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The role of the foreland in the late geotectonic evolution of the Mediterranean arcs at the continental stage

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Geologia. — *The role of the foreland in the late geotectonic evolution of the Mediterranean arcs at the continental stage.* Nota di MARIO BOCCALETTI (*), presentata (**) dal Corrisp. A. AZZAROLI.

RIASSUNTO. — Gli archi alpino-mediterranei sembrano aver subito una evoluzione geotettonica bistadiale: un primo stadio, di età Cretaceo-Eocene, corrispondente all'« arco oceanico »; un secondo stadio, dopo le principali « collisioni » continentali, dal Miocene in poi, corrispondente all'« arco continentale ». Lo stile evolutivo degli archi cenozoici durante lo stadio continentale non segue quello precedente dello stadio oceanico. La evoluzione geotettonica dell'arco nello stadio continentale sembra essere strettamente condizionata dalla « eterogeneità » crostale dell'avampaese, che determina differenze nello sviluppo di distinti segmenti di arco. Ciò si osserva particolarmente negli archi continentali attivi Carpatico orientale e Calabro. Viene infine avanzata una ipotesi sul possibile meccanismo dei processi di subduzione allo stadio di arco continentale.

1. INTRODUCTION

In recent years various attempts have been made to interpret the geodynamic evolution of the Mediterranean arcs on the basis of the Plate Tectonic theory [1-4]. It has been suggested that significant similarities exist between the megastructural elements of the Mediterranean continental arcs and those of the West Pacific island arc systems, as the former could very well represent a more advanced stage of evolution of the latter [5, 6]. As Dewey pointed out [7], it is by no means easy—and in certain cases almost impossible—to trace the changing active margins of the plates of the orogenic belts in time and space. As regards the Mediterranean area s.l., a further difficulty exists in that the geodynamic evolution of the arcs continues long after the supposed continental " collision ". It is generally accepted that the Mediterranean no longer has any important residual areas of Mesozoic oceanic crust (Tethys ocean or Mesozoic marginal basins), but that the present oceanic crust areas are the result of expansion in Cainozoic times [8]. Even the Black Sea basin is apparently not a remnant of the original Tethys [9, 10]. These newly expanded oceanic areas of the Mediterranean (Ligurian and Tyrrhenian Basins) or areas of Neogene crustal extension—evolved to a greater or lesser extent (Pannonian, Aegean and Transylvanian Basins)—may be considered to be back arc areas which developed behind the folded and magmatic continental arc during their Neogene migration [5]. On the other hand, the ophiolitic sequences occurring in the Mediterranean arcs—considered to be remnants

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of the Mesozoic oceanic crust—were probably obducted onto sedimentary units with a continental basement during Cretaceous and Eocene times. It is therefore at this time that the oceanic areas closed up with " impacts " of sialic elements, due to complete destruction of the subducted Mesozoic oceanic crust. However, the arcs continued to migrate until recent times, although discontinuously and not uniformly, so that the belts have become increasingly arched and complex in shape and are not longitudinally coeval. Important tecto-orogenetic events in the folded arcs and frequent volcanic activity in the magmatic belts and in the contiguous back-arc areas occurred in Neogene times. These phenomena were probably connected with processes of lithospheric subduction. At present the subduction activity is restricted to the East Carpathian, the Calabrian and Aegean arcs. Owing to this peculiar evolution of the Mediterranean arcs, their tectonic features do not readily fit into a simple and clear picture like the current models of the Plate Tectonic theory. In this paper the discussion will deal with the active Carpathian and Calabrian arcs with the aim of clarifying the post-collision evolution of these Mediterranean continental arcs, the former of the European plate, the latter towards the peri-African margin. Attention will be given to the type of foreland lying in front of these arcs, analyzing the possible role that the nature and previous tectonic history of the foreland can have played in the continental stage evolution of the Mediterranean arcs.

2. The East Carpathian continental arc

The East Carpathian continental active arc is a segment of more extensive continental arc active during Cainozoic time, in continuity with the northern orogenic Carpathian chain developed on the European plate. Geophysical and geological data indicate that a lithospheric slab is still underthrusting in the maximum bend of the East Carpathians, although it is in a senile stage of geodynamic evolution. This is supported by: *a*) the foci of the earthquakes in the Vrancea area [11], which get gradually deeper towards the inside of the arc; *b*) the considerable thickness of the Foçsani depression [12]; *c*) the pericarpatic axis of minimum Bouguer gravity anomalies which is clearly outside the arc in this zone [13]; *d*) by recent tectonic movements which affected this area [14]. The East Carpathian arc-trench system consists of an outer trench (Foçsani trough), a folded arc (East Carpathian arc-segment) formed by Cretaceous and Tertiary tectonic phases, a calc-alkaline magmatic arc (Calimani-Harghita Mts.) and a rear arc ensialic basin (Transylvanian basin) which separates the Apuseni Mts. from the East Carpathian arc.

The continental foreland of the whole Carpathian arc is made up of some distinct structural elements (figs. 1, 2). The oldest platform is to be found in the external northern part of the Carpathian segment and represents the podolo-Moldavian portion of the East European platform whose basement is approximately epiproterozoic in age (Stille's *PaleoEurope*). The Moho discontinuity is at a deepth of approximately 40–50 km [15]. The Southern

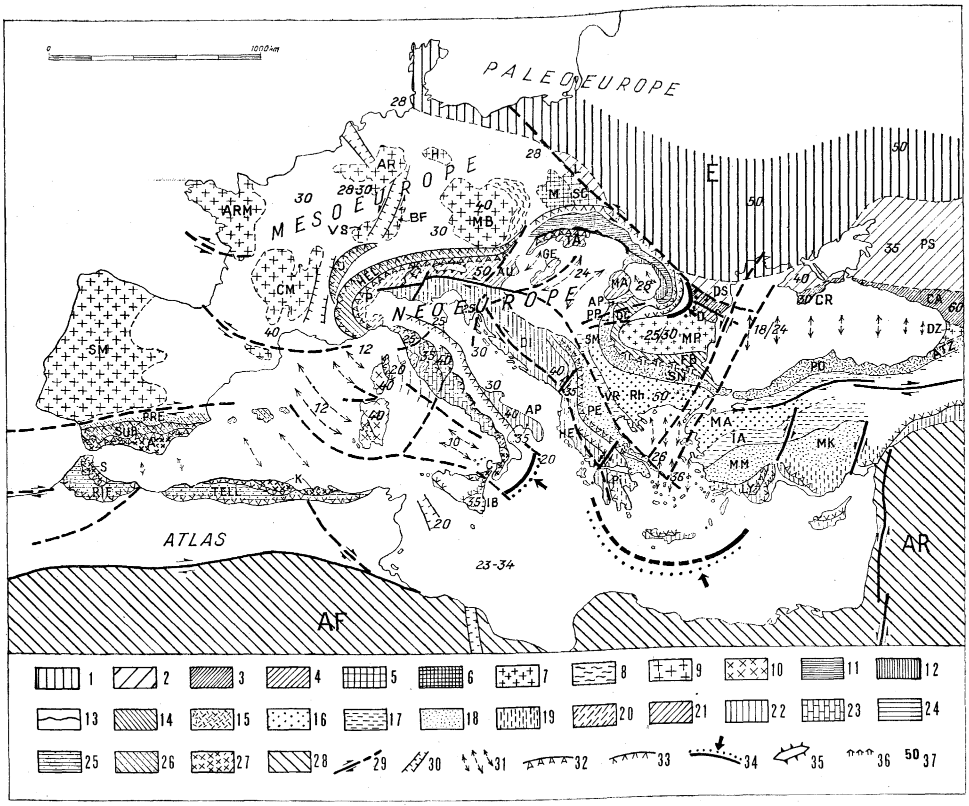

Fig. 1. – 1) East–European platform (E); 2) Scythian platform (PS) and Lvov–Lublin depression (L); 3) Intracratonian chain of Northern Dobrogea (DS), Crimea (CR) and Caucasus (CA); 4) Central Dobrogea; 5) Saint–Croix Mts. (SC); 6) Miechov depression (M); 7) Moesic platform (MP) and Dzurila massif (DZ); 8) Sudetes and Moravo-Silesien; 9) older massifs welded and incorporated during Hercynian orogenesis in *MesoEurope* (MB: Bohemian massif; H: Harz massif; ARM: Armorican massif; AR: Ardennes massif; VS: Vosges massif; BF: Black Forest massif; CM: Central massif; SM: Spanish Meseta massif); 10) Corsica and Sardinia remnant arcs, originally attached to European Block; 11) Moldavides (Carpathians); 12) Eastern Dacides; 13) Pienine klippen zone; 14) external Alpine tectonic units of the northern continental margin of Tethys: (J) Jura Mts, (HEL) Helvetic and Ultrahelvetic zones, (DC) Southern Dacides, (FB) Fore Balkans and Starra Planina zones; 15) back-arc areas of Cretaceous volcano-clastic deposition: (SN) Srednogorie (Balkans), (PP) Poiana Rusca (Apuseni Mts.), (PO) Pontides and (ATZ) Adjaro-Trialetica zone; 16) Rhodope massif (Rh), Serbo-Macedonian zone (SM), Northern Anatolian massif (MA); 17) oceanic scar of Vardar zone (VR) (Inner Dinarides and Hellenides), Metaliferi Mts. (AP) and Izmir-Ankara zone (IA); 18) Pelagonian s.l. zone (Pelagonian, Korab and Golija zone (PE)), Menderes massif (MM), and Kirsheyr (MK) massifs; 19) Pindos s.l.-type units (Pi) and radiolarian and ophiolitic units, Lyciennes units, Taurids p.p. units (Ly); 20) oceanic units (Ligurian and Piemontais units and these of Corsica and Calabria); 21) Alpine tectonic units of the southern continental margin of Tethys with northward polarity (Austroalpine units, western Dacides, Tatrides (TA) and Gemerides (GE), and Apuseni Mts. units (MA); 22) Alpine tectonic units of the southern margin of Tethys with a general southward polarity: Dinarides (DI), Hellenides (HE) Taurids p.p.; 23) Alpine tectonic units of the southern margin of Tethys of the Northern Apennines and carbonate platforms of central and southern Apennines affected by European and subsequent Apennine polarity with general counterclockwise rotations, and Apulian platform (AP); 24) Iblean platform (IB); 25) Structural units of Tell and Rif chains; 26) Subbetic (SUB) and Prebetic (PRE) units; 27) microsialic elements originally detached from the paleo-African plate during the Cretaceous and Eocene alpine northwards migration of the arcs, overthrusted onto Iberian-European plate (Alpujarrides (A)) and partially pushed back on the African border during the Neogene tectonic phases (Septides (S)), Kabylides (K) and Calabrides (C); 28) African (AF) and Arabian (AR) forelands; 29) transcurrent or transform faults; 30) main graben; 31) back-arc extended areas (ensialic and oceanic marginal basins); 32) Main Cretaceous-Eocene folded arcs; 33) Main Miocene and post-Miocene folded arcs; 34) arc-trench segment with active subduction; 35) Engadine and Tauern windows; 36) Cretaceous-Eocene back-arc thrust belt; 37) Moho surface depth.

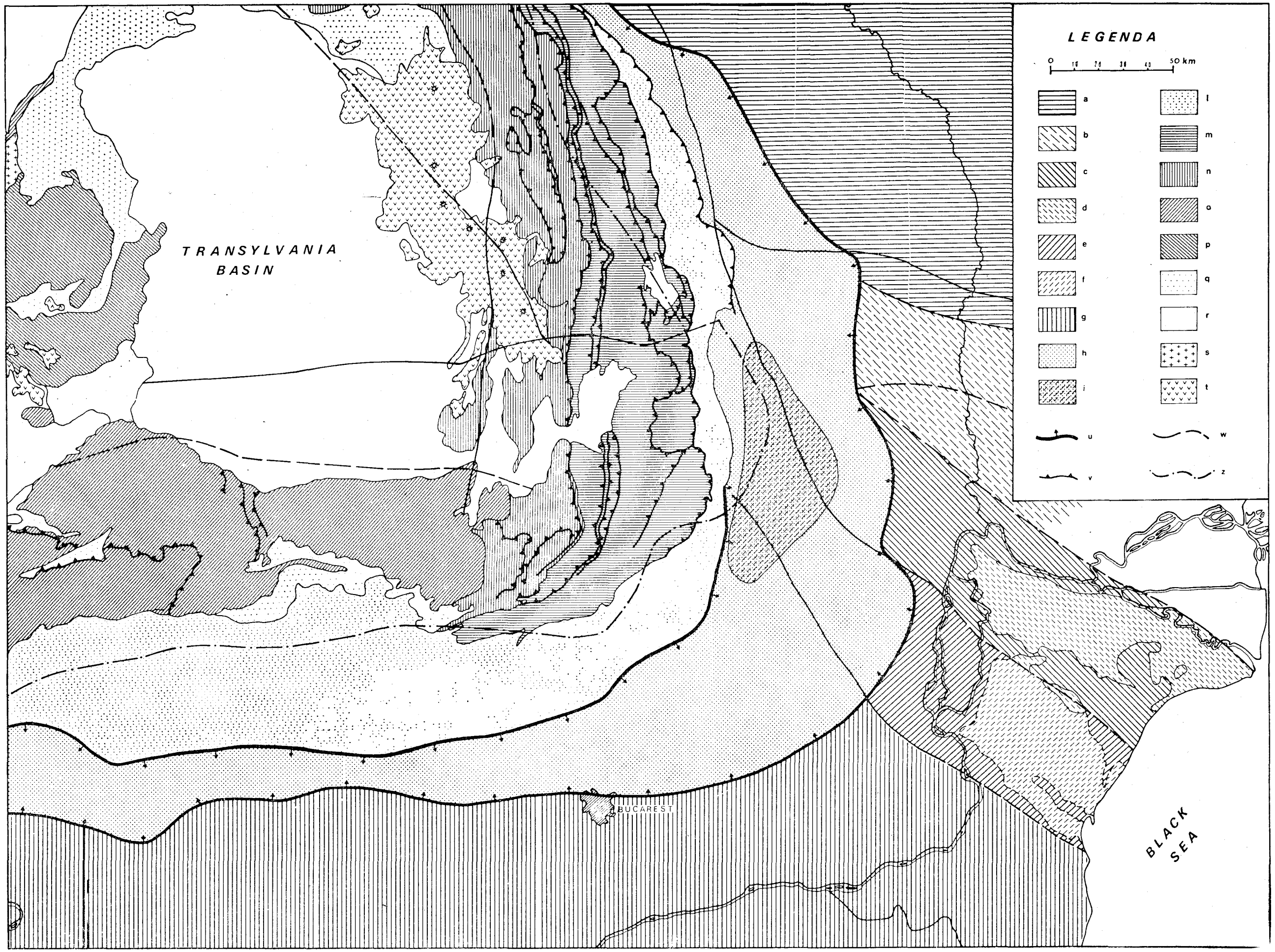

Fig. 2. – Tectonic schematic map of the East Carpathian arc. *a*) East European foreland (Epialgonian platform); *b*) Scythian platform; *c*) Northern Dobrogea (Hercynian-old Kimmerian basement); *d*) area of the Northern Dobrogea affected by Cymmerian Alpine tectogenesis; *e*) Central Dobrogea (Assyntic basement); *f*) greenschists of Central Dobrogea; *g*) Moesic Platform; *h*) epiplatformic flank Neogene Molasse of the outer fore-deep; *i*) Foçsani-Odobeşti depression; *l*) epicarpathian flank of fore-deep affected by Styrian-Moldavian or Rodhanian-Valacchian tectonic phases; *m*) Moldavides (flysch tectonic units p.p.) affected by the Styrian tectogenesis; *n*) Eastern Dacides; *o*) Southern Dacides; *p*) Western Dacides; *q*) Mesozoic post-tectonic (Laramide) cover; *r*) Quaternary deposits; *s*) Banatite intrusive magmatism (Cretaceous-Paleogene age) of calc-alkaline type; *t*) Neogene-Quaternary calc-alkaline volcanism; *u*) flexural faults; *v*) main overthrusts of the Alpine tectonic units; *w*) axis of pericarpatic gravimetric minimum.

Carpathian edge of this platform is overthrust by the flysch nappes of the Carpathians so that the *NeoEurope* is closely in contact with the *PaleoEurope* (fig. 1). To the South of this platform is the Epihercynian platform (Stille's *MesoEurope*) which crops out North (Polono-Bohemian zone), East and South (Pontic zone) of the Carpathian arc [16]. Structurally different sectors may be distinguished in this zone. Next to the East European platform is the more recent Scythian platform, which runs in a North–West direction and disappears under the Carpathian flysch nappes, probably reappearing in the Lvov-Lublin depression (Saint-Croix Mts.) of the Polono-Bohemian zone [16]. Immediately to the South is the intracratonal chain of Northern Dobrogea which continues eastward in the Crimean-Caucasian orogenic system and disappears west of the Danube under the external Carpathian molasses. It does not seem to have any correlating structural elements in the Polono-Bohemian zone. The Northern Dobrogea is made up mainly of Paleozoic and Mesozoic formations that have undergone various tectonic phases, the most recent of which are Alpine in age. South of this sector, divided from it by an important tectonic accident (Peceneaga-Camena fault) (fig. 2) is the Moesic platform whose Precambrian shelf outcrops in Central Dobrogea (greenschist zone). The Moesic platform, whose Moho depth is of approximately 30 Km, is one of the old blocks welded and incorporated during Hercynian orogenesis in *Meso Europe*. Part of this platform can be correlated with the Moldanubicum of the Bohemian massif that outcrops in the Polono-Bohemian zone [16]. The active segment of the East Carpathian arc is migrating over the northern and central Dobrogea foreland, basement zones of *MesoEurope* that have been subjected to Alpine remobilizations. It can be assumed that the dying out in Late Tertiary of lithospheric underthrusting in the northern sector of the Carpathian arc was brought about by the "impact" of the arc against the East European platform having a crustal thickness of approximately 50 Km (*NeoEurope* on *PaleoEurope*). This caused a shifting of the dynamic events East and South-Eastwards which continued until recent times. At present this activity is confined to the maximum bend segment of the East Carpathians, migrates obliquely towards those areas of the *MesoEurope* platform (Northern and Central Dobrogea) which are structurally different. This discontinuous process of lithospheric underthrusting involves progressively minor segments and is accompanied by important horizontal crustal movements.

This is shown by certain LANDSAT satellite images where important regional alignments can be observed. The Eastwards and Southeastwards shifting of subduction is accompanied by a correspondent shifting of tectonics and calc-alkaline magmatism which become increasingly younger going from the Northern to Southeastern Carpathians [17, 18].

Geophysical investigations in the maximum bend zone of the East Carpathians have shown that sheets exist in the substratum. These overthrust planes run more or less parallel to the main shear plane [19] along which the most important foci of the Vrancea earthquakes are situated. The foci have been connected with the process of lithospheric subduction [11]. These reverse faults in the substratum indicate a shortening of the crustal layer. In conclusion, the Carpathians would appear to represent a fair example of a continental arc whose evolution in the continental stage is to a large extent conditioned by the crustal heterogeneity of the foreland.

3. The Calabrian arc-trench system

The Calabrian arc is an active arc-trench segment of a more extensive Cainozoic Sicilian-Calabrian-Southern Apennines arc-trench system, in migration towards the carbonate platforms bordering the African paleo-margin, on a thin sialic crust. It is characterized by: *a*) an external trench (Ionian trench); *b*) a folded arc (Calabrian arc), formed in several tectonic phases (the

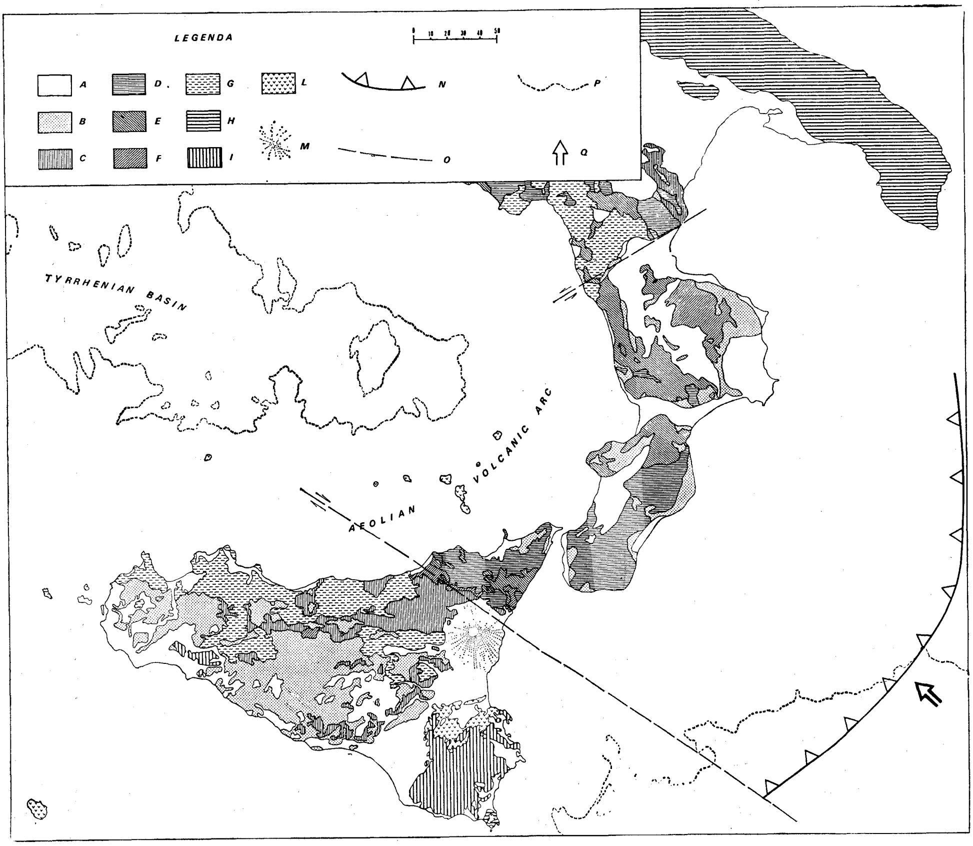

Fig. 3. – Tectonic schematic map of the Calabrian Arc and adjoining areas. A) Plio-Quaternary sediments; B) Transgressive sediments affected by Upper Miocene and Middle Pliocene orogenic events; C) Sicilide s.l. units; D) Incertae sedis units; E) Tectonic units of Alpine chain with European polarity; F) Tectonic units of Alpine chain with Southeastern polarity; G) Neogene tectonic units of Apennine-Maghrebide chains with respectively eastward and southward polarity; H) Apulia foreland; I) Ragusa foreland; L) Plio–Quaternary volcanics; M) Etna volcano; N) Active subduction zone; O) Sangineto and Taormina crustal lines.

older phases being Mesozoic and Lower Tertiary in age with Alpine polarity, and the later phases Cainozoic and even recent with SE polarity [8]; *c*) a magmatic arc (Aeolian arc) and rear arc basin (Tyrrhenian basin) whose expansion occurred from Messinian onwards [5, 8, 20] (figs. 1, 3). The Ionian Sea floor constitutes the foreland of the active arc whose geophysical characteristics are not well-defined. There is a thick sedimentary cover on a crustal substratum, considered to be of thin continental or intermediate type with a thickness of about 19 Km [21]. This Ionian floor foreland divides the Apulian of the South Apennines arc segment from the Ragusan platform to the South (foreland of the Sicilian arc segment), both of which have a sialic basement. The Moho discontinuity is at 30 Km depth under both the Apulian and Ragusan platforms [22]. The Apulian foreland is characterized by a Mesozoic shelf carbonatic sequence locally overlapped by Neogene and Quaternary sediments, while the Ragusan foreland is characterized by a " trough "-type geosyncline evolution similar to the Marche sequences. Lithospheric underthrusting ceased in these segments in Neogene times. The Apulian and Ragusan forelands can be considered as two distinct structural elements whose crusts are not homogeneous or in continuity, the Apulian platform instead being in continuity with the external carbonate platforms of the Hellenids. At present subduction is confined to the Calabrian sector which has a foreland with a thin crust (Ionian foreland), while the contiguous segments of the Southern Apennines and Sicilian arcs are blocked respectively by the Apulian and Ragusan platforms which lie on a thicker sialic crust. Thus, the foreland of the Southern Apennine-Calabrian-Sicilian arcs is characterized by three structurally distinct segments having different crustal thickness and sedimentary evolution. So that also the Sicilian-Calabrian-Southern Apennines Neogene arc-trench system represents a fair example of a Mediterranean arc in the continental stage which is conditioned in the geotectonic evolution by the crustal heterogeneity of the foreland.

4. FINAL REMARKS

In the compressive geotectonic evolution of the Alpine-Mediterranean folded arcs two distinct stages can be recognized: an early one of Cretaceous-Eocene age, corresponding to an oceanic arc-type, followed by a second post-" collision " stage from Miocene onwards. The latter, whose tectonic dynamics is still under debate, corresponds to a continental arc-type and its fitting in the " classical " plate Tectonic models is not well suited. In fact, if the Cretaceous-Eocene oceanic arcs can be related to a general contraction between European and African plates at the expense of the interposed oceanic crust (Tethys ocean or Mesozoic marginal basins), the post-" collision " contraction phenomena, occurring from Miocene onwards, raise questions regarding the mechanism which allows the arcs to continue their migration.

The idea is generally accepted that the Mediterranean continental arcs are characterized by the occurrence of some megastructural elements as in active island arcs, i.e. folded arc, magmatic arc and rear arc basin, although the latter shows differences in the dimensions and type of crust [23]. In addition recent studies on the petrology and geochemistry of the Neogene volcanic rocks of some Mediterranean chains, namely the Calabrian and East-Carpathian arcs, have shown close similarities to the volcanics lying above subduction zones along circumpacific island arcs [24, 20]. Accordingly, both from a tectonic and magmatic point of view the conclusion should be drawn that between circumpacific island arcs and Mediterranean continental arcs similarities are much more striking than differences. Thus one can infer that also the geodynamic evolution of the continental arcs with their consequent migration has to be related to subduction processes as hypothesized for the active Pacific island arcs. However, it is to be pointed out that the evolution of the arcs in the "continental" stage rarely follows that of the previous Cretaceous-Eocene arcs in the "oceanic" stage, but individual segments of the continental arcs evolve differently in time and space. In other words, the tectonic and magmatic activity together with the crustal underthrusting and arc migration occurred until recent times discontinuously and not uniformly affecting different arc-segments of decreasing extension. Two examples of this differential evolution are given by the Carpathian and Calabrian arcs, where both magmatism and tectonic activity migrate southeastward with time. Thus, owing to the contiguous migration in their southeastern stretch, the belts become increasingly arched and are not longitudinally coeval. These discontinuities in tectonics, magmatism and subduction, are not commonly found along the Pacific oceanic island arcs. The author's suggestion is that this different behaviour in the geodynamic evolution is to be related to the type of the foreland crust in front of the arc, which is relatively homogeneous in oceanic island arcs, whereas it presents important dishomogeneities in thickness and nature along the continental arcs, owing to its previous complex tectonic history. The main evidence for this hypothesis is given by the occurrence of the thinner and/or remobilized foreland crust just in front of the presently active continental arcs. In this view, the creasing or the continuation of the subduction activity along contiguous arc-segments is heavily conditioned by the thickness and nature of the crust foreland, that is the subduction probably continues when the crustal layer of the foreland in front of the arc is relatively thin and comes to a halt when this layer becomes too thick. This suggestion raises the question as to what kind of crust is consumed along the subduction zones during the contraction in the continental stage. Some authors believe that the contraction occurs at the expense of the thin subducting continental foreland crust (see discussion in Smith, [25]). However, if we accept the view that there is a close direct relationship between calc-alkaline magmatism and subducting crust, the possibility of a subduction of continental crust conflicts with the type of magmatism occurring above Mediterranean active subduction zones which, according to some authors, is similar to that of Pacific island arcs. Accordingly, the problem of the type of crust involved in subduction during the Neogene post-" collision " stage of the Mediterranean arcs is rather puzzling and the presently available data do not offer a satisfactory solution. In the opinion of the author one possibility could be that the contraction of the arcs in the " continental " stage can be explained by assuming " detachments " of the thin continental crust from their substratum, with formation of imbricate wedges and consequent subduction of the lower crust and upper mantle. In this view, every discontinuity between the crust and upper mantle can be a potential level of shear movements, detachments and thrustings, with deep horizontal planes which become rapidly steep at the surface levels. This model of crustal shortening goes on until the sialic layer of the foreland becomes so thick that it blocks lithospheric subduction. When subduction ceases along all the arc-segments of the continental arcs (final continental stage) the stress field changes shifting in the foreland crust so that the general compressive effects result in conjugate strike-slip faults cutting the arc, as can be well observed in the Alps [26].

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