Cainozoic magmatism in Sardinia and its geodynamic significance

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Sardinia, along with Corsica, makes up a microcontinent with a continental crust often about 30-35 km thick (Selli, 1973). During the Cainozoic, continental rift and drift, with counterclockwise translative and rotating movements, caused the separation of the microplate from the European paleocontinent, placing it in its present position (Alvarez, 1972). These events, along with the complex geodynamic evolution of the western Mediterranean, have been recorded and marked on the island by three magmatic cycles, each with petrogenesis and well-defined serial affinities. The first cycle, Eocene, with alkaline affinity, is correlated with extensive geodynamic movements along the continental European paleomargin; its products are present only in south-western Sardinia, in the Sulcis. The second cycle, Oligo-Miocene, with calcalkaline affinity (*l.s.*), is linked to the collision of the African and European plates; volcanics outcrop prevalently in western Sardinia, from the Golfo dell'Asinara to the Golfo di Cagliari, within and on the edges of a complex graben structure about 200 km long and an average of 50 km wide. The third cycle, Plio-Quaternary, with affinity varying from subalkaline to alkaline, is characterized by typical continental within-plate volcanic activity, related to tensional tectonics and intraplate volcanism in the Tyrrhenian Sea. In Sardinia, its products outcrop along the western strip and, to a lesser degree, also along the eastern one, respectively from the centre to the north and from the centre to the south (Fig. 1).

Eocene

Eocene magmatism occurs with a single subvolcanic body (Maccioni & Marchi, 1994) intruded into the lower part of the miliolitic limestone, Ilerdian-Cuisian in age (Fanni *et al*., 1982), in the sedimentary basin of the Sulcis. The sill is more or less consistently about 2 m thick and extends over an area, ascertained by sampling, of at least 8 km^2. K/Ar dates range from about 62 to 60 Ma; nevertheless, stratigraphic evidence assigns an Eocene age of between 55-54 Ma and 51(?) Ma, the latter date related to the Pyrenean folding stage (Cherchi & Montadert, 1982). Bulk rock composition shows clear alkaline serial affinity, shown not only by its major elements but also by the MORB-normalized "spydergram" (according to Pearce, 1983) and by REE patterns; the $^{87}Sr/^{86}Sr$ ratio (0.70467) is mantle-type. The panidiomorphic texture, mineralogical assemblage (olivine, clinopyroxene, amphibole, biotite, feldspars and analcite) and, above all, the occurrence of immiscible analcite and/or calcite ocelli are sufficient to classify the rock as a camptonitic-type alkaline lamprophyre according to Rock (1977). The petrochemical features of this lamprophyre would indicate a within-plate anorogenic setting and magma genesis by small degrees of partial melting of a strongly metasomatized, H_2O-CO_2 enriched mantle source, deep in the continental lithosphere (Beccaluva *et al*., 1992). On the basis of an overview of the alkaline igneous province in the Iberian Peninsula and its tectonic significance (Azambre, 1970; Velde & Tournon, 1970; Vitrac-Michard *et al*., 1977; Rock, 1982), the lamprophyre in the Sulcis could be included in this general context, and could represent one of the latest cases of magmatic activity in the "Iberian Province".

Oligo-Miocene

Oligo-Miocene volcanism occurred in western Sardinia, during a time span of about 20 Ma (Beccaluva *et al*., 1985), with a close time/space relationship. It has a prevailing calcalkaline (*l.s.*) character and may be related to a NW or NNW dipping subduction zone along the European continental paleomargin, which ultimately resulted in the formation of the Balearic back-arc basin and the counterclockwise drift of the Sardinia-Corsica microplate (Beccaluva *et al*., 1989, and references therein). Its genesis may be related to metasomatism of the mantle wedge by hydrous liquids and/or fluids whose composition is probably linked to the varying depths of the subduction slab, greater in the north than in the south (Beccaluva *et al*., 1989). Spatial zonation, from tholeiitic in southern areas to high-K in northern ones,

started around 21 Ma, along with a counterclockwise rotation of about 40 degrees, which took place in the time span 20.5÷19 Ma (Montigny *et al*., 1981), and with the enlargement of the Ligurian-Balearic back-arc basin between 21 and 18 Ma (Rheault *et al*., 1984).

The beginning of rifting between Sardinia and Provence may be indicatively fixed in the Early Oligocene (Cherchi & Montadert, 1982; Burrus, 1984), while magmatic activity on the island started about 32 Ma.

In the time span between 32 and 26 Ma, calcalkaline lavas sporadically poured forth on the inside and edges of the graben crossing western Sardinia from north to south (Beccaluva *et al*., 1989). Their products are present mainly as domes or lava flows and, to a lesser degree, as hypoabyssal bodies: *e.g.* microgabbro, in the Cixerri area (Savelli, 1975; Maccioni *et al*., 1992) in southern Sardinia, and as microdiorite and porphyrite at Calabona-Valverde (Giraud *et al.*, 1979; Montigny *et al*., 1981), in northern Sardinia.

Starting in approximately 23 Ma, highly explosive pyroclastic flows (composition ranging from rhyodacitic to rhyolitic), deriving from anatexis of the continental crust (Coulon, 1977) and/or fractionation of basic parental magmas (Savelli *et al*., 1979), poured out in vast sectors of the above-mentioned graben, alternating with basic, intermediate and acid lavas. Both effusive and explosive activity continued until approximately 13 Ma, when drift movements ended and the Sardinian volcanic arc became inactive.

Most of the products of this volcanic activity were ejected and deposited in a subaerial environment. However, in some areas, basic to intermediate volcanics, such as pillow lavas, hyaloclastites and explosion breccias (Maccioni, 1969, 1974), generated by syn-rift submarine volcanic activity (in the time span 21÷18 Ma, Cherchi, 1985; Casula *et al.*, 2001), are also present, interbedded in sedimentary rocks (*e.g.* marls, siltitic marls and sandstone of the Marmilla Formation). Low-welded pyroclastics (pumice and ash), rhyolite to rhyodacite, erupted by subaerial volcanoes, are found interbedded in post-rift marine pelagic sediments (after ~18 Ma, Cherchi, 1985; Casula *et al.*, 2001) -*e.g.* Marne di Gesturi Unit in Marmilla- or fluvio-lacustrine -*e.g.* "*Lacustre*" formation in the Valle del Tirso, Anglona and Logudoro.

Products quite different in composition, like ignimbrites or comenditic-type rhyolitic lavas, are found on the Islands of S. Pietro (~15 Ma, Araña *et al.*, 1974; ~18÷16 Ma, Garbarino *et al*., 1990a, b) and S. Antioco (~18 Ma, Maccioni *et al*., 1990) and in the Sulcis (Assorgia *et al.*, 1992). Shoshonites and high-K pyroclastics outcrop in northern Sardinia (Beccaluva *et al.*, 1994). Saturated trachytes have been found only in the composite neck on the Isola del Toro in south-westernmost Sardinia (13 Ma; Maccioni *et al*., 1990).

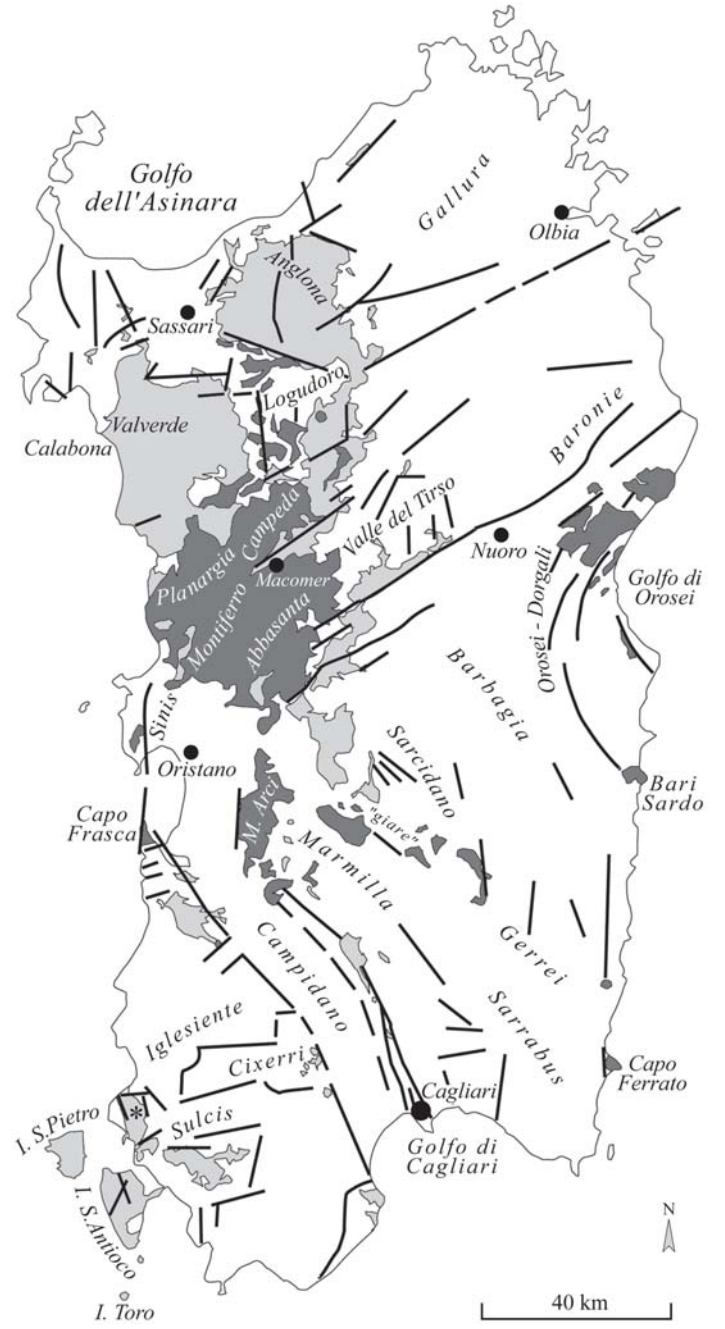
Plio-Quaternary

Between 13 and 5 Ma, Sardinia experienced a period of relative tectonic stability and volcanic inactivity; the latter resumed in the Early Pliocene and ended in the Upper Pleistocene, with outpourings of prevalently basic products with subalkaline to alkaline affinity (Beccaluva *et al*., 1981, 1983b; Assorgia *et al*., 1983). According to Beccaluva *et al.* (1985 and references therein), volcanic activity resumed in the Capo Ferrato sector (~5 Ma) and then extended to other areas of Sardinia: in the Montiferro (3.9÷1.6 Ma), at Monte Arci (3.8÷2.7 Ma), in the "*Giare*" in south-central Sardinia (3.8÷1.7 Ma) and on the plateaux in central Sardinia - Campeda, Abbasanta and Planargia - (3.7÷1.4 Ma), in the Orosei-Dorgali sector (2.9÷2.0 Ma) and, finally, in Logudoro (from 0.9 to < 0.1 Ma), where even older lavas are however present (2.9 Ma).

The Pliocene-Quaternary volcanic province of Sardinia represents a within-plate environment where lavas erupted in the same stable and structurally-continuous continental domain. Magmatic processes logically developed in the same lithospheric segment, with the same geothermic gradient and in similar conditions of tectonic stress and plate dynamics. Magmatic liquids ascended along normal or transform faults, with varying orientation and pre-existing as tectonic lines in the basement, giving rise to prevalently fissure volcanism.

The dikes in Logudoro, Montiferro and Monte Arci are generally oriented in a N-S direction, which is the most frequent in the Tyrrhenian Basin (Beccaluva *et al*., 1983a). Various volcano-tectonic alignments are also present in other areas in Sardinia, as for example in the Orosei-Dorgali sector, where volcanic centres are arranged in concentric alignments parallel to the direction of the Golfo di Orosei (Beccaluva *et al*., 1983b). Prevalent directions clustered around NW-SE are also present in the "*Giare*" in south-central Sardinia (Assorgia *et al.*, 1983).

SKETCH MAP OF CAINOZOIC MAGMATISM OF SARDINIA



Volcanics are generally only slightly fractionated, whereas in some areas, the entrapment and fractionation of basic magmas, in magmatic chambers at various depths, has led to the formation of evolved liquids: *i.e.* phonolites and peralkaline phonolites at Montiferro; trachy-phonolites (Deriu *et al*., 1974) and transitional, saturated to quartz-bearing trachytes (Cinus, 1996) at Macomer; oversaturated trachytes (Brotzu *et al*., 1975) at Capo Ferrato; oversaturated alkali trachytes and rhyolites on Monte Arci (Beccaluva *et al*., 1977).

Further details on the three most representative volcanic complexes (Montiferro, Monte Arci and Capo Ferrato) are reported later.

The Montiferro volcanic complex is located in west-central Sardinia at the intersection of two N-S and NE-SW-oriented fault systems, and extends aerially over a surface area of about 400 km^2 (Assorgia *et al*., 1981). Two principal series with alkaline affinity are present (Beccaluva *et al*., 1977). The oldest consists of analcite-basanite, analcite-phonolitic tephrite and analcite-tephritic phonolite lavas, erupted in the time span between 3.9 Ma (basanites) and 3.2 Ma (tephritic phonolites); low-Mg analcite-basanites, undated and of uncertain stratigraphic position, also outcrop in the south-eastern Montiferro. The second consists mainly of alkalic basalts, trachybasalts, hawaiites, phonolitic trachytes, phonolites and peralkaline phonolites; it makes up the majority of the volcanic complex and is dated between 3.0 and 2.8 Ma. Mildly alkalic and transitional basic lavas outcrop in various areas. Smaller amounts of subalkaline basaltic andesites are present in the central (3.0 Ma), south-eastern and south-western areas of the Montiferro.

Basic lavas usually overlie trachytic phonolitic massive lava flows and domes, but a few tristanites have been found interbedded in basaltic sequences in the south-eastern sector.

Monte Arci is a volcanic complex, elliptical in shape, which extends over a surface of about 150 km^2 on the eastern edge of the N-S oriented and westward-dipping graben of the Campidano (Assorgia *et al*., 1976a, b). It consists mainly of subalkaline lava sequences made up of basaltic andesites and basalts (3.7÷3.3 Ma) overlying and at times underlying thick dacite (3.2 Ma). Thick flows of rhyolitic lavas make up the base of the series, in spite of displaying a radiometric age of 3.4÷3.3 Ma. Smaller quantities of transitional lavas, represented by basalts (3.4÷3.3 Ma) and low silica-oversaturated alkali trachytes (2.7 Ma) also occur. Very rare alkalic basalt outcrops as well.

The volcanics at Capo Ferrato, outcropping in an area of a little less than 2 km^2 in south-eastern Sardinia, are the oldest products of within-plate volcanism on the island. According to Brotzu *et al*. (1975), they constitute a transitional series represented by small lava flows, domes, dykes and composite necks of trachybasalt (5.0 Ma, Beccaluva *et al*., 1976-77), tristanite and trachyte (5.2 Ma, Beccaluva *et al*., 1976-77); quartz-latite and quartz-trachyte (Cinus, 1996) are also present.

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