(Reprinted from Nature, Vol. 276, No. 5688, pp. 604-606 December 7 1978)

Eastwards migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines

AT the northern apex of the Tyrrhenian Sea, two mountain chains face each other displaying opposite vergence: the Corsican alpine chain and the Northern Apennines (Fig. 1). The Corsican alpine chain consists of both oceanic and continental nappes transported towards the West which are assumed to have derived from the peeling off of European, Tethyan and African (Austroalpine domains) lithosphere sectors. The age of metamorphism and orogenic transport towards the European foreland is mainly Cretaceous–Palaeogene. We present here an interpretation of the available data on post-collision continental anatectic magmatism in the Tuscan province (Italy) in the light of geodynamic evolution of the Tyrrhenian Sea.

The northern Apennines consist of east and northeastwards transported continental nappes peeled off from the African (Insubric–Apulian domains) litosphere sector. Here, the age of metamorphism and orogenic transport is mainly Neogene. The Ligurian nappes, considered to represent slices of oceanic crust[1], are interpreted here as part of the Cretaceous–Palaeogene Europe-verging Alpine chain. During the late Oligocene and early Miocene they partially overthrust as a whole on to the Insubric domains that in Neogene times formed the Africa-verging Apennine chain (Fig. 2).

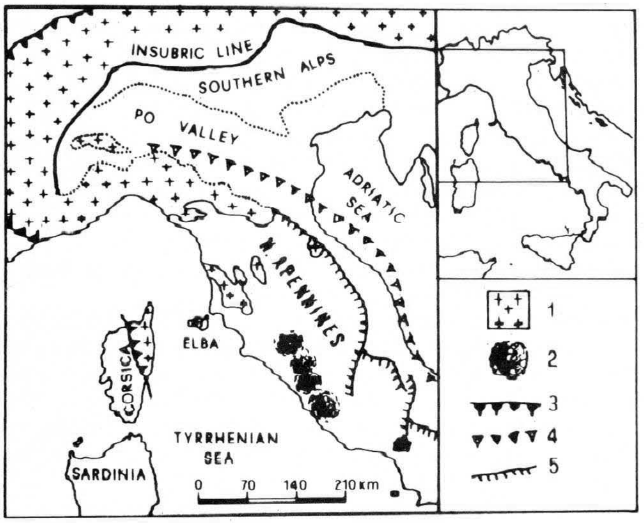

Fig. 1 Tectonic sketch map of northern Italy. 1, Palaeogene and Neogene Europe-verging Alpine nappes; 2, main upper Tertiary–Quaternary volcanoes; 3, European front of the Alpine chain; 4, front of the Apennines; 5, front of the carbonate units in the northern and central Apennines.

Extensive magmatic activity (the Tuscan province) developed between Corsica and Tuscany, within the strongly deformed belt marking the collision zone between the two chains. The crustal anatectic origin of this magmatic province is indicated both by petrological evidence (xenocrysts of quartz, cordierite and sometimes sillimanite, corundum normative composition[2] and isotopic data (high $^{87}Sr/^{86}Sr$ ratios[3,4] high $\delta^{18}O$ (ref. 5). Absolute age determinations range from 8.5 on Elba Island in the west to 0.43 Myr in Mt Amiata in the east[4,6] (Fig. 3).

The deep crustal structure in this area is controversial. The interpretation of gravimetric data[7] suggests crustal thicknesses under western Tuscany of ~25 km. This value is too small for the root zone of a Neogene mountain chain, which implies that the crust here has been thinned and rifted after continental collision. A new interpretation has been proposed based on seismic results and the best fitting of seismic, gravimetric and magnetic data[8,9]: according to this model, the area between Elba and western Tuscany is characterised by the existence of two crust–mantle boundaries, the first 15–25 km deep and the second 45–50 km deep. The body between the two discontinuities might contain continental crustal material, a possible source for the observed magmatism. Accepting crustal thicknesses around 45–50 km the western Tuscany area might correspond to a normal or slightly thinned root zone for the northern Apennines.

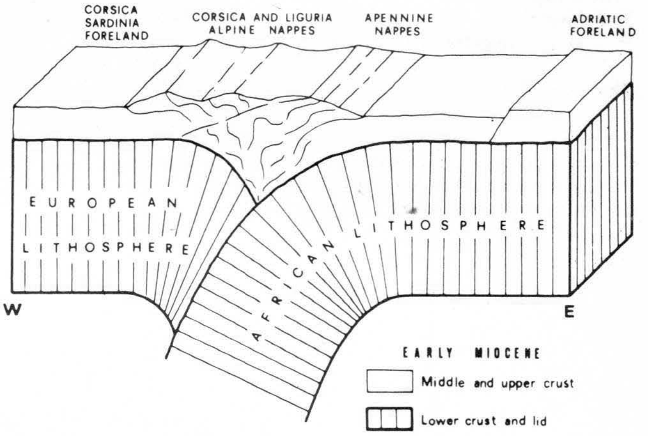

Fig. 2 Palinspastic resoration of the Corsica–Sardinia and Apulia margins at the end of Palaeogene.

Figure 3 shows all the published geochronological data available concerning the Tuscan province; new K/Ar age determinations on a peralkaline lamprophyre outcropping near Sisco (northeastern Corsica) are added here.

Velde[10] first defined the potassic peralkaline nature of the Sisco lamprophyres. The mineralogy is phlogopite, sanidine, olivine, quartz and an uncommon amphibole (potassic richterite). All the data strongly support the geochemical affinity of these rocks with those of the Tuscan province[11]. The dated samples were collected from the outcrop described and analysed by Velde[10] and belong to a sill intruded within the ophiolitic nappes (Schistes lustrés). Whole rock and separated phases were dated by the K/Ar method (Table 1). The errors (1σ) have been evaluated using the Cox and Dalrymple formula[12]. The K/Ar dates range from 14.3 to 15.4 Myr. In a plot of $^{40}Ar/^{36}Ar$ against $^{40}K/^{36}Ar$ they define an isochron of 14.2 ± 0.2 Myr with an initial $^{40}Ar/^{36}Ar$ value of 300.1 ± 0.6. This age is the oldest so far found in the north-Tyrrhenian post-Palaeogene magmatic

Fig. 3 Simplified map of the Tertiary and Quaternary magmatic activity in the Tuscan province. Figures indicate the ages (Myr).

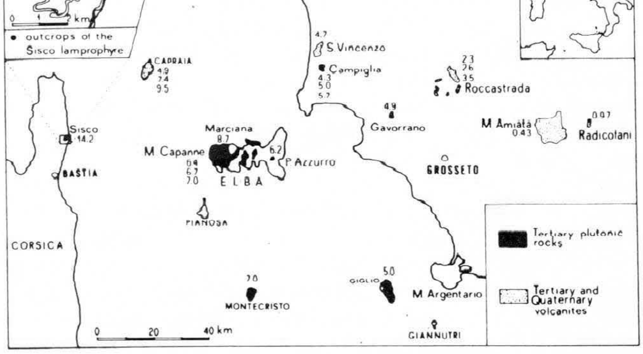

Table 1 K–Ar ages of the Sisco peralkaline lamprophire*

Analysed phase	K (%)	^{40}Ar rad (%)	^{40}Ar rad ($\times 10^{-10}$mol g^{-1})	^{40}Ar/^{36}Ar	^{40}K/^{36}Ar ($\times 10^3$)	Age (Myr)
Whole rock	7.15	57.6	1.82	696.3	481	14.3 (±0.4)
K-Feldspars	8.86	32.1	2.44	430.1	152	15.4 (±0.5)
Phologopite (60–100 mesh)	8.00	21.0	2.06	373.9	93.4	14.4 (±0.5)
	8.00	46.7	2.10	551.1	298	14.7 (±0.4)
Phlogopite (100–140 mesh)	8.11	21.1	2.23	372.9	87.3	15.3 (±0.5)
	8.11	27.9	2.13	409.0	132	14.7 (±0.5)

^{40}Ar was determined by isotope dilution mass spectrometry, using a GD-150 Varian Mat mass spectrometer and the ^{38}Ar-enriched Zurich spike. The calibration was checked by LP-6 USGS standard, a muscovite internal standard (MCT) and Bern LP-6 biotite. K was determined in duplicate by flame atomic absorption with a Perkin Elmer 303.

* $\lambda_\varepsilon = 0.585 \times 10^{-10}\text{yr}^{-1}$; $\lambda_\beta = 4.72 \times 10^{-10}\ yr^{-1}$; $^{40}K/K = 1.19 \times 10^{-4}$ atom/atom.

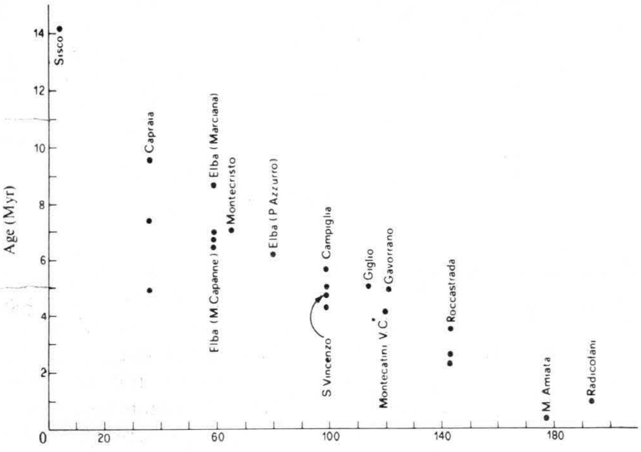

Fig. 4 Ages versus the distances of the magmatic episodes in the Tuscan province. The distances have been computed by projecting the magmatic centres on the Bastia–Radiocofani line.

province. Figure 4 shows these new data, and literature values, in an age against distance plot; the distances have been computed by projecting the magmatic centres on the Bastia–Radicofani line. The new data from North Corsica confirm the eastwards migration of the magmatism[4,6] giving 1.3 cm yr^{-1} as a mean migration velocity.

Contrasting models have been proposed to explain this age–space relationship. Alvarez[13] argued that the Tuscan magmatic activity belongs to a calc-alkaline sequence related to a former Benioff plane dipping eastwards under Italy. According to the Alvarez model the eastwards migration of the magmatism results from the subduction and simultaneous anticlockwise rotation of the Corsica–Sardinia microplate. Marinelli[11] postulated the existence of a hot spot under Tuscany ('Etruscan swell') and suggested that the eastwards migration of the magmatic activity is evidence of a movement of the Tuscan continental lithosphere towards the west with a velocity of about 1 cm yr^{-1}.

Our new model might explain better the genesis and the eastwards migration of the Tuscan magmatic activity, taking into account the main geodynamic events occurring in the Tyrrhenian area during Neogene and Pleistocene times.

The beginning of the Tuscan anatectic magmatism overlaps with the final phases of the Sardinian calc-alkaline volcanism[14]. This volcanism has been recently associated with the subduction of the continental Insubric–Apulian lithosphere dipping westwards beneath the Corsica–Sardinia block (Iberia plate)[15]. The Oligocene and Neogene Africa-verging nappes of the Apennines are interpreted, in this scheme, as peels detached from this subducing lithosphere and pushed toward the east and northeast[15] (Fig. 2).

Sialic material packed in the roots of the Apennine chain during the main compression phases might represent the source of the anatectic magmas. At that time, before the middle Miocene, the Tyrrhenian Sea had not yet developed as an extensional basin. Starting from middle–late Miocene times, tensional tectonics characterised the Tyrrhenian area, until an oceanic plain had developed by Messinian times[16,17]. The Tyrrhenian seafloor spreading is supposedly connected with an anticlockwise rotation of the Apennines[15]. According to this model, and assuming a rotation pole in the Tuscan area or further north, it is possible to reconcile the simultaneous continental magmatic activity in Tuscany with the tholeiitic activity on the Tyrrhenian abyssal plain during late Miocene and Pleistocene times.

The generation and ascent of the magma is probably a result of heat flow increase, pressure relief and fluid mobilisation during a period of tensional rift tectonics. The heat flow increase could be due to a hot spot[11] and/or a general rise of the isotherms in response to thinning of the lithosphere during rotation of the Italian peninsula. In any case, the considerable radioactive heat generation of the upper crustal material in the root zone should be taken into consideration. Furthermore isotopic and geochemical data reported for the Tuscan magmatic rocks support this model and suggest a mixing of upper crustal materials[2,18] with mantle derived magmas.

The eastwards migration of the magmatism can be easily related to a progressive crustal thinning and subsequent rifting due to the anticlockwise rotation of the Apennines. The Tyrrhenian abyssal plain, being far from the rotation pole, is the area in which tensional tectonics are most apparent, so that thinning and rifting of the continental crust was followed by the generation of new oceanic crust in the south.

Finally, such a rotation model may explain the simultaneous late Miocene–Pliocene longitudinal rifting of the chain along the Tyrrhenian border and the nappe and fold development along the Adriatic front.

We thank Professor F. Innocenti and G. Marinelli for helpful discussion. This work was sponsored by the CNR, Geodynamic project, publ. N.132.

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Received 1 August; accepted 2 October 1978.

1. Elter, P. & Pertusati, P. *Mem. Soc. Geol. Ital.* 21 (1973).
2. Barberi, F., Innocenti, F. & Mazzuoli, R. *Mem. Soc. Geol. Ital.* **6,** 643–681 (1967).
3. Vollmer, R. *Geochim. cosmochim. Acta* **40,** 283–295 (1976).
4. Barberi, F., Innocenti, F. & Ricci, C. A. *Rc. Soc. Ital. miner. Petrol.* **27,** 169–210 (1971).
5. Taylor, H. P. Jr & Turi B. *Contr. Miner. Petrol.* **55,** 33–54 (1976).
6. Borsi, S. *Atti Soc. tosc. Sci. nat.* **74,** 232–243 (1967).
7. Giese, P. & Morelli, C. *Quad. Ric. Scient. CNR* **90,** 453–489 (1975).
8. Morelli, C. *et al. Struct. Hist. Medit. Bas. Symp. Int., Split,* 281–286 (1976).
9. Carrozzo, M. T. & Nicholich, R. *Int. Rep. No. 2, Univ. of Trieste* (Ist. Min. e Geof. Appl. 1977).
10. Velde, D. *Bull. Soc. fr. Miner. Cristallogr.* **90,** 214–223, (1967).
11. Marinelli, G. *Geology of Italy* 165–219 (Earth Sci. Soc. Lybian Arab. Rep. Ed., 1975).
12. Cox, A. & Darlymple, G. B. *J. geophys. Res* **72,** 2603–2614 (1967).
13. Alvarez, W. *Nature phys. Sci.* **235,** 103–105 (1972).
14. Coulon, C., Demant, A. & Bellon, H. *Tectonophysics* **22,** 41–57 (1974).
15. Scandone, P. *Boll. Soc. Geol. Ital.* (in the press).
16. Barberi, F. *et al. Init. Rep. DSDP* Leg 42A, site 373A (1977).
17. Dietrich, V., Emmermann, R., Keller, J. & Puchlet, H. *Earth planet. Sci. Lett.* **36,** 285–296 (1977).
18. Vollmer, R. *Contr. Mineral. Petrol.* **60,** 109–118 (1977).

Printed in Great Britain by Macmillan Production Ltd., Basingstoke, Hampshire