerea Fm on top of the structural high (Edgar 2), as well as the absence of upper Oligocene deposits in adjacent basinal areas (Patrizia 1), are related to non-deposition and sediment starvation.

– Correlazione stratigrafica tra i depositi eocenici-miocenici traversati dai pozzi Patrizia 1 ed Edgar 2 (v. ubicazione in fig. 4). Le dettagliate informazioni di carattere biostratigrafico contenute nei composite logs di questi pozzi sono state un utile strumento di calibrazione dei profili sismici. I dati di pozzo indicano inequivocabilmente La condensazione dei depositi miocenici e l'assenza della Scaglia Cinerea sull'alto strutturale di Edgar, nonché l'assenza di depositi dell'Oligocene superiore nelle aree bacinali adiacenti (v. Patrizia 1) sono stati messi in relazione a fenomeni di non deposizione.

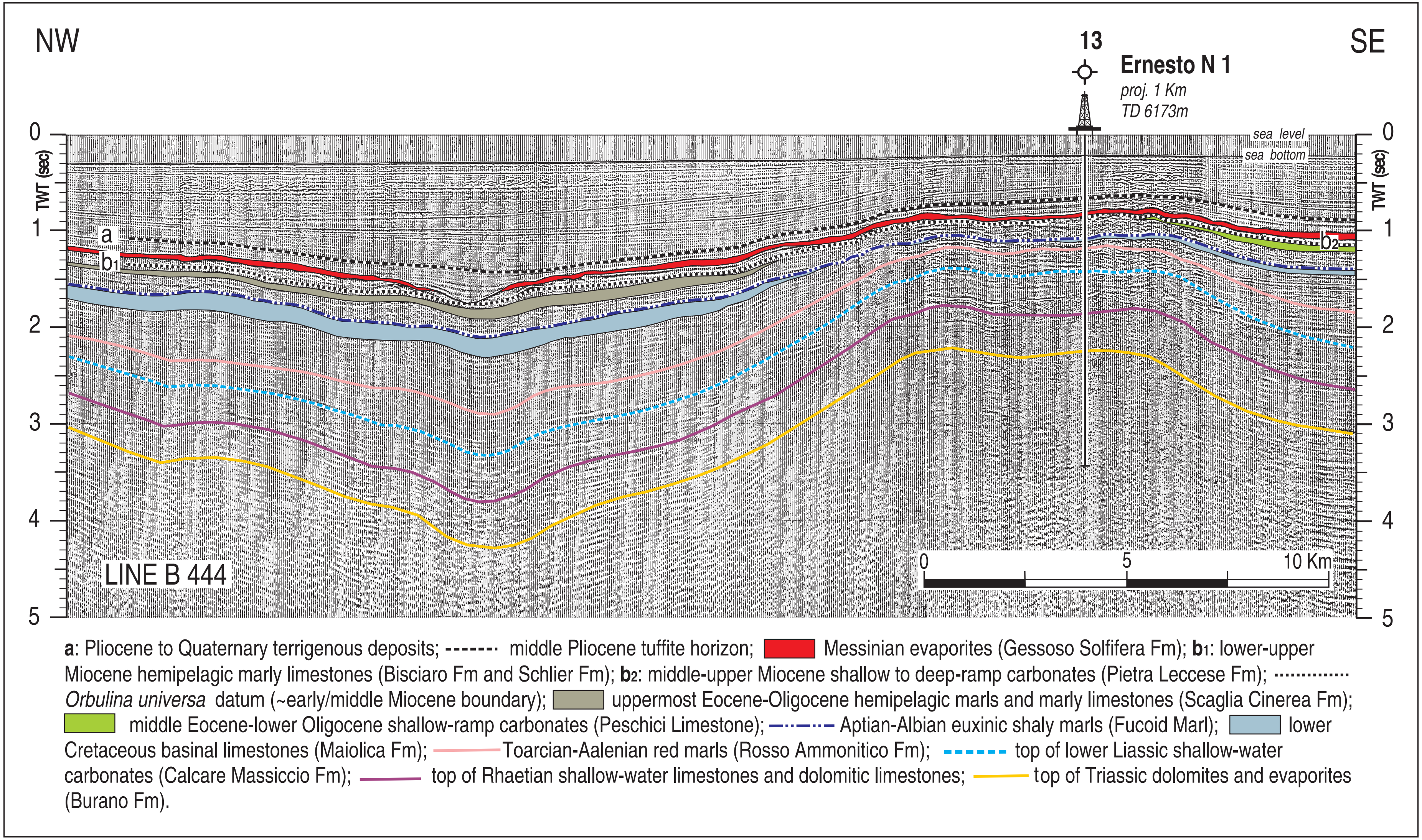

Fig. 8 - Interpreted reflection seismic profile showing the transition between the Ernesto-Famoso structural high and the Northern Adriatic Basin. The evident convergence of the most prominent reflectors between the key horizons featuring the Rosso Ammonitico Fm and the Fucoid Marl and the progressive thinning by condensation of the Aptici Limestone and Maiolica Fm indicate that the bulk of the tectonic uplift in the area took place between the middle Jurassic and the Early Cretaceous. Note on top of the relief the strong erosion at the base of the Pietra Leccese Fm, which is documented in Ernesto Nord 1 by an unconformity surface between the Eocene portion of the Scaglia Fm and the overlying marly deposits of Tortonian age.

– Interpretazione di un profilo sismico mostrante il passaggio dall'alto strutturale di Ernesto-Famoso al Bacino Nord-Adriatico. L'evidente convergenza dei riflettori tra gli orizzonti rappresentativi del Rosso Ammonitico e delle Marne a Fucoidi e il progressivo assottigliamento per condensazione dei Calcari ad Aptici e della Maiolica indicano che il grosso del sollevamento tettonico della struttura è avvenuto tra il Giurassico medio e il Cretacico inferiore. Si noti sulla sommità del rilievo l'importante erosione alla base della Pietra Leccese documentata in Ernesto N 1 da una superficie di inconformità che mette a diretto contatto depositi tortoniani con la porzione eocenica della Scaglia.

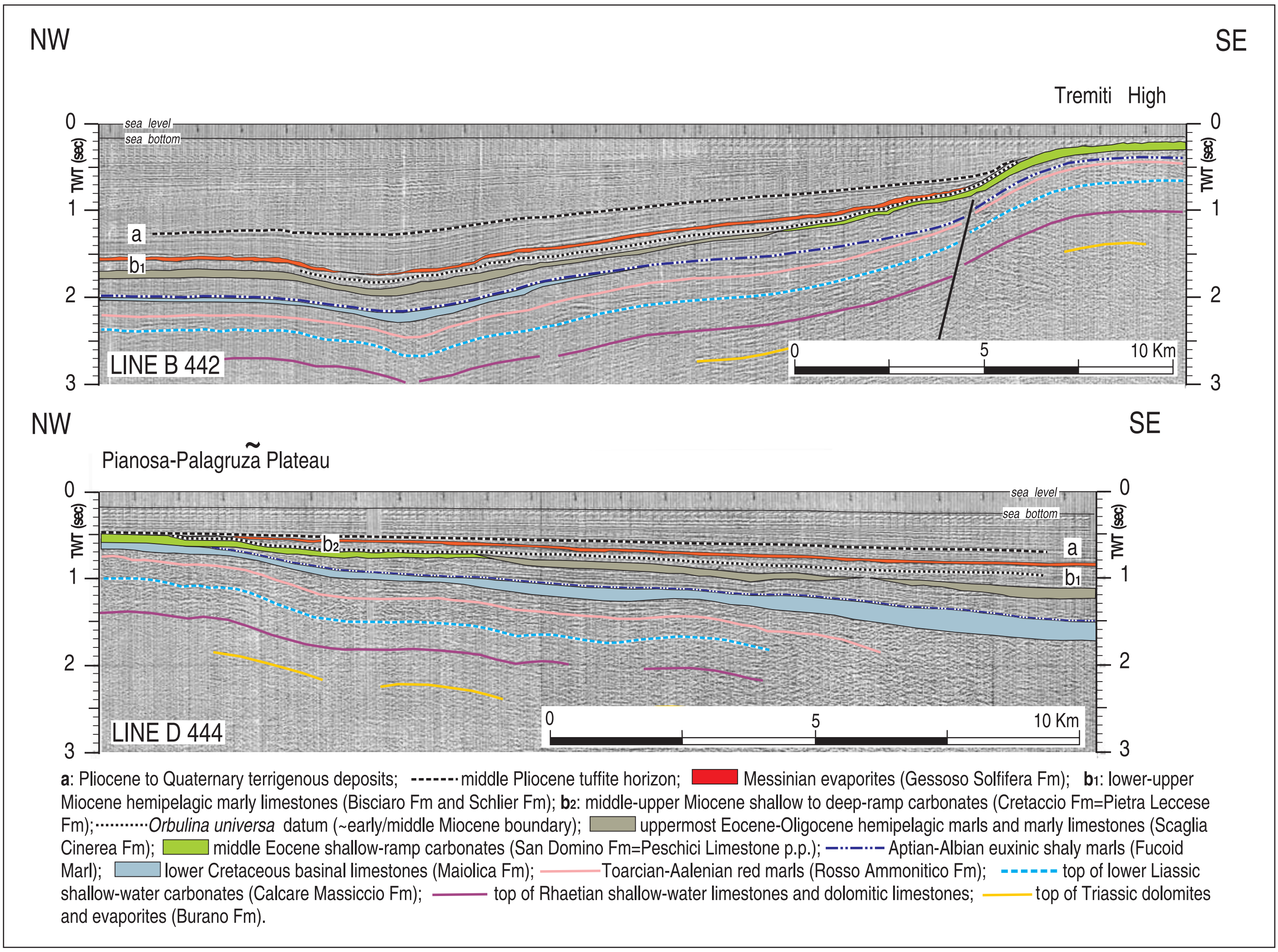

Fig. 9 - Selected reflection seismic profiles showing the transition between the Northern Adriatic Basin and the Tremiti High (line B-442) and the transition between the Pianosa-Palagruža Plateau and the Southern Adriatic Basin (Line D-444). As in the line shown in fig. 6, selected horizons and units evidence the influence of the synsedimentary salt-related tectonics in the creation of shallow-water conditions in the Central Adriatic region during Tertiary times. Both profiles show a prominent disconformity at the base of the shallow-water Peschici Limestone and the progressive drowning of the Central Adriatic Swell, which in this area underwent definitive flooding only in the Pleistocene. Tilted Pliocene deposits NW of the Tremiti High attest the very young age of the final uplift of this structure. In the Line B-442, an erosional channel at the base of the Pliocene deposits is responsible for the local absence of the Messinian evaporites.

– Profili sismici a riflessione mostranti la transizione tra il bacino nord-Adriatico e l'alto delle Tremiti (linea B-22) e la transizione tra il plateau Pianosa-Palagruža e il bacino sud-adriatico (linea D-44). Come nel caso della fig. 6, sono stati marcati gli orizzonti e i corpi geologici che evidenziano l'influenza della tettonica sinsedimentaria, sopratutto tettonica salina, nel raggiungimento di condizioni di mare basso nell'area centro-adriatica in tempi terziari. Entrambi i profili mostrano un'importante di disconformità alla base dei Calcari di Peschici e documentano il progressivo annegamento dell'alto centro-Adriatico che in questa zona fu definitivamente sommerso soltanto nel Pleistocene. La pendenza dei depositi pliocenici a NW delle Isole Tremiti mostra l'età molto giovane dell'ultimo sollevamento della struttura. Nella linea B-442, un canale di erosione alla base dei depositi Pliocenici e responsabile per la locale assenza delle evaporiti messiniane.

of the contiguous Edgar High, by the gradual pinching-out of the middle Liassic-lower Cretaceous basinal deposits, which reached maximum starvation in the early Cretaceous (only 27 meters of Maiolica Fm in Ernesto 1). The occurrence of shallow-water nummulitid-rich limestones (Peschici Limestone) on top of the Ernesto-Famoso High (documented in Famoso 1) together with the onlap of the Scaglia Cinerea Fm against its flank indicates that the positive structure, the build-up of which started to rise in the middle/late Liassic, reached a considerable elevation and shallow depths in the late Eocene-early Oligocene.

North of Pianosa, the NW-SE Ernesto-Famoso High merges with the SW-NE oriented Tremiti High. The prominent Tremiti Islands are a mostly post-Miocene positive structure (Argnani *et alii,* 1993, 1994; see also the deformed Plio-Pleistocene deposits on the flank of the Tremiti High in fig. 9). Therefore, they did not exist at the time when the ancestors of the Scontrone-Gargano vertebrates began to swarm into the Abruzzi-Apulia domain. However, most of the Central Adriatic region, including the Tremiti Islands, Pianosa and Eastern Gargano, constituted during the middle Eocene a wide shallow-water plateau characterized by high-energy bioclastic sand bars rich in larger benthic foraminifers (Arni & Lanterno, 1976). These shallow-marine carbonates (Peschici Limestone p.p. of Martinis & Pavan, 1967; Monte Saraceno Limestone of Bosellini *et alii,* 1993; upper portion of the

San Domino Fm of CREMONINI *et alii,* 1971, see fig. 5) represent the regressive, high-stand portion of an uppermost Ypresian-Lutetian carbonate-ramp sedimentary sequence deposited in disconformity over upper Cretaceous-lowermost Paleocene deep-ramp to basin foraminiferal limestones (Monte Acuto Fm and Scaglia Fm, see BOSELLINI *et alii,* 1993).

5. DISCUSSION AND CONCLUSIONS

The onset of shallow-water conditions in the basinal Central Adriatic area during the Eocene was certainly favoured by the Paleocene global sea-level fall, which caused the generalized emergence of the Apulia Platform and its margin. A decisive role, however, was played by the salt tectonics, which created in the Central Adriatic a number of prominent intrabasinal structural highs. These highs coalesced into a gently bumped swell, here called the Central-Adriatic Swell, which became seat of neritic sedimentation before the mid-Oligocene sea-level fall. This shallow-water domain included the Ernesto-Famoso High, the Tremiti Islands and the wide Pianosa-Palagruža Plateau. Karstic features between the nummulitid-rich shallow-water carbonates of the San Domino Fm/Peschici Limestone and the transgressive deposits of the Cretaccio Fm/Pietra Leccese Fm indicate a subaerial exposure between the middle Eocene and the middle Miocene. The gap at the unconformity between the San Domino Fm and the Cretaccio Fm in the Tremiti Islands, as well as between the Peschici Limestone and the Schlier Fm in the Ernesto 1 well, is chronologically correlated with the deposition, in the adjacent basin, of the hemipelagic Scaglia Cinerea Fm plus Bisciaro Fm, the onlap termination of which against the Central Adriatic Swell is evident on the seismic profiles shown in figs. 6, 8 and 9. Erosional features at the top of the Scaglia Cinerea Fm record the mid-Oligocene global sea-level drop.

The gray shaded areas in the paleogeographic map of fig. 4 indicate the spatial distribution of the Scaglia Cinerea Fm in the Adriatic region and in the Apennines, and therefore the extent of the basinal marine areas that represented a natural barrier for land mammal migration. The white colored zones, by contrast, indicate areas characterized by the generalized absence of Oligocene deposits. In this area, transgressive Miocene carbonates unconformably overlie shallow-water Eocene or, more often, older carbonate deposits with the local presence of interposed «terra-rossa» soils.

In summary, in the whole Central Adriatic region a generalized disconformity surface with a well documented subaerial erosion separates the upper Paleocene-middle Eocene shallow-water Peschici Limestone (which in a few cases reaches the early Oligocene, see Famoso 1) from overlying deepening-up middle/upper Miocene transgressive limestones (Pietra Leccese Fm).

Many lines of geological evidence indicate the Oligocene (likely around the early-late Oligocene boundary, i.e. at 29-30 Ma, when a major sea-level fall occurred at the global scale) as the time when land mammals colonized Apulia and identify the Central Adriatic corridor as a plausible route of immigration followed by the ancestors of the Scontrone and Gargano fauna (Dalmatia-Gargano landbridge). Through this landbridge and in this time interval representatives of the ancestor stock of the Hoplitomerycids, together with the forerunner of the giant insectivore *Deinogalerix*, spread into the Abruzzi-Apulia realm. The low number of taxa that migrated into Abruzzi-Apulia proves the strong filtering the landbridge had on the fauna.

The birth of an Oligocene landbridge across the Central Adriatic region was a fortuitous event determined by the combined effect of three favourable factors:

– Salt-related synsedimentary tectonics in the Central Adriatic region, mostly active between the middle/late Liassic and the early Cretaceous, that caused the creation of prominent structural highs, which interrupted the continuity of the middle Liassic basinal corridor between the Adriatic and the Apulia Platforms

– important sea level drop around the end of the early Paleocene, which caused in the whole Central Adriatic area a widespread seaward progradation of upper Paleocene-Eocene shallow-water carbonates over older deeper-marine deposits, thus favouring the coalescence of several isolated submarine highs and the creation of a gently bumped shallow-water swell between the Gargano Promontory and the Dalmatian islands. This shallow-water domain (Central Adriatic Swell) separated the Adriatic Basin into a Northern Adriatic Basin and a Southern Adriatic Basin;

– major global sea-level fall around 29-30 Ma, which caused the generalized exposure of the shallow-water Central Adriatic Swell and the development of a landbridge for mammal migration from Dalmatia to Gargano.

The sea-level rise subsequent the mid-Oligocene event led to the deposition of transgressive carbonate deposits on the landbridge connecting the Apulia Platform with the Balkan mainland. The pathway became progressively narrower until maximum flooding was reached around the end of the Langhian, i.e. around 14.8 Ma (see BERGGREN *et alii,* 1995). As a consequence, the landbridge was submerged and Apulia was inexorably isolated. The generalized middle Miocene transgression, however, did not affect the bulk of the Apulia Platform that kept emerged until the Tortonian, allowing the development of a fairly varied landscape where relatively few land taxa flourished, endemized and diversified. The isolation of Apulia ended with the Messinian salinity crisis, when a new extensive sea level fall well documented in the whole Mediterranean region opened a new and wider subaerial pathway across the Central Adriatic Sea. This new route, however, exerted an even stronger filtering effect than the previous one. In fact, while the Paleogene wave of immigration included both large and small mammals, the Messinian one involved only micromammals as no new large mammal joined the already residing communities.

The palinspastic restorations of the peri-Adriatic region in the Oligocene and Tortonian shown in figs. 4 and 1 respectively indicate the existence of a vast Abruzzi-Apulia paleobioprovince, which remained isolated for a minimum of 4-5 million years (from the sinking of the landbridge around the end of the Langhian to the accumulation of the Scontrone vertebrate remains) to a maximum of over 15 million years (time interval bracketing the onset of the landbridge in the Oligocene and the deposition of the vertebrate bonebeds of Scontrone in the Tortonian). The presence both at Scontrone and Gargano, of *Deinogalerix* and *Hoplitomeryx*, with their weird endemic features, is perfectly consistent with this reconstruction. In addition, the integrated study of the paleogeographic setting of the Central Adriatic region and of the paleontological characteristics of the Abruzzi-Apulia paleobioprovince suggests a possible common origin of the Scontrone and Gargano giant insectivore *Deinogalerix* from insectivores distributed in the Balkan region in the second half of the Oligocene.

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