Boll. Soc. Geol. It., Volume Speciale n. 4 (2005), 119-125, 3 ff.

Post-Eocene calcalkaline activity and basin opening in the western and central Mediterranean region: implications for magma source metasomatism linked to Hercynian orogeny

CARLO SAVELLI (*)

ABSTRACT

Distinct, short-lived extension pulses formed the Balearic, Vavilov and Marsili basins at ~22-16, ~8-6 and ~1.9-1.5 Ma. Basin opening was accompanied by migration of arc magmatism from southeastern France to the Aeolian-southeast Tyrrhenian region which is subducted by the Ionian Sea oceanic lithosphere. Formation of the Balearic basin occurred amidst the Oligo-Miocene calcalkaline (orogenic) cycle which affected the Hercynian European lithosphere between Sardinia-Corsica and southeastern France. By contrast, two distinct short-lived periods of formation of oceanic crust in the basins of Vavilov and Marsili predated the adjacent calcalkaline arc volcanism. Chrono-petrological evidence and the adopted geodynamic setting suggest different ages for the calcalkaline volcanism and the subduction-related, metasomatic modifications of its magma source(s) in the area of study. Unlike the calcalkaline activity of the Aeolian arc (~1-0 Ma), that of Sardinia (~33-14 Ma) may reflect a previous metasomatic event probably coinciding with the older Hercynian orogeny.

KEY WORDS: *Central-western Mediterranean, «back-arc» basins, arc volcanism migration, Hercynian metasomatism, subduction*.

RIASSUNTO

Attività calcalcaline e formazione di bacini post-Eocenici nel Mediterraneo centro-occidentale: implicazioni per un evento metasomatico di età Ercinica.

Tre brevi, distinte pulsazioni estensionali hanno dato origine ai bacini balearico, Vavilov e Marsili a ~22-16, ~8-6 e ~1.9-1.5 Ma. L'apertura dei bacini è stata accompagnata da migrazione del vulcanismo di arco dalla Francia sud-orientale alle Eolie e da subduzione di litosfera oceanica del Mar Ionio. La formazione del bacino Baleárico avvenne durante il periodo di attività calcalcalina che ha interessato la litosfera Ercinica tra la Sardegna-Corsica e la Francia sud-orientale. Diversamente, i due brevi periodi di formazione di crosta oceanica nei bacini del Vavilov e Marsili hanno preceduto il relativo vulcanismo calcalcalino di arco. I dati crono-petrologici ed il contesto geodinamico adottato suggeriscono età diverse per le fasi vulcaniche calcalcaline ed i relativi processi metasomatici connessi a subduzione che hanno modificato la composizione delle aree sorgenti del magmatismo orogenico nell'area in studio. L'arco vulcanico eoliano (~1-0 Ma), sovrastando una porzione di litosfera ionica subdotta, riflette una concomitanza tra attività magmatica e relative modificazioni metasomatiche. I prodotti calcalcalini della Sardegna (~33-14 Ma), a differenza di quelli Eoliani, possono essere la conseguenza di una fusione parziale di un cuneo mantellico antico formatosi durante un evento collisionale precedente il vulcanismo stesso e probabilmente connesso con l'orogenesi Ercinica.

TERMINI CHIAVE: *Mediterraneo centro-occidentale, bacini «retro-arco», migrazione di archi vulcanici, metasomatismo Ercinico, subduzione*.

(*) Geologia Marina (ISMAR-CNR), Via Gobetti 101, 40129 Bologna. E-mail: carlo.savelli@bo.ismar.cnr.it

INTRODUCTION

The calcalkaline igneous products are characterized by geochemical signatures such as the high LILE/HFSE (large ion lithophile elements/high field strength elements) ratios that are thought to originate from magma sources the composition of which has been modified by addition of materials brought down to depth during, contemporaneous and previous, subduction processes. Similarly to the extensive Quaternary calcalkaline (orogenic) volcanic associations of the earth convergent margins which overlie slabs of oceanic lithosphere, subduction of the Ionian Sea oceanic lithosphere beneath the SE Tyrrhenian Sea indicates that eruptive activity and metasomatic imprinting of the magma sources are temporally associated. A constant dip to the west of the Ionian-Adria lower plate is a conventionally accepted notion for generation of the post-33 Ma magmatic activity extending from SE France to the Aeolian arc and implies a synchronism of subduction and orogenic volcanism through time. Notwithstanding that subduction and orogenic volcanism are coeval events during the recent geological periods, there are geological evidences indicative of diachronism between old calcalkaline magmatic associations and metasomatic processes in the past (e.g.: DUDÁS *et alii*, 1987, 1991; KEMPTON *et alii*, 1991; WEAVER, 1991; COX, 1992; HAWKESWORTH *et alii*, 1992; STOREY *et alii*, 1992; UTO *et alii*, 1994; TOMMASINI *et alii*, 1995; MORRIS & HOOPER, 1997; WENZEL *et alii*, 1997; COMIN-CHIARAMONTI *et alii*, 1999; PECCERILLO, 1999; FROST *et alii*, 2000; LUTTINEN & FURNES, 2000; MORRIS *et alii*, 2000; SAVELLI, 2000; 2002; SMITHIES & CHAMPION, 2000; FEELEY, 2003; LINDSAY & FEELEY, 2003; GHEZZO, 2004). In the light of time-space distribution of volcanic activity in a portion of the west Mediterranean and adjacent orogens, this paper aims to evaluate whether the calcalkaline event of the Sardinia-southeastern France region (~33-14 Ma) has been subsequent to the enrichment processes of the relative magma sources or not. A diachronism would require the existence of an old subduction beneath Sardinia the polarity of which was most likely different from that linked to the Aeolian Quaternary arc volcanism, with significant implications for the late Cenozoic tectonic and magmatic evolution of the western and central Mediterranean. This area is controlled by a west-directed subduction process akin to those of the «classical» marginal basins at the western rim of the Pacific ocean (see, e.g., KARIG, 1975; SARTORI, 1980; 1981; DOGLIONI *et alii*, 1999 and references therein).

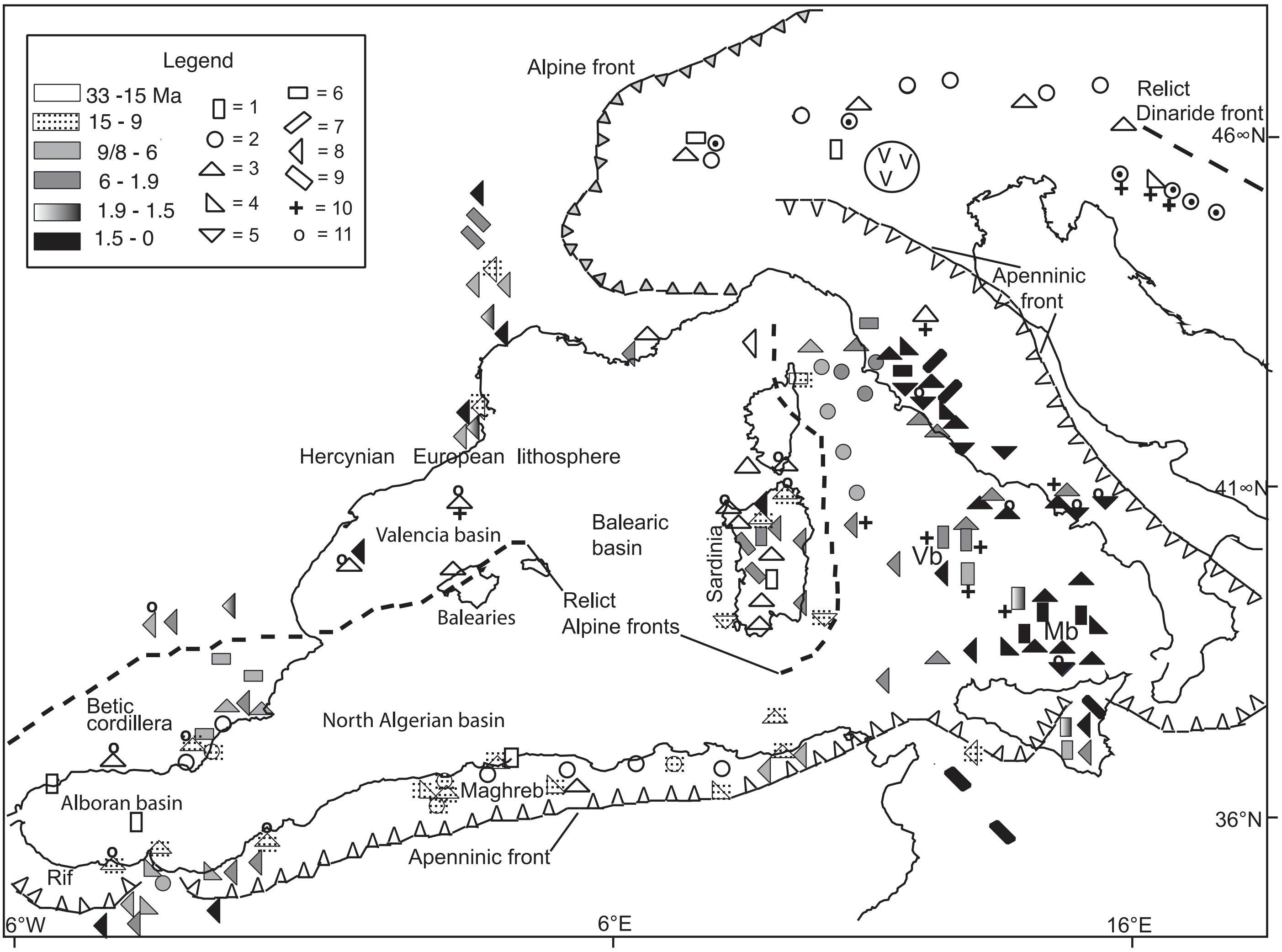

Fig. 1 - Time-space distribution of six magmatic phases (~33-0 Ma) in the Balearic, Vavilov (**Vb**), Marsili (**Mb**) back-arc basins and their peripheral orogens (modified from SAVELLI, 2002). LEGEND, rock types: **1**=tholeiites; **2**=medium-K and high-K calcalkaline plutons (circles with dots = ~54-34 Ma old plutons); **3**=medium-K and high-K calcalkaline volcanics; **4**=shoshonites; **5**=ultrapotassic volcanics; **6**=lamproites; **7**=carbonatites; **8**=intraplate volcanics; **9**=rocks from intraplate, large central volcanoes; **10**=igneuos rocks from deep drillings (DSDP & ODP sites, Neapolitan area and Pieve S. Stefano, central-northern Apennines); **11**=pyroclastic and/or ignimbritic rocks; **VV**=Veneto Oligo-Miocene volcanic district. Granitoids of Eocene age (> 33, < 53 Ma) of the Alps and western Dinarides are indicated by dot and circle.
*– Distribuzione spazio-temorale di sei fasi magmatiche (~33-0 Ma) nei bacini retro-arco Balearico, Vavilov (Vb), Marsili (Mb) e negli orogeni adiacenti (modificato da SAVELLI, 2002). LEGENDA, tipi di rocce: **1**=tholeiiti; **2**=plutoni di affinità calcalcalina medio- e alto-potassica (cerchietti con puntini = plutoni con età di ~54-34 Ma); **3**=vulcaniti di affinità calcalcalina medio- e alto-potassica; **4**=shoshoniti; **5**=vulcaniti ultrapotassiche; **6**=lamproiti; **7**=carbonatiti; **8**=vulcaniti di affinità intraplacca; **9**=grandi edifici vulcanici intraplacca; **10**=roccie ignee recuperate con perforazioni profonde (siti DSDP e ODP, area Napoletana e Pieve S. Stefano); **11**=rocce piroclastiche e/o ignimbritiche; **VV**=distretto vulcanico Oligo-Miocenico del Veneto. Alcuni granitoidi di età Eocenica delle Alpi e Dinaridi occidentali sono indicati da cerchietto e puntino.*

GEOLOGICAL SETTING

The geodynamic scenario adopted for the diverse orogenic domains of the area of study is depicted in fig. 1: the Hercynian European lithosphere is located to the west while the younger Alpine/Apenninic belt, to the east, is subducted by west-dipping Ionian oceanic lithosphere. The relict front of the Alpine orogenic wedge testifies prelate Cretaceous subduction-related collision processes extending from NE Corsica to the Betic cordillera, in internal position with respect to the Neogene Apenninic convergence (from the north Apennines to the Maghrebian and Rifan chains; e.g.: AMODIO-MORELLI *et alii*, 1976; REHAULT *et alii*, 1984; DOGLIONI *et alii*, 1991, 1998, 1999; KELLER & PIALLI, 1994; ARGNANI, 2002; SAVELLI, 2002). The Balearic basin (also named Algero-Provencal or Sardo-Balearic basin) is bordered by the Hercynian domain of Corsica-Sardinia, to the east, and Provence to the north. By contrast, the Tyrrhenian Sea rests on stretched Alpine/Apenninic lithosphere.

The western portion of Sardinia bordering the Balearic basin saw the eruption of abundant volcanics with calcalkaline affinity concomitant with extensional tectonics during the time interval from late Oligocene to mid Miocene (~33-15 Ma ago). Hercynian granitoids are widespread in eastern Sardinia as well as in the western portion of the adjacent Corsica island (e.g., TOMMASINI *et alii*, 1995).

Joint tectonic and magmatic processes which started in the Oligocene have accompanied through time thinning and extension of Hercynian and Alpine lithosphere on one side, and roll-back of the Apenninic compression and basin opening on the other. Extension was most severe in the south Tyrrhenian up to the point to cause magmatic emplacement of MORB-like basalts.

TIME-SPACE DISTRIBUTION OF MAGMATIC PHASES AND BASIN OPENING

Magmatic rocks of variable age (~33-0 Ma) and composition crop out extensively in the central and western Mediterranean region. In the present study they are tentatively subdivided according to their ages and serial affinities (see, e.g., SAVELLI, 1984, 2002 and references therein; KASTENS *et alii*, 1986, 1987, 1990; FRANCALANCI & MANETTI, 1994). Inspection of fig. 1 shows the time-space distribution of six igneous phases. They include a large variety of magmatic associations such as, e.g., medium-K calcalkaline, high-K calcalkaline, shoshonitic, ultrapotassic, lamproitic, carbonatitic, tholeiitic and Na-alkaline. Basalts with tholeiitic affinity were erupted in the central Tyrrhenian oceanic domain as well as in the volcanic arcs of Sardinia and Aeolian area. Also, the silica saturation of magmatic products in the region of study is highly variable ranging from (undersaturated) basic to intermediate and to acidic magma types which were most likely derived from both the mantle and the felsic crust.

A post-33 Ma migration of volcanism from southeastern France to the Aeolian arc was accompanied by successive opening of «back-arc» basins, i.e. the Balearic (~21-16 Ma), the Vavilov (~8-6 Ma) and the Marsili (~1.9-1.5 Ma). The histogram of chronological data of fig. 2 shows the Oligo-Miocene (~33-15 Ma), Pliocene (~6-1.9 Ma) and Quaternary (~1.5-0 Ma) magmatic phases of the southeastern France-Sardinia-Tyrrhenian Sea-western Italy region and their relationships with basin openings. During the first igneous phase (~33-15 Ma), opening of the Balearic basin has been accompanied by the drift of Sardinia-Corsica away from the Provencal margin. Paleomagnetic evidence by MONTIGNY *et alii* (1981) indicates the short time span of ~20.5-19 Ma for the ~30° anticlockwise rotation of the two islands. REHAULT *et alii* (1984) envisage ~18 Ma as the age of cessation of drifting, whereas ~16/15 Ma are suggested by VIGLIOTTI & KENT (1990), VIGLIOTTI & LANGENHEIM (1995) and OTTAVIANI-SPELLA *et alii* (2001). In Sardinia sub-alkaline basalts with a tholeiitic tendency group mainly in the middle period (~20-16 Ma, Burdigalian) of the calcalkaline volcanic cycle (SAVELLI *et alii*, 1979; MATTIOLI *et alii*, 2000).

Besides the Hercynian Europe (i.e., Sardinia, southeastern France, Balearics and Valencia basin) calcalkaline products belonging to the ~33-15 Ma event are widespread also in western regions of the relict Alpine orogen. The Betic cordillera and the Maghrebian chain, between the Alpine and the Apenninic front of subduction were sites of volcanic activity of calcalkaline and tholeiitic affinity. This volcanism was accompanied by magmatic emplacement of granitoids with dominant acidic compositions (BELLON, 1981). Intrusive rocks with similar compositions are conspicuously lacking in the European Hercynian region.

In the Apenninic thrust belt and Tyrrhenian margin of the Italian peninsula there is no evidence of exposed, primary Oligo-Miocene «andesitic» volcanic edifices. By contrast, numerous volcanoclastic calcalkaline horizons are interbedded in sediments of Oligo-Miocene age from the Northern and Southern Apennines, the Sicilian Maghrebids and the north African and Betic internal thrusts (e.g.: SELLI, 1948; CARMISCIANO & SPADEA, 1973; BORSETTI *et alii*, 1984; MEZZETTI *et alii*, 1991; BALOGH *et alii*, 1993; CRITELLI & MONACO, 1993; GUERRERA *et alii*, 1993; ANELLI *et alii*, 1994; PUGLISI, 1994; MONTANARI *et alii*, 1995; AMOROSI *et alii*, 1995; ODIN *et alii*, 1997, 1997a; CIBIN *et alii*, 1998; DE CAPOA *et alii*, 2002; MATTIOLI *et alii*, 2002). Overall, these volcanoclastics which yielded K/Ar datings ranging from ~32 to ~18 Ma show prevailingly intermediate and acidic calcalkaline compositions. An exception to this are the volcanic clasts from the Canetolo unit of the Northern Apennines with prevailingly mafic-intermediate affinity (MATTIOLI *et alii*, 2002).

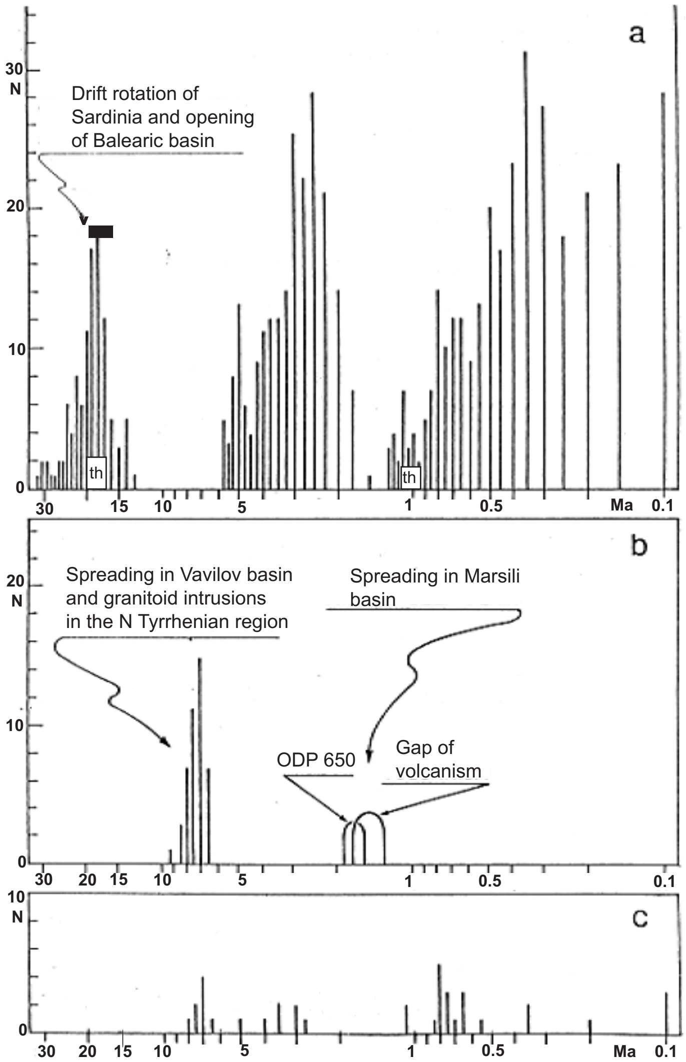

Fig. 2 - Radiometric age histogram of magmatic products of the Sardinia-Tyrrhenian Sea-western Italy region showing: (**a**) the Oligo-Miocene, Pliocene and Quaternary magmatic phases (~33-14; ~6-1.9 and ~1.5-0 Ma, respectively) and the opening of the Balearic basin (~21-16 Ma); (**b**) the openings of the Vavilov and Marsili basins (~8-6 and ~1.9-1.5 Ma); (**c**) the datings of magmatic rocks from the Tyrrhenian seafloor; **th**=tholeiites.

*– Istogramma di età radiometriche di prodotti magmatici della regione Sardegna-Mar Tirreno-Italia occidentale che mostra: (**a**) le fasi magmatiche di età Oligo-Miocenica, Pliocenica e Quaternaria (~33-15; ~6-1,9 e ~1,5-0 Ma, rispettivamente) e l'apertura del bacino Balearico (~21-16 Ma); (**b**) le aperture dei bacini del Vavilov e Marsili (~8-6 e ~1.9-1.5 Ma); (**c**) le datazioni di rocce magmatiche del fondale Tirrenico; **th**=tholeiiti.*

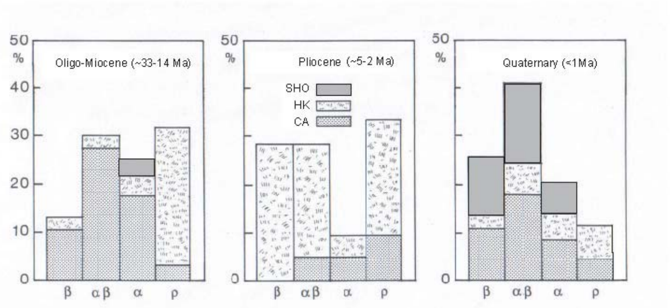

Fig. 3 - Frequency distribution of serial character of calcalkaline volcanics of the cycles: Oligo-Miocene (Sardinia; 92 rocks), Pliocene (Anchise seamount, Ponza island, Volturno plain; 21 rocks) and Quaternary (Aeolian arc and southeastern Tyrrhenian Sea, 250 rocks). Rock type: (β) = basalt and tholeiite ($\leq$ 52 wt% SiO_2), ($\alpha\beta$) = andesitic basalt (52-57 wt% SiO_2); (α) = andesite (57-63 wt% SiO_2), (ρ) = rhyolite and dacite ($\geq$ 63 wt% SiO_2). Serial affinity: medium- and low-K calcalkaline (CA), high-K calcalkaline (HK), shoshonitic including leucite bearing products (SHO); modified from ARGNANI *et alii* (1995).
– Distribuzione della frequenza del carattere seriale di prodotti vulcanici calcalcalini dei cicli: Oligo-Miocenico (Sardegna; 92 rocce), Pliocenico (seamount Anchise, isola di Ponza e sottosuolo della piana del Volturno; 21 rocce) e Quaternario (arco Eoliano e Tirreno sud-orientale; 250 rocce). Tipo di roccia: (β) = basalto e tholeiite ($SiO_2 \leq$ 52%), ($\alpha\beta$) = andesite basaltica (SiO_2 52-57%); (α) = andesite (SiO_2 57-63%), (ρ) = riolite e dacite ($SiO_2 \geq$ 63%). Affinità seriale: calcalcalina medio- e basso-potassica (CA), calcalcalina alto-potassica (HK), shoshonitica, compresi i prodotti a leucite (SHO); modificato da ARGNANI et alii *(1995).*

In the Tyrrhenian Sea the short-lived, late Miocene period of activity (~8-6 Ma) was characterized by a pulse of extensional tectonics. The Vavilov basin saw eruption of E-MORB tholeiites (DSDP drilling 373A, BARBERI *et alii*, 1978), while calcalkaline granitoids (islands of Elba, Montecristo and seamount Vercelli), and trachy-dacites and andesites (Capraia island; BORELLI *et alii*, 2003) were emplaced in the north Tyrrhenian Sea region to the north of the 41° parallel structural discontinuity. In this period magmatic activity was conspicuously lacking in all of the peri-Tyrrhenian areas (fig. 2). The regional distribution of the highly different late Miocene products is most likely a consequence of the tectonic framework, in other words the intensity of lithosphere extension and thinning processes may have been much larger in the south than in the north Tyrrhenian (SAVELLI, 1988; ARGNANI & SAVELLI, 2001 and references therein).

Also the late Pliocene-early Quaternary period (~1.9-1.5 Ma; fig. 2) saw an extensional pulse which has been accompanied by eruption of basalts with E-MORB/calcalkaline affinity in the Marsili basin (ODP drilling 650, BECCALUVA *et alii*, 1990). Even though such spreading event was short-lived and restricted to a small area of the southeast Tyrrhenian Sea it appears to have had regional implications since it is arduous to recognize, outside the basin, coeval magmatic products.

The fast openings of the Vavilov and Marsili have been followed by the Pliocene and Quaternary igneous phases (~6-1.9 and ~1-0 Ma) which comprise products of Na-alkaline (anorogenic), calcalkaline (orogenic) and tholeiitic serial affinity that reflect emplacement in distinct geodynamic domains (fig. 1). During these periods the Tyrrhenian Sea region saw intra-basinal formation of large seamounts with dominant vertical tectonism (SAVELLI & GASPAROTTO, 1994; FAGGIONI *et alii*, 1995; MARANI & TRUA, 2002). Such magmatic and tectonic processes as well as their periodicity can be related to strong pulses alternating with periods of quiescence of roll-back.

Besides the orogenic and tholeiitic volcanism, also the anorogenic (intra-plate) manifestations which erupted mostly in the time span ~5-0.1 Ma are an important source of information on the Mediterranean dynamic processes subsequent to the Vavilov spreading. Differently from the Oligo-Miocene orogenic products, rocks with intra-plate affinity are present in both the western and eastern sectors of the island of Sardinia. Inspection of fig. 1 suggests that, overall, anorogenic volcanics are younger if compared with the age of rocks located at similar distance from the active front of roll-back above the west-dipping subduction of Ionian oceanic lithosphere.

DISCUSSION

Inspection of fig. 2 shows that the back-arc spreading of Vavilov and Marsili basins associated to west-dipping subduction predated the Pliocene and the Quaternary (~6-1.9 and ~1.5-0 Ma) volcanic phases. By contrast, the opening of Balearic basin occurred amidst the period of calcalkaline volcanic activity (~33-15 Ma). The emplacement of tholeiitic lavas that is thought to reflect strong extension took place in clearly distinct times with respect to the orogenic products of Sardinia and the Aeolian-southeast Tyrrhenian region (SAVELLI *et alii*, 1979; BECCALUVA *et alii*, 1985; MATTIOLI *et alii*, 2000). It coincided more or less with the magmatic climax of Sardinia (~21-17 Ma; fig. 2) and it has been a precursor, at ~1 Ma, of the Aeolian volcanism. Regarding the serial character of orogenic products, fig. 3 shows that volcanics of shoshonitic affinity are widespread in the Aeolian arc and scarce in Sardinia. Shoshonite rocks are considered to derive from magma sources which underwent deep-seated metasomatism. Seismicity generated by west-dipping subduction beneath the south Tyrrhenian basin reaches depth of ~500 km. Given a spreading rate of ~4-5 km/Ma such geodynamic scenario is compatible with a setting up of Ionian lithosphere consumption approximately subsequently to the wane of Sardinian orogenic activity and ahead of the Vavilov spreading (i.e., between ~20/15 and ~8 Ma).

With respect to formation of the Alpine orogenic wedge of the study area one can not exclude Hercynian subduction in the European lithosphere, a process which could have provided the metasomatic modification of mantle source(s) of calcalkaline volcanism in Sardinia.

Because the orogenic rocks of the first phase (~33-15 Ma) crop out in both Hercynian and Alpine regions (fig. 1; NE Corsica, Betic and Kabylian regions) an open question may be whether the CA metasomatic imprinting of their magma sources took place during or prior to Alpine collision. To begin with, it is considered that the Alpine orogenic wedge was built above a SE-dipping subduction of European lithosphere (see, e.g., AMODIO-MORELLI *et alii*, 1976; DOGLIONI *et alii*, 1999) which matched the present-day dip of subduction beneath the Alpine chain s.s. In this case the calcalkaline volcanic suite of the Sardinia region should reflect an old metasomatic event which most likely occurred during the previous, Hercynian orogeny as a foreland setting of the island at the times of Alpine collision cannot coincide with a calcalkaline imprinting.

An opposite view contemplates the formation of the Alpine orogenic wedge due to persistent NE- and E-dipping subduction of Africa/Ionian/Adria lithosphere. The high pressure-low temperature (blueschists) facies metamorphism of the west-verging core complex of NE Corsica is dated at ~55-40 Ma ago, i.e. prior to the start at ~33 Ma of extension-related calcalkaline activity in Sardinia (JOLIVET *et alii*, 1998; BRUNET *et alii*, 2000). Also, ~38-33 Ma is a minimum age estimate of exhumation of HP/LT metamorphic rocks of the Calabrian orogenic wedge (ROSSETTI *et alii*, 2002).

The core complex portions exhumed more to the east in the north Tyrrhenian-Tuscany region exhibit younger ages of blueschist metamorphism (~30-25 and ~25-20 Ma). The NW vergence of thrusting at the time of severe Alpine compression and crustal thickening (~55-40 Ma) argues against concomitant occurrence of a NW-dipping (synthetic) descent of Adria/Ionian lithosphere producing metasomatic modification of the mantle beneath Corsica-Sardinia and Provence. In fact, the main vergence of an accretionary prism is, overall, antithetic relative to the dip of subducting lithosphere. Moreover, a long-lasting subduction of Adria-Ionian lithosphere can hardly explain how the Alpine (synthetic) build up shifted to the Apenninic thrust belt which is a younger antithetic structure (E-verging thrusting and W-dipping subduction) with dominant roll-back.

As a consequence, metasomatic modification of mantle sources of calcalkaline volcanis in Sardinia took most likely place in concomitance with the Hercynian orogeny rather than during the Alpine phase of convergence.

CONCLUSIONS

Three distinct, short-lived pulses of extension and magmatic activity formed the Balearic, Vavilov and Marsili basins at ~22-16, ~8-6 and ~1.9-1.5 Ma.

Formation of the Balearic basin occurred during the peak of the Oligo-Miocene calcalkaline (orogenic) activity which affected the Hercynian European lithosphere between Sardinia-Corsica and southeastern France. By contrast, the two short-lived pulses of Vavilov and Marsili spreading in the Alpine/Apenninic domain of the south Tyrrhenian Sea region predated the adjacent calcalkaline arc volcanism.

The Oligo-Miocene calcalkaline phase (~33-14 Ma) was linked to widespread extensional tectonics and geothermal rise that affected clearly distinct orogenic domains, the Hercynian European lithosphere and the Alpine belt. This igneous phase postdated the HP/LT metamorphic events of the relic orogenic wedge in the north Tyrrhenian (~55-40 Ma) and in Calabria (~38-33 Ma).

The joint examination of chrono-petrological data and adopted geodynamic setting in the area of study suggests the existence of diverse timing between the magmatic emplacement of calcalkaline volcanism and the subdution-related metasomatic modification of its magma source(s). The metasomatic event appears to predate the calcalkaline activity of Sardinia-southeastern France and to be almost contemporaneous to that of the Aeolian-southeast Tyrrhenian region.

Vavilov and Marsili are proper supra-subduction *back-arc basins*. By contrast, the Balearic most likely is not a similar structure as its formation has not been accompanied by concomitant foreland lithosphere consumption. In this view, it may be useful to distinguish better one from the other the two Mediterranean regions of orogenic activity and basin opening by adopting different terms. For the Balearic Sea region a term like *internal basin* instead of *back-arc basin* could be appropriate.

ACKNOWLEDGEMENTS

The quality of the paper has been improved by two anonymous reviewers. ISMAR-Bologna contribution N. 1444.

REFERENCES

AMODIO-MORELLI L., BONARDI G., COLONNA V., DIETRICH D., GIUNTA G., IPPOLITO F., LIGUORI V., LORENZONI S., PAGLIONICO A., PERRONE V., SCANDONE P. & ZANETTIN-LORENZONI E. (1976) - *L'arco calabro-peloritano nell'orogene Appenninico-maghrebide*. Mem. Soc. Geol. It., **17**, 1-60.

AMOROSI A., RICCI LUCCHI F. & TATEO F. (1995) - *The lower Miocene siliceous zone: a marker in the paleogeographic evolution of the northern Apennines*. Palaeogeogr., Palaeoclimatol., Palaeoecol., **118** (1-2), 131-149.

ANELLI L., GORZA M., PIERI M. & RIVA M. (1994) - *Surface well data in the northern Apennines (Italy)*. Mem. Soc. Geol. It., **48**, 461-471.

ARGNANI A., MARANI M., SAVELLI C. & GALASSI B. (1995) - *Migrazione del vulcanismo di arco cenozoico ed apertura di piccoli bacini oceanici nel contesto geodinamico intraorogenico del Mar Tirreno meridionale: un riesame*. Scritti e Documenti, Accad. Naz. delle Scienze, **14**, 377-396.

ARGNANI A. & SAVELLI C. (2001) - *Magmatic signature of episodic backarc rifting in the southern Tyrrhenian Sea*. In: Ziegler P., Cavazza W., Robertson A.H., Crasquin-Soleau (Eds.), Peri-Tethys Memoir 6: PeriTethyan Rift/Wrench Basins and Passive Margins. Mem. Museum Nat. Histoire Natural (Paris), **186**, 735-754.

ARGNANI A. (2002) - *The northern Apennines and the kinematics of Africa Europe convergence*. Boll. Soc. Geol. It., Special Volume (Geological and geodynamic evolution of the Apennines), **1**, 47-60.

BALOGH K., DELLE ROSE M., GUERRERA F., RAVASZ-BARANYAI L. & VENERI F. (1993) - *New data concerning the inframiocenic «Bisciaro» volcaniclastic event (Umbro-Marche Apennines) and comparison with similar occurrences*. Giorn. Geol., **55** (2), 83-104.

BARBERI F., BIZOUARD H., CAPALDI G., FERRARA G., GASPARINI P., INNOCENTI F., JORON J.L., LAMBERT B., TREUIL M. & ALLEGRE C. (1978) - *Age and nature of basalts from the Tyrrhenian abyssal plain*. Initial Reports DSDP, **42** (1), 509-514.

BECCALUVA L., GABBIANELLI G., LUCCHINI F., ROSSI P.L. & SAVELLI C. (1985) - *Magmatic character and K/Ar ages of volcanics dredged from the Eolian seamounts: implications for the geodynamic evolution of the southern Tyrrhenian Sea*. Earth Plan. Sci. Lett., **74**, 187-208.

BECCALUVA L., BONATTI E., DUPUY C., FERRARA G., INNOCENTI F., LUCCHINI F., MACERA P., PETRINI R., ROSSI P.L., SERRI G., SEYLER M. & SIENA F. (1990) - *Geochemistry and mineralogy of volcanic rocks from ODP Sites 650, 651, 655 and 654 in the Tyrrhenian Sea*. In Kastens K.A., Mascle J. *et alii*, Proceedings of the Ocean Drilling Program, Scientific Results, **107**, 49-74.

BELLON H. (1981) - *Chronologie radiometrique (K/Ar) des manifestations magmatiques autour de la Mediterranee occidentale entre 33 et 1 Ma*. In: Wezel F.C., Ed., Sedimentary Basins of Mediterranean Margins, CNR Italian Project of Oceanography, Tecnoprint, Bologna, 341-360.

BELLON H., BORDET P. & MONTENAT C. (1983) - *Chronologie du magmatisme neogene des Cordilleres betiques (Espagna meridionale)*. Bull. Soc. Geolog. de France, **25**, 205-217.

BORELLI E., GROPPELLI G., PASQUARÈ G., SERRI G., TESTA B. & WIJBRANS J. (2003) - *Evoluzione geologica dell'isola di Capraia (Arcipelago Toscano) nel quadro geodinamico del Tirreno settentrionale*. Convegno in memoria di R. Selli e R. Sartori, Bologna 11-12 dicembre 2003, Geoacta, **3** (suppl. CD), 19-22.

BORSETTI A.M., CATI F., MEZZETTI R., SAVELLI C. & TONI G.C. (1984) - *Le intercalazioni vulcanoclastiche nei sedimenti oligo-miocenici dell'Appennino settentrionale (dati petrologici, K/Ar e micropaleontologici)*. Giorn. Geol., **45**, 159-198.

BRUNET C., MONIE P., JOLIVET L. & CADET J-P. (2000) - *Migration of compression and extension in the Tyrrhenian Sea, insights from 40Ar/39Ar ages on micas along a transect from Corsica to Tuscany*. Tectonophys., **321**, 127-155.

CARMISCIANO R. & SPADEA P. (1973) - *Cineriti riodacitiche mediomioceniche presso Piazza Armerina (Sicilia)*. Geol. Romana, **12**, 205-225.

CIBIN U., TATEO F., CATANZARITI R., MARTELLI L. & RIO D. (1998) - *Composizione, origine ed età del vulcanismo andesitico oligocenico inferiore dell'Appennino settentionale: le intercalazioni vulcano-derivate della formazione di Ranzano. Composition, origin and age of the early Oligocene andesitic volcanism of the northern Apennines: the volcaniclastic beds of the Ranzano formation*. Boll. Soc. Geol. It., **117**, 569-591.

COMIN-CHIARAMONTI P., CUNDARI A., DEGRAFF J.M., GOMES C.B. & PICCIRILLO E.M. (1999) - *Early Cretaceous-Tertiary magmatism in Eastern Paraguay (western Paraná basin): geological, geophysical and geochemical relationships*. J. Geodynamics, **28** (4-5), 375-391.

COX K.G. (1992) - *Karoo igneous activity, and the early stages of the break-up of Gondwanaland*. In: Magmatism and the causes of continental break-up. Geolog. Soc. Special Public., **68**, 137-148.

CRITELLI S. & MONACO C. (1993) - *Depositi vulcanoclasici nell'unità del flysch calabro-lucano (complesso liguride, Appennino meridionale). Volcaniclastic deposits of Calabro-lucanian flysch (Liguride complex, southern Apennines)*. Boll. Soc. Geol. It., **112**, 121-132.

DE CAPOA P., DI STASO A., GUERRERA F., PERRONE V., TRAMONTANA M. & ZAGHLOUL M.N. (2002) - *The lower Miocene volcaniclastic sedimentation in the Sicilian sector of the Maghrebian flysch basin; geodynamic implications*. Geodin. Acta, **15** (2), 141-157.

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

DOGLIONI C., MONGELLI F. & PIALLI G. (1998) - *Boudinage of the Alpine belt in the Apenninic back-arc*. Mem. Soc. Geol. It., **52**, 457-468.

DOGLIONI C., GUEGUEN E., HARABAGLIA P. & MONGELLI F. (1999) - *On the origin of west-directed subduction zones and applications to the western Mediterranean*. Geol. Soc. London, Spec. Public., **156**, 541-561.

DUDÁS F.O., CARLSON R.W. & EGGLER D.H. (1987) - *Regional middle Proterozoic enrichment of the subcontinental mantle source of igneous rocks from central Montana*. Geology (Boulder), **15**, 22-25.

DUDÁS F.O. (1991) - *Geochemistry of igneous rocks from the Crazy mountains, Montana, and tectonic models for the Montana alkali province*. J. Geophys. Res., **96** (B8), 13261-13277.

FAGGIONI O., PINNA E., SAVELLI C. & SCHREIDER A. (1995) - *Geomagnetism and age study of Tyrrhenian seamounts*. Geophys. J. Intern., **123**, 915-930.

FEELEY T.C. (2003) - *Origin and tectonic implications of across-strike geochemical variations in the Eocene Absaroka volcanic privince, U.S.* J. of Geology, **111**, 329-346.

FRANCALANCI L. & MANETTI P. (1994) - *Geodynamic models of the southern Tyrrhenian region: constraints from petrology and geochemistry of the Aeolian volcanic rocks*. Boll. Geofis. Teor. e Appl., **36**, 283-292.

FROST C.D., FROST B.R., HULSEBOSCH T.P & SWAPP S.M. (2000) - *Origin of the Charnockites of the Louis Lake Batholith, Wind River Range, Wyoming*. J. Petrol., **41** (12), 1759-1776.

GHEZZO C. (2004) - *Hercynian magmatism in the Sardinia-Corsica microplate: implications for late Paleozoic regional tectonic evolution*. 32° Int. Geol. Congr., Florence, Italy, August 20-28, 2004, Abstract, part 2, p. 227.

GUERRERA F., MARTIN-ALGARRA A. & PERRONE V. (1995) - *Late Oligocene-Miocene syn-/late-orogenic successions in western and central Mediterranean chains from the Betic cordillera to the south Apennines*. Terra Nova, **5**, 525-544.

HAWKESWORTH C.J., GALLAGHER K., KELLEY S., MANTOVANI M., PEATE D.W., REGELOUS M. & ROGERS N.W. (1992) - *Paranà magmatism and the opening of the South Atlantic*. In: Magmatism and the causes of continental break-up. Geolog. Soc. Special Public., **68**, 221-240.

JOLIVET L., FACCENNA C., GOFFÈ B. *et alii* (1998) - *Midcrustal shear zones in postorogenic extension: example from the northern Tyrrhenian Sea*. J. of Geophys. Res., **103** (B6), 12123-12160.

KARIG D.E. (1975) - *Basin genesis in the Philippine Sea*. Initial Repts. DSDP, **31**, 857-879.

KASTENS K., MASCLE J., AUROUX C., BONATTI E., BROGLIA C., CHANNELL J.E.T, CURZI P., EMEIS K.C., GLASON G., HASEGAWA S., HIEKE W., MASCLE G., MCCOY F., MCKENZIE J., MASCLE G., MENDELSON J., MUELLER C., REHAULT J-P., ROBERTSON A., SARTORI R., SPROVIERI R. & TORII M. (1986) - *Young Tyrrhenian Sea evolved very quickly*. Geotimes, **31** (8), 11-14.

KASTENS K.A., MASCLE J. *et alii* (1987) - Proceedings of the Ocean Drilling Program Init. Repts. (A), **107**, 1013 p.

KASTENS K.A., MASCLE J. *et alii* (1990) - Proceedings of the Ocean Drilling Program, Scientific Results, **107**, College Station TX, 772 p.

KEMPTON P.D., FITTON J.G., HAWKESWORTH C.J. & ORMEROD D.S. (1991) - *Isotopic and trace element constraints on the composition and evolution of the lithosphere beneath the southwestern United States*. J. Geophys. Res., **96** (B8), 13713-13735.

KELLER J.V.A., MINELLI G. & PIALLI G. (1994) - *Anatomy of late orogenic extension: the northern Apennines case*. Tectonophys., **238**, 275-294.

LINDSAY C.R. & FEELEY T.C. (2003) - *Magmagenesis at the Eocene Electric Peak-Sepulcher Mountain complex, Absaroka Volcanic Province USA*. Lithos, **67** (1-2), 53-76.

LUTTINEN A.V. & FURNES H. (2000) - *Flood Basalts of Vestfjella: Jurassic Magmatism Across an Archaean-Proterozoic Lithospheric Boundary in Dronning Maud Land, Antarctica*. J. of Petrology, **41** (8), 1271-1305.

MARANI M.P. & TRUA T. (2002) - *Thermal constriction and slab tearing at the origin of a superinflated spreading ridge; Marsili Volcano (Tyrrhenian Sea)*. J. Geophys. Res., B, **107** (9), 2188-2203.

MATTIOLI M., GUERRERA F., TRAMONTANA M., RAFFAELLI G. & D'ATRI M. (2000) - *High-Mg Tertiary basalts in Southern Sardinia (Italy)*. Earth Planet. Scie. Lett., **179**, 1-7.

MATTIOLI M., DI BATTISTINI G. & ZANZUCCHI G. (2002) - *Petrology, geochemistry and age of the volcanic clasts from the Canetolo unit (northern Apennines, Italy)*. Boll. Soc. Geol. It., Special Volume (Geological and geodynamic evolution of the Apennines), **1**, 399-416.

MEZZETTI R., MORANDI N., TATEO F. & DONDI M. (1991) - *Il contributo vulcanoderivato in successioni pelitiche oligo-mioceniche dell'Appennino settentrionale*. Giorn. Geol., **53** (2), 167-185.

MONTANARI A., CAREY S., COCCIONI R. & DEINO A. (1994) - *Early Miocene tephra in the Apennine pelagic sequence: an inferred Sardinian provenance and implications for western Mediterranean tectonics*. Tectonics, **13** (5), 1120-1134.

MONTIGNY R., EDEL J.B. & THUIZAT R. (1981) - *Oligo-Miocene rotation of Sardinia: K-Ar ages and paleomagnetic data of Tertiary volcanics*. Earth Planet. Scie. Lett., **54**, 261-271.

MORRIS G.A. & HOOPER P.R. (1997) - *Petrogenesis of the Colville igneous complex, NE Washington: Implications for Eocene tectonics in the U.S. Cordillera*. Geology, **25** (9), 831-834.

MORRIS G.A., LARSON P.B. & HOOPER P.R. (2000) - *«Subduction style» magmatism in a non-subduction setting; the Colville igneous complex, NE Washington State, USA*. J. Petrol., **41** (1), 43-67.

ODIN G. S., D'ATRI F., TATEO F., COSCA M. & HUNZIKER J.C. (1997) - *Integrated stratigraphy near the Oligocene/Miocene boundary in the Piedmont basin (Italy):biostratigraphy and geochronology*. Developments in Palaeontology and Stratigraphy, Monograph, **15**, 209-219.

ODIN G. S., AMOROSI A., TATEO F., COCCIONI R., COSCA M., NEGRI A., PINI G.A. & HUNZIKER J.C. (1997a) - *Integrated stratigraphy (biostratigraphy and geochronology) of the early Miocene sequence from the Emilian Apennines (Italy)*. Developments in Palaeontology and Stratigraphy, Monograph, **15**, 221-247.

OTTAVIANI-SPELLA M.-M., GIRARD M., ROCHETTE P., CHEILLETZ A. & THINON M. (2001) - *Le volcanisme acide burdigalien du sud de* *la Corse: petrologie, datation K-Ar, paleomagnetism*. C.R. Acad. Sci. Paris, **333**, 113-120.

PECCERILLO A. (1999) - *Multiple mantle metasomatism in central-southern Italy: geochemical effects, timing and geodynamic implications*. Geology, **27** (4), 315-318.

PUGLISI D. (1994) - *Caratteri petrochimici delle arenarie delle unità torbiditiche oligo-mioceniche della Sicilia nord-orientale*. Mineral. Petrogr. Acta, **37**, 393-415.

REHAULT J.P., BOILLOT G. & MAUFFRET A. (1984) - *The western Mediterranean basin geological evolution*. Mar. Geol., **55**, 447-477.

ROSSETTI F., FACCENNA C., GOFFÈ B., FUNICIELLO R. & MONIÈ P. (2002) - *Tectono-metamorphic evolution of the ophiolite-bearing HP/LP Gimigliano-Monte Reventino unit (Gimigliano, Sila Piccola): Insights for the tectonic evolution of the Calabrian Arc.* Boll. Soc. Geol. It., **121**, 51-67.

SARTORI R. (1980) - *Tectonic significance of the sedimentary column at Site 449 (western Parece Vela Basin), Deep Sea Drilling Project Leg 59*. Initial Reports of the Deep Sea Drilling Project, **59**, 609-614.

SARTORI R. (1981) - *Evolution of tectonic and volcanic processes in the Parece Vela interarc basin (Philippine Sea)*. Rend. Soc. Geol. It., **4** (3), 301-304.

SAVELLI C., BECCALUVA L., DERIU M., MACCIOTTA G. & MACCIONI L. (1979) - *K-Ar geochronology and evolution of the Tertiary «calcalkalic» volcanism of Sardinia (Italy)*. J. Volcanol. and Geother. Res., **5**, 257-269.

SAVELLI C. (1984) - *Evoluzione del vulcanismo cenozoico (da 30 Ma al presente) nel Mar Tirreno e nelle aree circostanti: ipotesi geocronologica sulle fasi dell'espansione oceanica*. Boll. Soc. Geol. It., **27**, 111-119.

SAVELLI C. (1988) - *Late Oligocene to Recent episodes of magmatism in and around the Tyrrhenian Sea: Implications for the processes of opening in a young inter-arc basin of intra-orogenic (Mediterranean) type*. Tectonophys., **146**, 163-181.

SAVELLI C. & GASPAROTTO G. (1994) - *Calcalkaline magmatism and rifting of the deep-water volcano of Marsili (Aeolian back-arc, Tyrrhenian Sea)*. Mar. Geol., **119**, 137-147.

SAVELLI C. (2000) - *Subduction-related episodes of K-alkaline magmatism (15-0 Ma) and geodynamic implications in the north Tyrrhenian-central Italy region: a review*. J. Geodynamics, **30**, 575-591.

SAVELLI C. (2002) - *Time-space distribution of magmatic activity in the western Mediterranean and peripheral orogens during the past 30 Ma (a stimulus to geodynamic considerations)*. J. Geodynamics, **34**, 99-126.

SELLI R. (1948) - *Una sabbia vulcanica Oligocenica nel subappennino bolognese*. Acc. Naz. Lincei, Rdc. Cl. Sci. fis. mat. nat., s. **8** (4), 88-93.

SMITHIES R.H. & CHAMPION D.C. (2000) - *The Archaean High-Mg Diorite Suite: Links to Tonalite-Trondhjemite-Granodiorite Magmatism and Implications for Early Archaean Crustal Growth*. J. Petrol., **41** (12), 1653-1671.

STOREY B.C., ALABASTER T., HOLE M.J., PANKHURST R.J. & WEVER H.E. (1992) - *Role of subduction-plate boudary forces during initial stages of Gonwana break-up: evidence from the proto-Pacific margin of Antarctica.* In: *Magmatism and the causes of continental break-up*. Geolog. Soc. Special Public., **68**, 149-163.

TOMMASINI S., POLI G. & HALLIDAY A.N. (1995) - *The role of sediment subduction and crustal growth in Hercynian plutonism: Isotopic and trace element evidence from the Sardinia-Corsica batholith.* J. Petrol., **36** (5), 1305-1332.

UTO K., TAKAHASHI E., NAKAMURA E. & KANEOKA I. (1994) - *Geochronology of alkali volcanism in Oki-Dogo island, SW Japan: geochemical evolution of basalts related to the opening of the Japan Sea*. Geochemical Journal, **28**, 431-449.

VIGLIOTTI L. & KENT V.D. (1990) - *Paleomagnetic results of Tertiary sediments from Corsica: evidence of post-Eocene rotation*. Phys. of Earth and Planet. Interior, **62**, 97-108.

VIGLIOTTI L. & LANGENHEIM V.E. (1995) - *When did Sardinia stop rotating? New paleomagnetic results.* Terra Nova, **7**, 424-435.

WEAVER B.L. (1991) - *The origin of ocean island basalts end-member compositions: trace element and isotopic constraints*. Earth Planet. Scie. Lett., **104**, 381-397.

WENZEL T., MERTZ D.F., OBERHAENSLI R., BECKER T. & RENNE P.R. (1997) - *Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen massif (northern Bohemian massif) and implications for related occurrences from the mid-European Hercynian*. Geol. Rundschau, **86**, 556-570.

Manoscritto pervenuto il 29 Marzo 2004; testo approvato per la stampa il 16 Febbraio 2005; ultime bozze restituite il 16 Marzo 2005.