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DYNAMICS OF DEEP STRUCTURES IN THE TYRRHENIAN - APENNINES AREA AND ITS RELATION TO NEOTECTONICS(*)

E. Locardi
Istituto di Scienze della Terra, Università di Messina, Messina, Italy

ABSTRACT - *Dynamics of deep structures in the Tyrrhenian - Apennines area and its relation to neotectonics* - Il Quaternario, **6**(1), 1993, p. 59-66 - New data on the origin and dynamics of deep structures in the Apennines are presented and their possible effect on neotectonics is discussed. The crustal underplating of a thick (5÷20 km) "layer" of heavy magmatic melts beneath the western Apennines is shown as the most striking process that has occurred from Tortonian times to Present. It is the effect of hot plumes rising up from the deep mantle; the origin and evolution of the basin-chain system is assumed to be the consequence of the migration of such plumes. Magma types and their space-time evolution are suggestive of the plumes dynamics and of the related Tyrrhenian Sea spreading and chain formation. The various structural units of the Apennines would have moved from their original position in the Tyrrhenian area at the roof of the subcrustal magmatic accumulation along well-defined routes formed by deep-rooted transcurrent faults transverse to the Apennines main axis. DSS profiles corroborate this hypothesis. The tectonic blocks between transcurrent faults will possibly undergo a marked differential uplift both before and during the transcurrent slippage, and elongated basins may form due to the differential crustal dragging occurring above the underplated melt.

RIASSUNTO - *Dinamica delle strutture profonde nel Tirreno-Appennino e sue relazioni con la neotettonica* - Il Quaternario, **6**(1), 1993, p. 59-66 - Vengono presentati nuovi dati sulla natura e dinamica delle strutture profonde nell'area appenninica e le loro possibili ripercussioni sulla neotettonica. Il processo più rilevante viene indicato nell'accumulo di uno spesso livello (5÷20 km) di magmi pesanti sotto la crosta dell'Appennino occidentale ("*underplating* ") a partire dal Tortoniano fino all'Attuale. Questo processo consegue al sollevamento di diapiri termici dal mantello profondo. La creazione e l'evoluzione del sistema bacino-catena viene messo in relazione con la migrazione di detti diapiri. I tipi magmatici e la loro evoluzione spazio-temporale segnalano la dinamica dei diapiri, e con essa quella dell'apertura tirrenica e della formazione della catena. Le diverse unità strutturali dell'Appenino sarebbero state traslate dalla loro originaria posizione tirrenica a tetto del materiale magmatico sottocrostale lungo binari rappresentati dalle faglie transcorrenti trasversali all'asse della catena. Si prevedono forti sollevamenti differenziali dei blocchi tettonici limitati da due faglie trasversali prima e durante i moti trascorrenti, e la formazione di bacini allungati per effetto di trascinamento differenziale della crosta a tetto del pannicolo fuso.

Key-words: Geodynamics, hot plumes, neotectonics, Tyrrhenian, Apennines, Italy
Parola chiave: Geodinamica, diapiri termici, neotettonica, Tirreno, Appennino, Italia

1. INTRODUCTION

New data and interpretations presented in the last 10 years have largely modified our knowledge on the asthenosphere-lithosphere model beneath the Italian peninsula that was valid when the *Progetto Finalizzato Geodinamica* (the Geodynamics Project of the National Research Council of Italy) started. At that time the scientific community was trying to integrate the traditional geological concepts with new ideas, whose source was the plate tectonic model.

The identification of deep-seated earthquakes underneath a basin undergoing oceanization and below calc-alkaline volcanoes, and of tectonic nappes piled-up over a foredeep on the Adriatic foreland, were major features conforming to a subduction model and its parts —*i.e.,* back-arc basin, volcanic arc, accretionary wedge, foredeep, and foreland.

Moreover, seismic exploration showed the presence of perityrrhenian and periadriatic deep reflectors that were interpreted as subduction zones (Giese & Reutter, 1978). This was sustained by the knowledge of convergence rate values of several cm/a for the African and European plates, requiring a kinematic compensation by means of a lithosphere consumption through a subduction process.

In reality, the available basic data — namely, presence of a deep seismic zone beneath the Tyrrhenian area, and calc-alkaline character of some volcanoes — are indicative of tectonic mechanisms of plate subduction.

Recently, Frohlich (1989) denied that a lithospheric slab at a depth greater than 60÷70 km may elastically respond to tectonic stresses with release of seismic energy. The origin of deep earthquakes has to be otherwise explained. Experimental data suggest that, under stress conditions and presence of fluids, the olivine to spinel to elemental oxide transitions occur along flat surfaces (Green & Burnley, 1989). Thus, the focal mechanisms of deep earthquakes and those of shallow earthquakes which are explained as the effect of faulting, may be assumed to be similar. The maximum depth of earthquake foci is 670 km because at greater depths, phase changes with a sharp volume decrease — *i.e.,* quake-accompanied implosions — do not occur any more.

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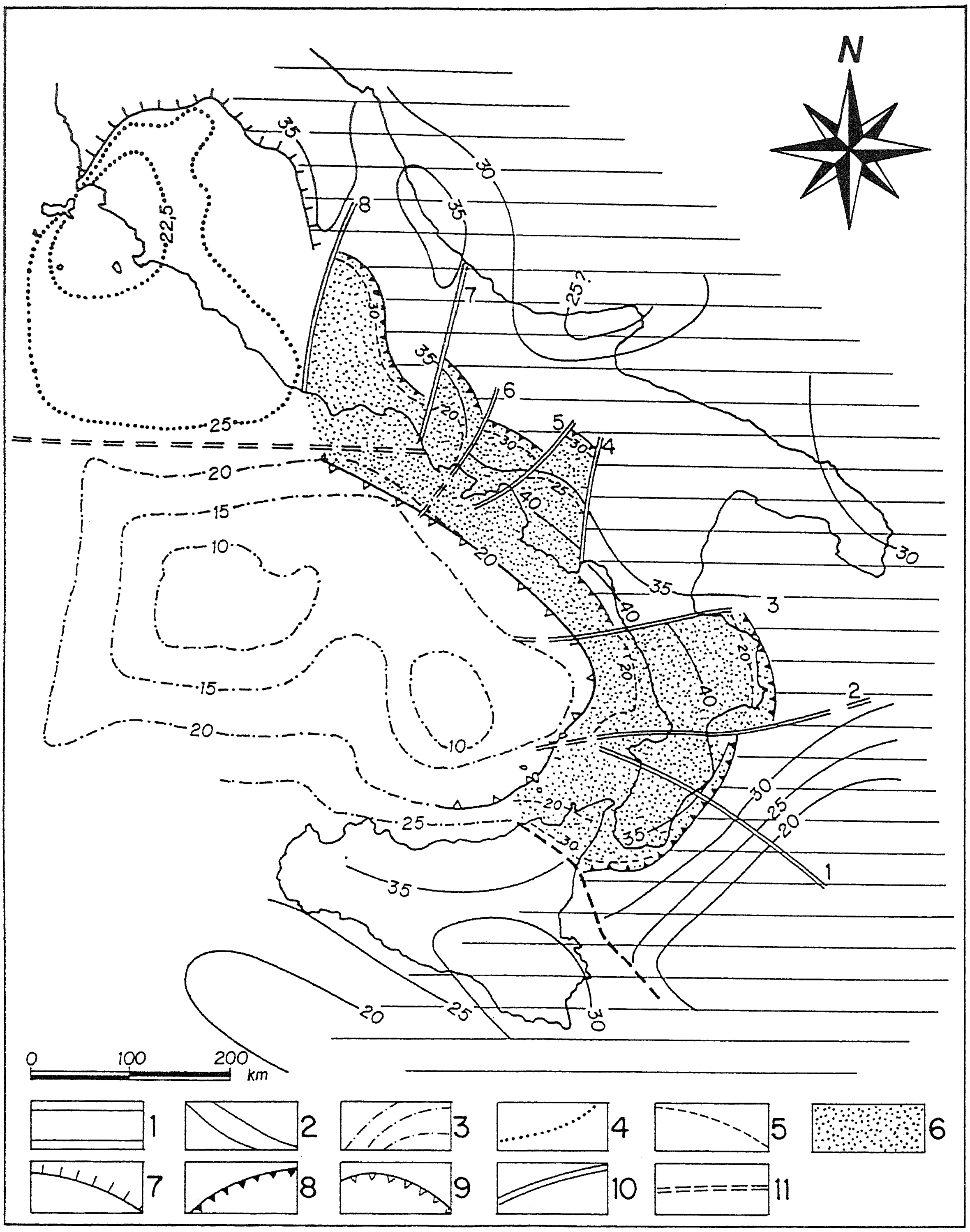

Fig. 1 - The Moho map as obtained from new DSS profiles and all available geophysical data (from Locardi & Nicolich, 1992).
1) The Adriatic and Ionic foreland; 2) Moho isobaths in continental lithosphere; 3) Moho isobaths at the roof of the southern Tyrrhenian asthenolith; 4) Isobaths of the roof of the low-velocity material rooted on the northern Tyrrhenian asthenolith; 5) Isobaths of the roof of the low-velocity material forming an intrusion between continental LID and reduced crust; 6) Attitude of low-velocity material intrusion on the side of the southern Tyrrhenian asthenolith; 7) Steep front of low-velocity material rooted on the northern Tyrrhenian asthenolith; 8) Front of the low-velocity material intrusion; 9) Steep front of the southern Tyrrhenian asthenolith; 10) Crustal and subcrustal faults crossing the Apennines axis; 11) 41°N parallel alignment.

Carta della Moho, elaborata da nuovi profili DSS e da tutti i dati geofisici disponibili (da Locardi & Nicolich, 1992). 1) "Avampaese" adriatico e ionico. 2) Isobate della Moho nella litosfera continentale. 3) Isobate della Moho a tetto dell'astenolite basso-tirrenico. 4) Isobate del tetto del materiale a bassa velocità sismica radicato sull'astenolite alto-tirrenico. 5) Isobate del tetto del materiale a bassa velocità sismica in posizione intrusiva tra il LID continentale e la crosta assottigliata. 6) Giacitura del materiale a bassa velocità sismica in posizione intrusiva a lato dell'astenolite basso-tirrenico. 7) Fronte ripido del materiale a bassa velocità sismica radicato sull'astenolite alto-tirrenico. 8) Fronte del materiale a bassa velocità sismica in posizione intrusiva. 9) Fronte ripido dell'astenolite basso-tirrenico. 10) Faglie crostali e subcrostali trasversali all'asse appenninico. 11) Lineamento del 41° parallelo.

Various authors (Foley & Wheller, 1990; Kelemen *et al.*, 1990; Dudas, 1991; Gibson *et al.*, 1991) disagree with the conclusion assuming an exclusively orogenic origin of calc-alkalic magmas. The calc-alkalic character of magmas is typical of volcanic arcs above subduction zones, but does not necessarily derive from the mixing of crustal and mantle materials. This chemical character may be observed under the most varied tectonic conditions depending on the mechanisms of melt extraction and ascent in the mantle. Thus, it cannot be considered as a diagnostic character of subduction conditions.

Other authors (Miyashiro, 1986; Nohda *et al.*, 1988; Tatsumi *et al.*, 1990) object to the relationship between subduction and back-arc marginal basin. The oceanized back-arc basin is not the effect of a subduction process but rather of a heat flow from the deep mantle. Whatever the subduction duration, marginal basins have the typical duration of 10 Ma, and migrate along geometrical patterns independent of those of the subduction zones. Subduction creates a discontinuity in the mantle that may guide the ascent of the thermal plume.

Seismic wave velocities as measured in correspondence to perityrrenian deep reflectors, do not suggest a Moho duplication owing to a subduction process; rather these are indicative of a layer of mantle-derived magmas accumulating between the crust and the mantle itself (Locardi, 1988a; Locardi & Nicolich, 1992).

There are many structural features of the chain operating against the assumption of an accretionary wedge on the front of a subduction zone — *e.g.*, a reduced series owing to the delamination along low angle normal faults (D'Argenio *et al.,* 1986). Apart from compressive fronts, the structural features of the Apennines are more suggestive of delamination rather than accretion processes. The absence of seismic activity, and the presence of positive magnetic and thermal anomalies along the foredeep are data which do not conform to the concept that the foredeep is in fact a trench.

It is to be noted, however, that the decisive evidence against the adopted geodynamic model is supported by the new data on the Atlantic Ocean spreading rate; the convergence rate of Africa to Europe in the last 20 Ma, has turned out to be one order of magnitude lower than previously evaluated (Olivet *et al.,* 1984; Anderson & Jackson, 1987).

2. DEEP STRUCTURES AND NEOTECTONICS

In the last 10 Ma the area now occupied by the Tyrrhenian basin and the Apennines, was a system kinematically closed to convergence motions along parallels and meridians. However, a young oceanized basin developed together with a mountain chain with peculiar characters in it (Locardi, 1992); it is as if geodynamic forces originated inside the system itself not caused by the transport of plates from the outside according to plate tectonic mechanisms.

Anyway, the problem of the relationships between neotectonics and the geodynamic engines is as serious as the problem of the connection between the structures detected on the outcropping portions of a tectonic edifice and the deep structures that geophysical prospecting reveals in the crust and upper mantle. Structural geologists are convinced that surface structures can seldom or hardly ever be clues of the nature and pattern of deep structures (Bally, pers. comm.).

If we accept surface structures misleading as to the correct interpretation of deep structures, it is better to turn the argument upside down and start again from what geophysical and geochemical data suggest as to the nature and dynamics of deep structures in order to verify which bearing these may have on surface modifications — *i.e.,* on neotectonics, to keep to the point.

In neotectonic investigations one must take into account that, probably since upper Tortonian times, mantle melts have accumulated at the base of the crust because of an underplating process, forming a layer 5÷20 km thick according to DSS data. This mantle material (Fig. 1), which is characterized by a seismic wave velocity intermediate between that of the upper mantle and that of the lower crust, occupies a band corresponding to the western slope of the Apennines. This band of mantle material stretches from Tuscany to Sicily, with various attitude (Locardi & Nicolich, 1992):

- i) north of 41°lat N, the material occurs between the asthenospheric mantle dome and the thinned earth's crust;
- ii) south of the same parallel, it forms an intrusion between the apenninic crust and continental Moho, on the side of the southern Tyrrhenian mantle dome. The Moho flexed in correspondence with the low velocity layer, which is thus delimited by a concave surface at the bottom and by a flat surface on top.

The mantle melts added to the crust, which when re-equilibrated will form a new crust. This process of crustal growth and rooting occurred beneath the western slope of the Apennines. Here the crust thickness was measured being up to 20÷25 km thick. Owing to this magmatic addition it would consequently increase to 30÷45 km.

The literature reports on several cases of underplating as a structure typical of deep crust under conditions of continental rift (Bonatti & Seyler, 1987; Artyushkov *et al.*, 1990; Zorin, 1981) or of continental passive margins above high thermal anomalies (hot mantle plumes or hot regions) (White & McKenzie, 1989; Sleep, 1990; Furlong & Fountain, 1986). In oceanized rift areas, the underplated material is located in the transition zone between the continental and the oceanic crust. In the Apennines example, underplated material was identified just between the Tyrrhenian oceanic sector and the continental lithosphere bordering it eastwards (Fig. 1 and Locardi & Nicolich, 1992).

In the sequence of tectono-magmatic events as depicted by various continental rifting episodes (Bonatti & Seyler, 1987; Hutchinson *et al.*, 1990) underplating is

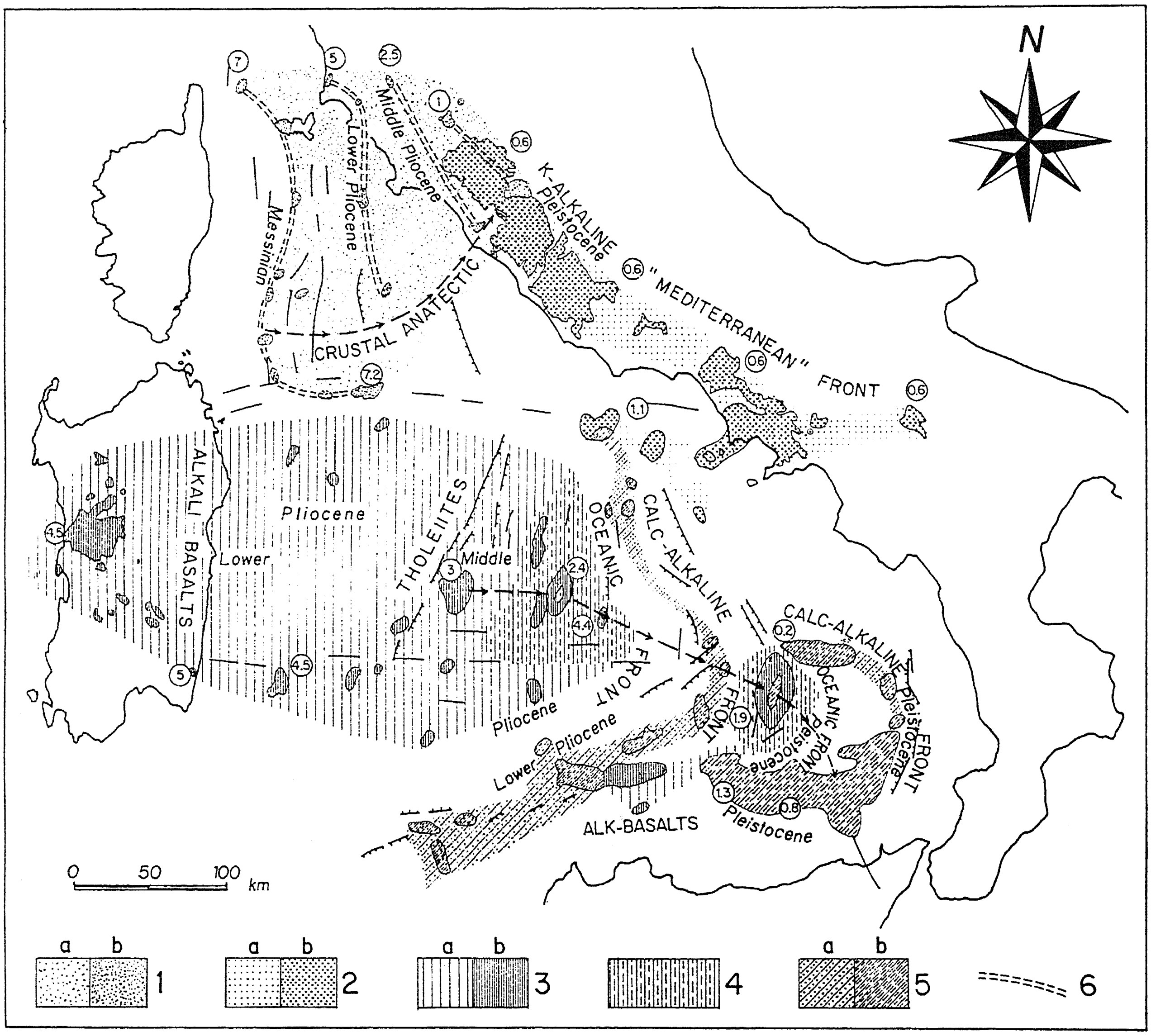

Fig. 2 - Map of the post-Tortonian magmatism (from *Synthetic structural-kinematric map of Italy,* C.N.R., 1989; Locardi, 1992).
1a) Domain of crustal anatectic magmatism ("Tuscan Magmatic Province"); 1b) Main intrusive and effusive edifices; 2a) Domain of potassic volcanism ("Roman Comagmatic Region"); 2b) Main volcanoes; 3a) Domain of mantle-tholeiitic and alkali-basaltic volcanism; 3b) Main volcanoes; 4) Oceanized areas; 5a) Domain of calc-alkalic volcanism; 5b) Main volcanoes; 6) Main eruptive alignments. Numbers in circles refer to absolute ages. Arrows show the direction of hot plume migration.

Carta del magmatismo post-tortoniano (eleborata da Synthetic structural-kinematic map of Italy, *C.N.R., 1989). 1a) Dominio del magmatismo anatettico crostale ("Provincia magmatica toscana"); 1b) Principali apparati intrusivi ed effusivi. 2a) Dominio del vulcanismo potassico ("Provincia comagmatica romana"); 2b) Principali apparati vulcanici. 3a) Dominio del vulcanismo mantellico tholeiitico ed alcali-basaltico; 3b) Principali apparati vulcanici. 4) Aree oceanizzate. 5a) Dominio del vulcanismo calco-alcalino; 5b) Principali apparati vulcanici. 6) Principali assi eruttivi.*
I numeri entro cerchi indicano i valori delle datazioni assolute. Le frecce indicano il verso della migrazione dei diapiri termici.

a pre- and syn-rift process occurring before crustal thinning, and during basin collapse and oceanization. Underplating is accompanied by a regional uplifting and produces the partial melting of the lowermost crust (Griffiths & Campbell, 1990; 1991).

The duration of mantle melts subcrustal accumulation can be inferred from the duration of the regional uplifting that occurs just before the beginning of magmatism.

Underplating does not occur at the same time everywhere because the hot plume above which magmas separate, migrates. Plume migration is caused by the lateral motion of single currents specially by the death and birth of new ascending currents. If ascending currents fade away at the western margin of a hot region while new currents originate at its eastern margin, an easterly migration of the hot plume will occur. Just such a process is occurring in the Tyrrhenian basin with the easterly migration of rifting and magmatism (Fig. 2).

Several authors (White & McKenzie, 1989; Campbell & Griffiths, 1990; Sleep, 1990) suggest that ascending hot plumes in the astenosphere impact the lowermost portion of the lithosphere giving rise to horizontal flows which move away radially from the central hot spot. Such flows warm the lithosphere up pushing and thinning it leading to its fragmentation into microplates. Thus, a migration of continental blocks occurs, together with the formation of marginal basins surrounded by compressive areas.

The age and type of magmatism in the Tyrrhenian sea (Fig. 2) suggest the presence of two independent and asynchronous plumes in the mantle, separated by the 41°N parallel. Both plumes migrate eastwards from the margins of the Sardinian-Corsican block. The northernmost plume is connected with a magmatism that commenced 7÷8 Ma ago contemporaneous with the beginning of the Tyrrhenian rifting process. The southern plume activity dates back only to 5 Ma ago. The migration rate of the northern plume is a little higher than 2 cm/a and from middle Pliocene has changed direction from E to NE. The southern plume moves at a rate of more than 5 cm/a and since the lower Pleistocene has changed its direction from E to SE. The different migration rates of the two plumes are reflected by the different magmatic composition and the different compressive tectonic stress at their fronts.

In the Apennines domain compressive tectonic pulses and migration steps of the foredeep are contemporaneous to the rifting phases occurring in the Tyrrhenian area. This suggests that compressive and extensive structures were both governed by a single geodynamic mechanism.

These tectono-magmatic processes would have occurred shortly after the underplating process. Moreover, because they occurred at different times in the various parts of the basin, underplating would also have been different in time and space. It is of recent age and may still be active beneath the Calabria-Peloritan arc; it is older beneath the northern Apennines.

Other structures are also indicative of the mechanism governing the subcrustal accumulation of mantle-derived melts and the age of such process. These structures correspond to faults which are transverse to the Apennine range, and are not much visible at ground level, whereas they are evident in depth. Here they bring into contact extremely different palaeogeographic domains (Scandone, pers. comm.; Ortolani, pers. comm.) and are much marked in the deep crust-upper mantle structures as shown by DSS profiles (see Fig. 1). These deep-rooted faults penetrating into the mantle and displacing the continental Moho might be the routes along which the subcrustal intrusion of mantle magmas occurred. Such mantle magmas (which can easily be identified with seismic prospections because of the typical seismic waves velocity) form a layer of various thickness and extent depending on the block delimited by two of such deep-rooted faults (Fig. 1).

One of these faults, stretching in the Ancona-Anzio direction, separates the Tuscany-Latium sector (where the underplated material is still rooted on the mantle dome) from the south-central Apennines sector; here this material occurs as an intrusion between the reduced crust and the Moho of the foreland.

Tranversal faults are older than the underplating process, and were re-activated by it (Locardi, 1988b). The question is whether the intrusion of mantle material occurred when the chain geography already had its present outline. If so, the subcrustal sill-type intrusion of several kilometres of mantle material would have caused the differential uplifting of blocks delimited by transversal faults. The strike-slip component of these faults would have the effect of shear stresses governed by the push of magmatic flow extruded by the adjacent mantle dome.

The other case to consider is that, the crust and the covers forming the western side of the Apennines were in a palaeogeographical context, still in the Tyrrhenian basin when the underplating process occurred. This took place in an area above the hot plume from which the magma forming the underplated material, came out. Thus, the upheaval due to the subcrustal accumulation of mantle material would have occurred within the Tyrrhenian domain, as well as the greater part of the tectonic transport of the blocks delimited by the strike-slip faults crossing the Apennines as single tectonic units. The Apennines structural pattern, consisting of a series of compressive arcs closing on strike-slip faults (Locardi, 1988b), may have been governed by such a mechanism.

This second hypothesis gives a better explanation of the sudden palaeogeographic changes characterizing the covers of the strike-slip fault-delimited tectonic blocks.

It should be borne in mind that the subcrustal material is a magmatic melt; shrinkage during its cooling might cause a regional differential subsidence depending upon the underplating age. The cooling time of a 10-km-thick layer of mantle melt is estimated in about 5 Ma.

Moreover, the passive transport of crust and covers over a sliding magma panel could cause fractures and pull-apart basins. Some of the apenninic "grabens" of Plio-Pleistocene age, which are not true grabens, may originate from this mechanism (subcrustal dragging). This phenomenon could more easily be recognized and verified where covers are formed by stiff carbonatic platforms rather than on flysch deposits.

3. CONCLUSIONS

According to seismic profiles, below the crust of the western side of the Apennines there is a 5 to 20 km thick layer of a basic magma, supposed to be of mantle provenance on the basis of seismic wave velocity; this underplating process was caused by a thermal anomaly. It was followed by a regional uplift, by the partial melting of the crust, its thinning, migration and oceanization, with widespread and varied magmatic manifestations.

The time sequence of volcano-tectonic phases suggests that the subcrustal contributions of mantle melts are not synchronous in the various sectors of the Tyrrhenian-Apennines domain. Magmatic evolution data suggest that two mantle plumes are active in the northern and southern Tyrrhenian sea, respectively; these are migrating eastward at various rates. Their present position as well as the distribution and attitude of subcrustal melts are shown on the new Moho map (see Fig. 1), obtained from DSS and other geophysical data.

The crust segments that are now next to each other and form the Apennines, would have been tranferred from the Tyrrhenian domain on the side of the migrating mantle plume and above the subcrustal magma, along routes predetermined by the great strike-slip faults crossing the Apennines. The age of the relative uplift of single blocks would correspond with the underplating age in the different sectors. The beginning of their tectonic transfer would correspond with the beginning of transcurrent motions. Some of the continental basins that are parallel to the Apennines would have originated from differential crust dragging during tectonic transfer. Other basins may be more recent than the emplacement of structural units, and would have formed in response to the subcrustal magma shrinkage during cooling.

If this geodynamic model is assumed, this does not conform to any neotectonic model unless the dynamics of change on the continent are integrated with those in the Tyrrhenian basin. Magma evolution and its relation to mantle domes on top of migrating thermal plumes, also has to be taken into account. A neotectonic map would thus represent the effects of a geodynamic cycle consequent to the uprise and migration of hot plumes starting from the deep mantle.

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