Rendiconti Seminario Facoltà Scienze Università Cagliari Supplemento Vol. 71 Fasc. 2 (2001)

The Cenozoic volcanism of San Pietro Island (Sardinia, Italy)

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Abstract. *During Miocene the San Pietro Island (Sulcis, Sardinia, Italy) has been the locus of an intense volcanic, both effusive and explosive, activity. The stratigraphic succession comprises several lava and welded pyroclastic units, generally well exposed on the island and in the Sulcis mainland as well. In particular, the intermediate portion of the sequence is characterized by three ignimbritic units and several coulees with a comenditic composition. Several vents can be located in correspondence of the main lava units. The large variability of the depositional and rheomorphic structures associated both to the lava flows and pyroclastics, their very peculiar composition and the high quality of the outcrops make the San Pietro Island a very interesting place for a volcanological fieldtrip.*

Riassunto. *L'isola di San Pietro (Sulcis, Sardegna) è stata interessata nel Miocene da una intensa attività vulcanica, sia effusiva che esplosiva, i cui prodotti sono attualmente ben esposti sull'intera isola. Sono state riconosciute numerose unità sia laviche che piroclastiche, la maggior parte delle quali ben correlabili con i prodotti vulcanici che affiorano estesamente nel Sulcis. In particolare, la porzione intermedia della sequenza stratigrafica comprende tre unità ignimbritiche saldate e numerosi duomi-colata a chimismo comenditico, i cui centri di emissione sono talvolta ben individuabili.*
La grande varietà delle strutture deposizionali e reomorfiche associate sia ai prodotti lavici che a quelli piroclastici, la peculiare composizione dei prodotti stessi e la qualità degli affioramenti rendono l'isola di San Pietro una meta estremamente didattica per una escursione vulcanologica.

INTRODUCTION

San Pietro Island, located at the southwestern tip of Sardinia, is part of the Sulcis complex and is completely formed by volcanic terrains. The geological peculiarity of this

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site is the presence of a peralkaline rhyolitic lavic and ignimbritic complex, interlayered in the products of a regionally extended calc-alkaline activity. In 1895 S. Bertolio studied for the first time the peralkaline lava flows of Le Commende, in the northern part of the S. Pietro Island, giving them the name of Comenditi. This name entered the petrographical literature, and is presently used to indicate peralkaline rhyolites which contrast with pantelleritic compositions for a lower normative content of mafic minerals and for an iron content less than 4% by weight [1].

From a volcanological point of view, the most interesting products are represented by variously welded ignimbrites and comenditic lava flows. Silicic alteration can be sometimes observed on the rhyolitic ignimbrites, while Mn-mineralizations are diffused along fractures or at the interface of different units.

After a general overview of the geological features of the island, three stops will be described, mainly focussing on the main textural and deformational features of ignimbritic and lava products.

GEOLOGIC SETTING

The Cenozoic volcanism of western Sardinia forms a magmatic arc running along the western margin of Sardinia and southern Corse microplates.

Volcanic activity occurred during Oligocene and Miocene (32.4-13.8 Ma, [2]) as a result of subduction of oceanic litosphere in a NNW direction along the Apennines-Maghrebides subduction zone ([3], [4]).

The activity preceded and partly accompanied the opening of the western Mediterrean sea through the formation of the Provençal Balearic and Algerian basins. This lead to a 60˚ counterclockwise rotation of Corsica-Sardinia blocks around a pole located at 42.7˚ N and 9.6˚ E [5].

The magmatic products related to this activity range from calc-alkaline basalts to dacites with more subordinate rhyolites. The rocks show mineralogical and geochemical features closely comparable to those from other orogenic areas, showing systematic regional variations for several lithophile elements. Dostal et al. [4] observed a progressive increase, from south to north and for a given SiO_2 content, of the abundance of K, Li, Rb and Sr and of the K/Na, K/Ba and Rb/Sr ratios, associated to a decrease of the K/Rb ratio.

THE SULCIS VOLCANIC PROVINCE

The Sulcis volcanic province (fig. 1) is located in the southern portion of the magmatic arc, west of the main branch of the «Sardinian rift», a Cenozoic N-S intra arc basin now occupying almost all of the western half of the island [6] [7].

Volcanic activity in the region was subaerial and can be grouped into two main phases (figs. 2 and 3):

- *Older Phase* (28.4-17.7 Ma), dominated by the emplacement of calc-alkaline

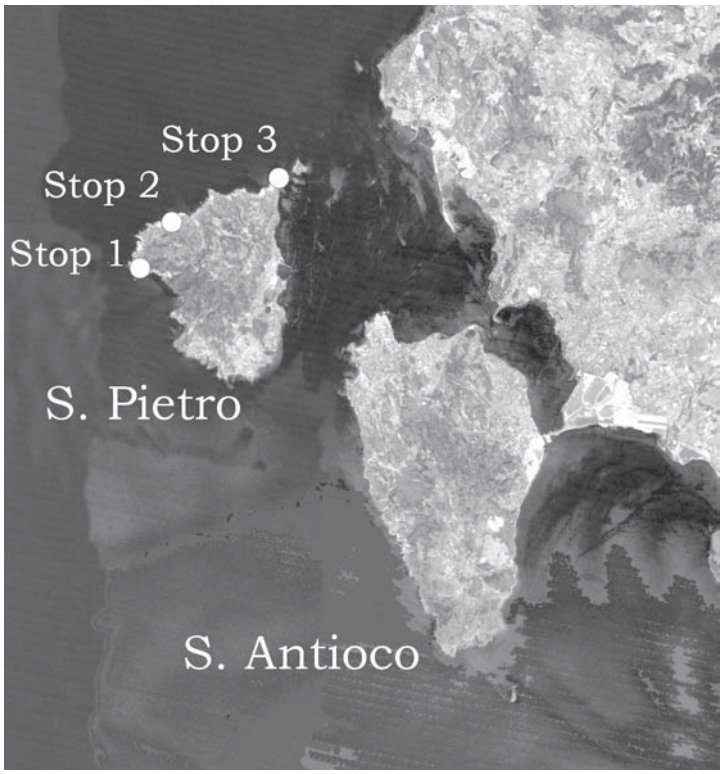

Figure 1. Satellite view of the Sulcis mainland and of the two islands of S. Pietro and S. Antioco. The location of the planned stops is also shown.

basaltic to intermediate lavas and subordinate pyroclastic products erupted from vents concentrated in the southern part of the basin (M. Narcao and southern S. Antioco island).

• *Younger phase* (17.6-13.8 Ma), characterized by the emission of large-volume dacite to rhyolite ash flow tuffs with calc-alcaline to peralkaline affinity [8] [9]. The succession includes 11 main ignimbrite sheets separated by paleosols and minor, non welded, pyroclastic deposits. The main tuffs are high-grade ignimbrites and are mostly distributed in the southern part of the sector.

No vents or caldera related to the younger phase are exposed in the basin, except for some effusive vents on the S. Pietro island. Field data (thickness variations, pumice and lithic maximum diameters, flow indicators) suggest a provenance for the main ignimbrites and fall deposits from a submerged sector located W of the island of S. Pietro [10] [11].

Comenditic products are quite important; they are best exposed and thickest on the Island of S. Pietro. They are represented by three ignimbritic sheets and subordinate volumes of comenditic to pantelleritic lava flows and domes. No effusive products occur in the Sulcis mainland.

Notwithstanding their age, volcanic products of the Sulcis province offer very good expositions and uncommon well preserved textures both at the meso- and micro-scale,

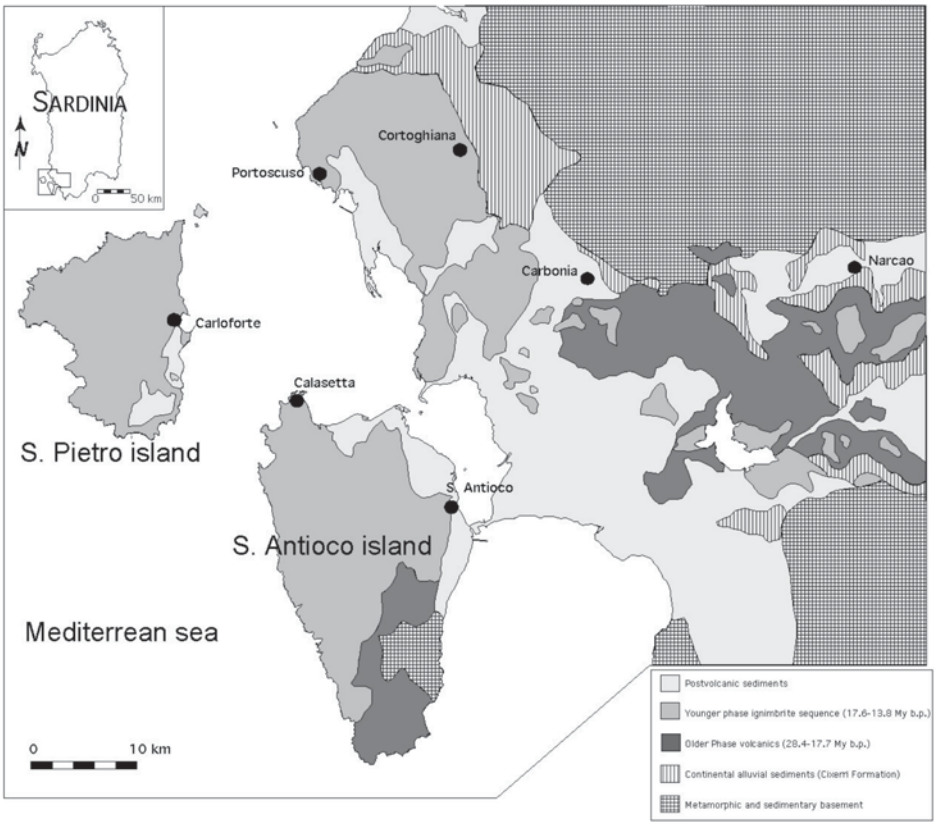

Figure 2. Geological sketch of the area.

allowing an in-depth study of the processes accompanying welding and sin-depositional deformation of large ignimbrite deposits.

There is no evidence of significant tectonics affecting volcanic deposits, except for a limited vertical faulting with maximum downthrow of 40 m and a tilting not larger than 10°.

PETROGRAPHIC AND COMPOSITIONAL FEATURES

The calc-alkaline Oligo-Miocene volcanism of Sardinia is characterized by a prolonged activity especially concentrated all along the western sector of the island. The final phases of this volcanism are concentrated in the Sulcis area, with the occurrence, around 15 Ma [12], of rhyolitic and comenditic products in a strict space and temporal association.

While the mainly pyroclastic products of the *Younger Phase* (Upper Sequence of MORRA et al. [9]) crop out extensively both in the Sulcis mainland and the two islands of S. Antioco and S. Pietro, the lavic sequences of the *Older Phase* are restricted to the southern tip of S.

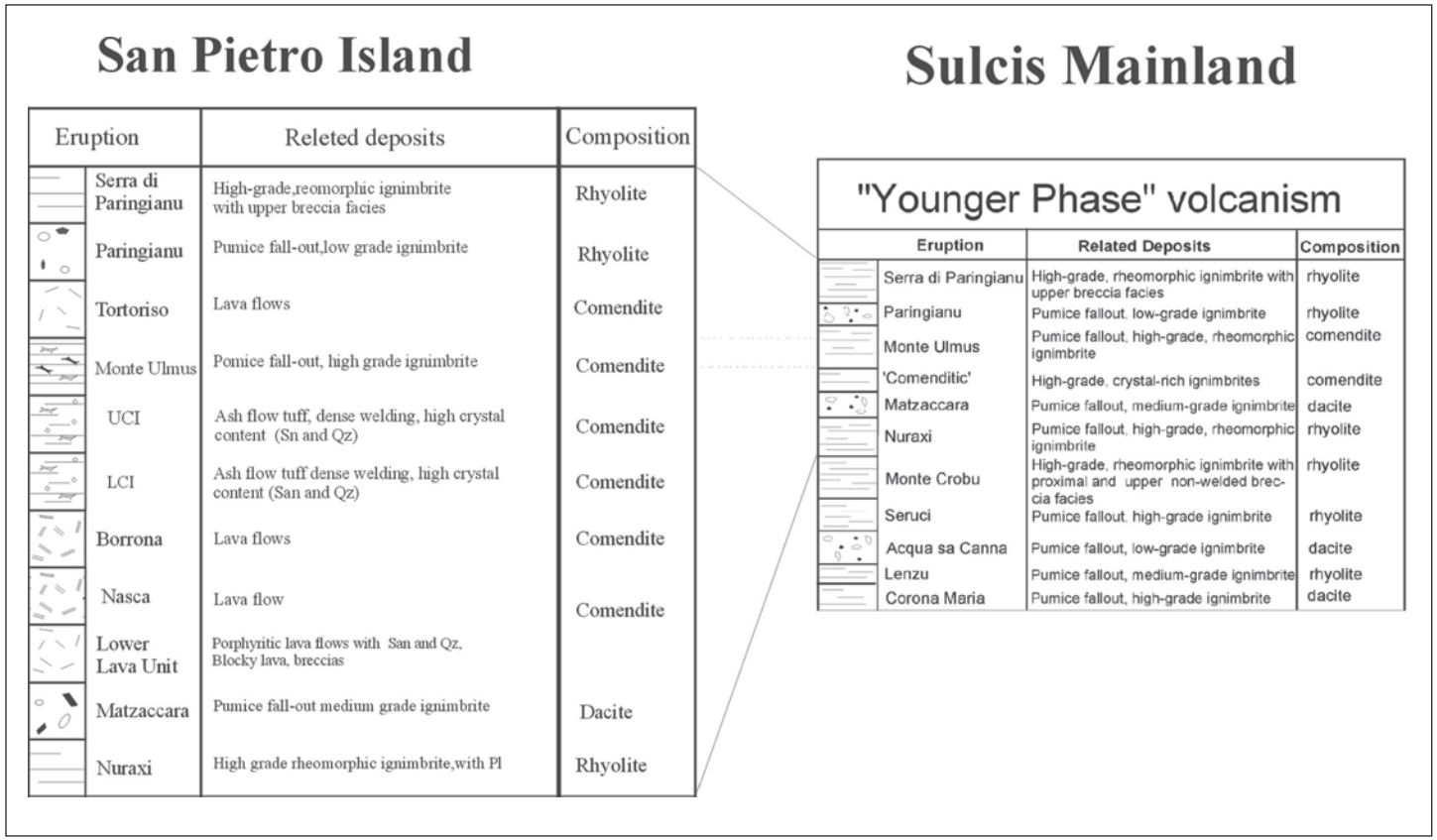

Figure 3. Stratigraphic scheme correlating the volcanic successions of the San Pietro Island with those outcropping in the Sulcis mainland (correlations after [11] and [15]).

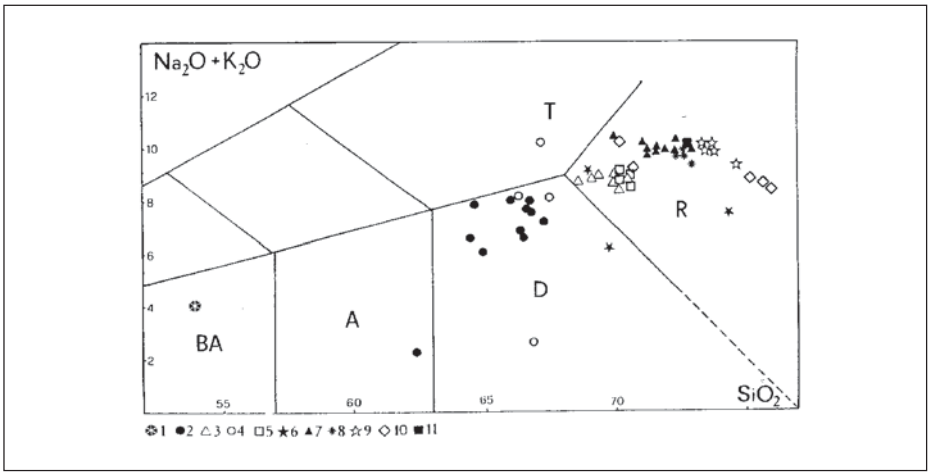

Figure 4. TAS diagram of the volcanics from the Sulcis volcanic province (data after [9]).

Antioco and to the Carbonia-Narcao area. Morra et al. [9] exhaustively discussed the main petrographical and geochemical features of the products; in the following we will briefly summarize their data (fig. 4).

The *Older Phase* is characterized by subaerial lava flows and domes, ranging from basaltic to andesitic in composition. Andesites are commonly porphyritic with phenocrysts of plagioclase, clinopyroxene and ortopyroxene. Hornblende-biotite varieties sparsely occur. Basaltic and basaltic-andesite flows are less common, and are characterized by phenocrysts olivine, plagioclase, clinopyroxene and minor ortopyroxene.

The products of the *Younger Phase* (fig. 3) comprise calc-alkaline and peralkaline compositions. They are mainly represented by variously welded ignimbritic flows, while comenditic lava domes and coulees are only restricted to the S. Pietro Island. Ignimbrites vary from dacite to rhyolite to comendite, with some rhyolites «transitional» to peralkaline.

Dacitic compositions are present in the three ignimbrite Units of Corona Maria, Acqua sa Canna and Matzaccara. The latter unit discontinuously crops out also in the northern part of the San Pietro Island, where it forms the base of the comenditic pyroclastic and lava units. The typical mineralogical assemblage is formed by plagioclase, ortopyroxene, clinopyroxene and minor olivine. Biotite and amphibole are sometimes abundant among the phenocrysts.

Rhyodacitic and rhyolitic compositions are generally associated to medium- to high grade ignimbrites (Lenzu, Seruci and Monte Crobu units), often with a marked eutaxitic texture. Plagioclase phenocrists are abundant, with subordinate clinopyroxene and ortopyroxene, and microphenocrysts of sanidine. Biotite and olivine, if present, are always altered; Ti-magnetite and ilmenite occur as accessory phases in the groundmass.

Rhyolites «transitional» to peralkaline rhyolites are both associated to the extremely

high-grade ignimbritic units of Nuraxi and Serra di Paringianu, and to the stratified fallout pumice and incoherent to low-grade pyroclastic flows of the Paringianu unit. They are strongly porphyritic, with the association of plagioclase and sanidine. Oligoclase is often mantled by anortoclase. Femic minerals (ortopyroxene, clinopyroxene, Ti-magnetite and ilmenite) are rare and generally strongly altered. Very good expositions of these rocks will be observed in the field trip.

Comendites extensively crop out on the northern half of the San Pietro Island, sandwiched between the «transitional» rhyolitic units. At least three ignimbrite units (Lower Comenditic Ignimbrite LCI, Upper Comenditic Ignimbrite UCI, Monte Ulmus) and several domes and coulees are present. These rocks are generally highly porphyiritic, with euhedral, mm-sized sanidine and quartz. Phenocrysts from both lavas and pyroclastics comprise Na-sanidine, anortoclase, quartz, and minor arfvedsonite and aegirina as microphenocrysts. Aenigmatite is present in some rocks transitional to pantellerites. Quartz from these ignimbrites is very rich in variously crystallized melt inclusions, representing the crystallization of these melts in a closed, volatile-rich environment (fig. 5).

VOLCANOLOGY OF THE S. PIETRO ISLAND

The volcanic succession cropping out on the San Pietro Island is described in two

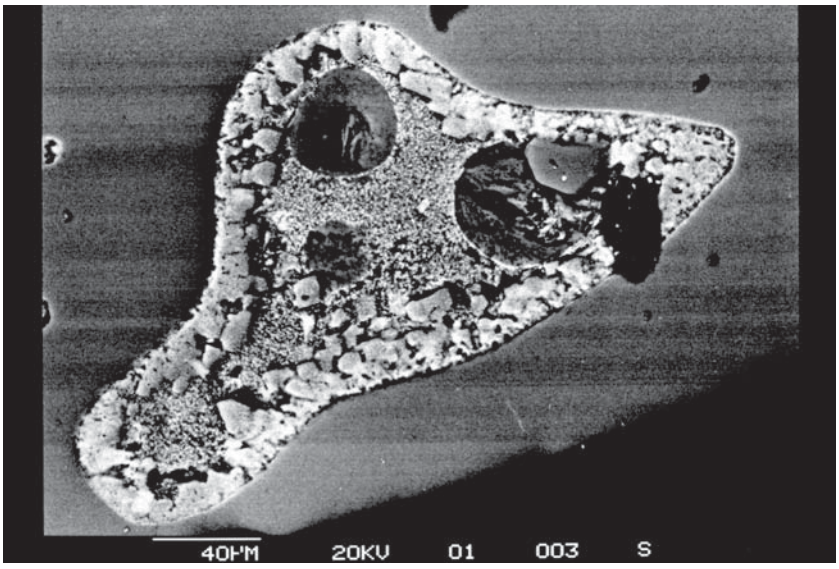

Figure 5. SEM backscattered image of a strongly crystallized melt inclusion in quartz from the UCI on S. Pietro Island. The corona of µm-sized minerals is formed by quartz. The two globule-shaped masses are a spherulitic growth of anortoclase, while the spotted central area is formed by Na-amphibole microlites and glass. Isolated white spots included in minerals and in the glass are F-, Cl- or REE-minerals.

geological maps [13], [14]. In this paper, the different stratigraphic units have been redefined, also proposing some correlations with the main units cropping out in the Sulcis mainland according to the general stratigraphy described in [8], [9], [11].

The S. Pietro Island can be subdivided into four different sectors, distinguished on the basis of their geological and morphological features:

- a southern sector, generally covered by the youngest ignimbrite sheet, characterized by a low, smooth relief and by a large depression;
- a northwestern sector, with the highest hills mainly formed by lava domes and coulees;
- a northeastern sector, formed by a small ignimbrite plateau cut by high cliffs along the coastline;
- a central sector, with a smooth relief, where the older volcanics of the S. Pietro Island crop out.

The volcanic succession cropping out on the San Pietro Island is represented by the units forming the upper half of that described in the Sulcis mainland (fig. 3). In particular, the older cropping units are the Nuraxi and Matzaccara ignimbrites, which mainly form the central sector of the island. The Matzaccara Ignimbrite forms the base of the comenditic sequence. This is particularly well exposed on San Pietro, with the occurrence of both effusive and pyroclastic products and where some vents can also be recognized.

In the following, we will briefly describe the main units of fig. 3, only focussing on the comenditic products and the overlaying deposits.

Lower Lava Unit

This unit is represented by blocky lavas cropping out discontinuously along the cliffs of the northern coastline, where they form the base of the comenditic ignimbrites. Where their central portion is exposed, they show a strongly porphyritic texture, with sanidine and quartz in a vesicular groundmass. The upper portion of the unit is a monogenic breccia formed by vitrophiric blocks, from centimetric to metric in size, suggesting a strong autobrecciation of the lava crust.

Upper Lava Unit (Nasca, Borrona, Tortoriso flows)

It comprises several comenditic and subordinate pantelleritic domes and coulees. They generally represent the base of the ignimbritic sequence.

All these products are characterized by very abundant phenocrysts of quartz and sanidine in a spherulitic groundmass. Mafic minerals are scarce, essentially represented by Na-clinopyroxene, biotite and minor arfvedsonite and aenigmatite.

Several coulees are associated to dome-like structures. Coulees are characterized by a typical folded surface morphology (fig. 6). Classical ramp structures are rare, only associated to the largest flows. Columnar jointing is very common.

Breccia layers with jig-saw fractured clasts are generally associated to the levees and to the frontal portion of the flows.

Figure 6. Aerial view of two comenditic coulees.

An intense flow folding, characterized by similar folds with non cylindrical axial surfaces is somewhere observed (Stop 2, Cala Fico).

Lower Comenditic Ignimbrite (LCI)

The LCI locally crops out mainly along the cliffs of the northern sector, where it directly covers the Lower Lava Unit.

An air fall deposit is found immediately below the ignimbrite. It is laterally continuos, with an average thickness of 10-20 cm, and is mainly formed by mm-sized crystals of quartz and sanidine and by completely altered pumice lumps.

The upper part of the unit can be subdivided in two members (referred to as A and B), mainly basing on their welding and crystal content. Member A, the lower, has a lower crystal content (around 10% by volume of the total) and is densely welded. It has a basal vitrophyre 20 cm thick, with a clear, thinly spaced columnar jointing that becomes more and more spaced toward the top of the Member. Flattened fiammae are very common, and the matrix shows a clearly eutaxitic texture. Member B generally shows a higher crystal

and lithic content. Juvenile material is represented by two types of fragments, mainly differing for their different flattening ratios, vesicularity and crystal abundance.

Upper Comenditic Ignimbrite (UCI)

This ash flow tuff crops out mainly in the nortwestern portion of the island, covering the main units of the Upper Lava Sequence. We will have a close view of this unit during Stop 1.

The basal portion of the UCI is a cross-stratified, non-welded to poorly welded, coarse ash deposit with a variable thickness, resting on a pumice fall deposit. Altered, highly vesicular pumice, porphyritic with quartz and sanidine, is present.

The central part of the unit shows the green facies typical of peralkaline welded tuffs. It is about 6 meters thick, and is moderately to densely welded. Toward the base it is characterized by lithophysae, while its top is densely welded and shows a well-developed eutaxitic texture with abundant fiammae.

Fiammae increase in size toward the topmost portion of the UCI, where they are up to 50 cm in size. Columnar jointing is well developed in this part of the unit.

Monte Ulmus Ignimbrite

This is the most widespread comenditic ignimbrite, cropping out also on the Sulcis mainland. At least three different facies in a strict vertical association can be distinguished.

- A thin, very typical, basal vitrophire, around 30 cm thick;
- a densely welded, fine-grained, crystal-poor strongly rheomorphic zone, with planar foliation. This facies is well developed in the outcrops of the Sulcis mainland, while it is restricted to few tens of centimeters on the San Pietro Island;
- an upper, densely welded zone characterized by very large (up to 150 cm), black fiammae, and white, rounded pumice fragments. Fiammae are porphyritic with sanidine. This is the main facies occurring on the island, while it is only sporadically present on the mainland.

Paringianu Unit

It is a complex unit, represented by an alternation of decimetric pumice fall layers interbedded with pyroclastic flow deposits. It probably groups the deposits of several plinian to phreatoplinian eruptions. Pumice fall layers are medium to fine grained. Accretionary lapilli-bearing beds are interlayered with the fine-grained beds. The lower pyroclastic flow units show a white color and are fine-grained and non-welded, with abundant loose crystals of plagioclase. The upper pyroclastic flow units are characterized by a progressive increase of welding and an increasingly reddish color upward. A marked columnar jointing characterizes this portion of the Paringianu Unit.

Serra di Paringianu Ignimbrite

It crops out both in the northern and in the southern sectors of the island.

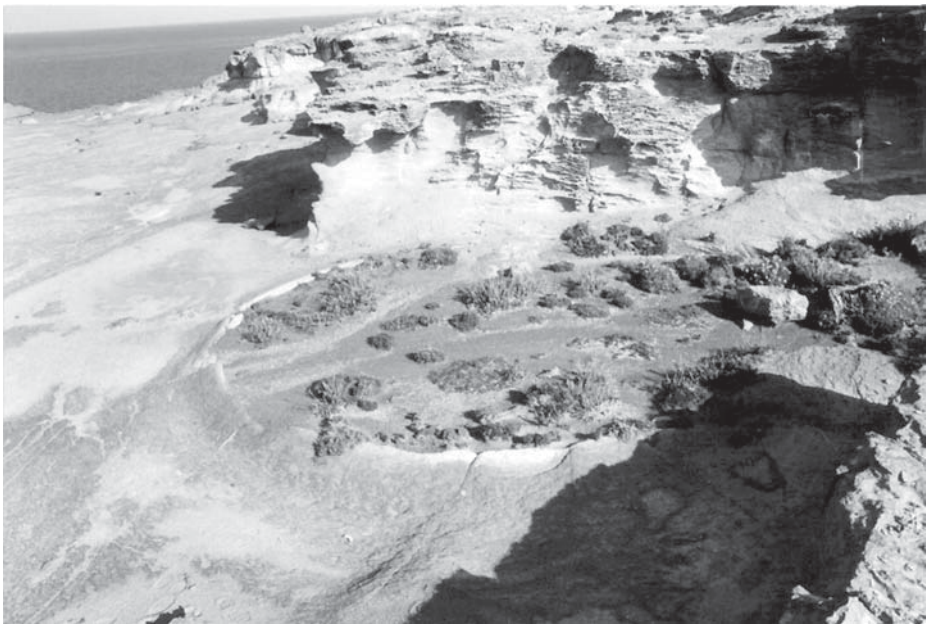

Figure 7. Large blister in the Serra di Paringianu Ignimbrite. La Punta (Stop 3).

The ignimbrite is characterized by a basal vitrophyre, up to 50 cm thick. The main body of the ignimbrite shows different facies, well visible at La Punta (Stop 3). A non-welded facies formed by a lithic-rich, whitish pumice flow unit with a fine-grained matrix is locally interlayered in the densely welded tuff. The welded portion of the unit has a typical appearance, with a highly developed foliation given by strongly flattened fiammae. Fiammae are porphyritic with plagioclase and sanidine, the latter often bordering the large plagioclase phenocrysts. Foliation is locally disturbed by rheomorphic movements, forming folds and ramps in the upper portion of the unit. Ramps structures in the top, vitrophyric portion of the ignimbrite clearly evolve toward autobrecciation.

At La Punta (Stop 3) foliation is also disturbed by sin-eruptive local inflation of the tuff, due to localized degassing which formed uncommon, emispheric blister structures (fig. 7). Similar structures have been only described in a pantelleritic ash flow tuff at Fantale (Ethiopia).

FIELD TRIP NOTES

The passage by ferry from Portovesme to Carloforte, the main village on the San Pietro Island, is only forty minutes long. Three stops are scheduled on the island (Fig. 1), especially focussed on the different structures and deformational features of lavas and ignimbrites.

Stop 1: Capo Sandalo: panoramic view and the UCI

Significance: *volcanological overview of the island and the structures of a densely welded ignimbrite*

After dropped off the ferry at Carloforte, we will cross the northern part of the island up to its westernmost point, Capo Sandalo. During the transfer we can have a look at the main geological features of the island. The main road ends at a large square, from where we have a panoramic view on the western coast of the island. On a small lane descending to the sea we have a close view of the Upper Comenditic Ignimbrite (UCI; fig. 8) observing interesting flow structures in the lower comenditic lavas.

Stop 2: Cala Fico lavas and dome

Significance*: Columnar jointing and flow structures in the comenditic lavas*

The bus will stop at a panoramic view on the Cala Fico bay. The main cliff (fig. 9) cuts a comenditic dome with a very clear columnar jointing. On the small road down to Cala Fico we cross a lava flow outpoured from the dome. On the left of the road we see the surface structures of a comenditic lava, with megafolds forming convex-shaped ramps.

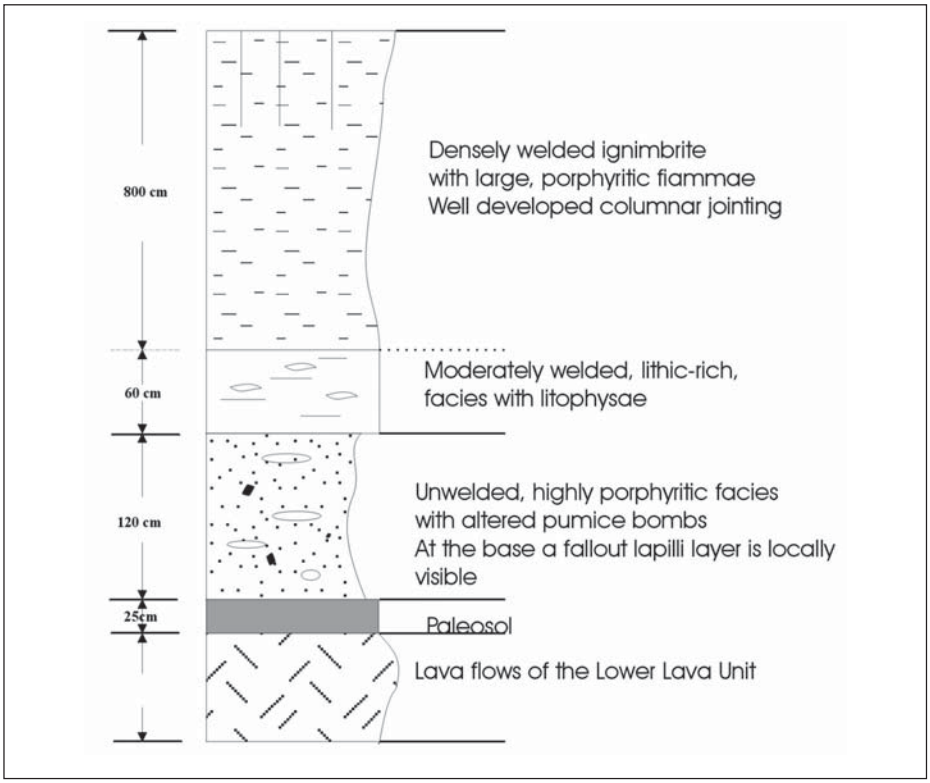

Figure 8. Stratigraphic log of the UCI at stop 2.

Figure 9. Cala Fico Bay.

The lava is crystal rich, with phenocrysts of sanidine and minor quartz. Sanidine shows a characteristic blueish reflection, that is peculiar of some of the comenditic units. The

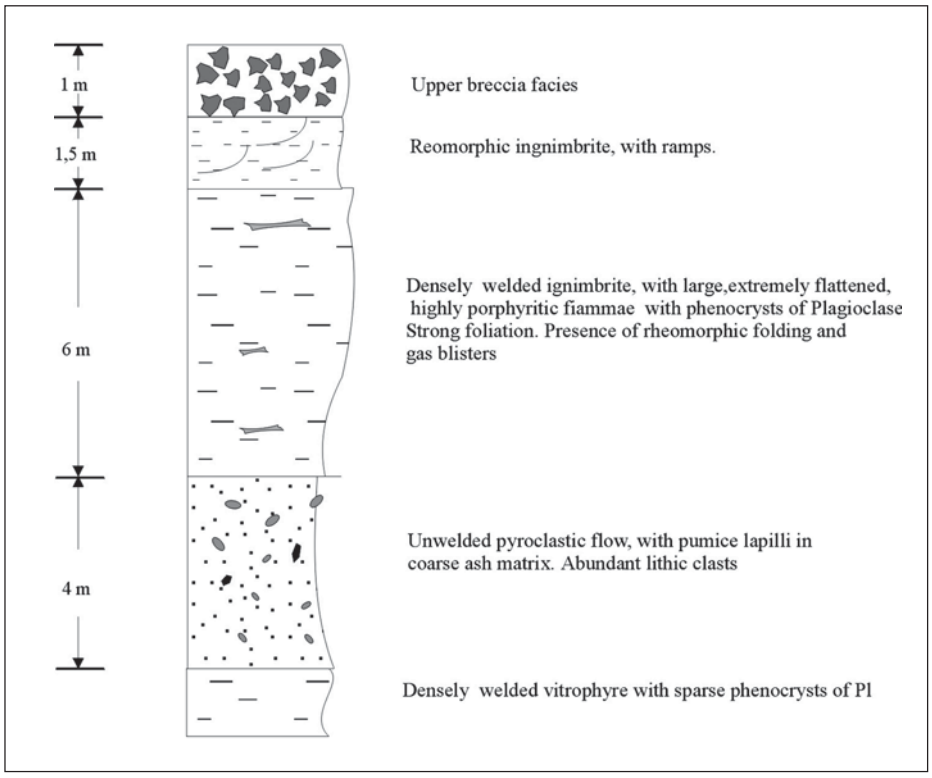

Figure 10. Stratigraphic log of the Serra di Paringianu Ignimbrite at stop 3.

lava shows a marked flow foliation and similar folds with a pluridecimetric wavelength. Flow folding on a lava flow is well exposed on the left cliff at the bay. In its upper part columnar jointing is well developed and foliation more indistinct.

Horizons of breccia are interbedded at different levels in the lava flow. They are formed by massive centimetric clasts in a grain- or matrix-supported framework, and are probably related to shear surfaces in the lava flow. Mn-mineralizations are scattered in the lava, mainly along a diffuse network of fractures. Small tunnels used for mining are visible.

Stop 3: La Punta: the Serra di Paringianu Ignimbrite

Significance: *facies variations, rheomorphic structures and gas blisters in a densely welded ignimbrite*

The last stop on the island is devoted to the subalkaline «transitional» rhyolitic ignimbrite of the Serra di Paringianu. This is one of the largest units of the Sulcis sequence. At this locality, strong vertical facies variations in the ignimbrite are exposed (fig. 10), from non-welded, to incipiently welded, to densely welded up to lava-like zones. Rheomorphic structures are well developed. A peculiarity of the site is the presence of large emispheric gas blisters (fig. 7) related to sin-depositional degassing from the still fluid ignimbritic sheet.

ACKNOWLEDGMENTS

We are grateful to G. Macciotta for his suggestions in reviewing the manuscript. The work was funded by a 1999 Local Research Project (ex-60%) grant to R. Cioni.

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