Stratigraphic and Petrographic Investigations into the Permian-Triassic Continental Sequences of Nurra (NW Sardinia)

Investigaciones estratigráficas y petrográficas en las secuencias continentales permo-triásicas de Nurra (NW de Cerdeña)

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ABSTRACT

The post-Hercynian continental succession in Nurra, northwestern Sardinia, displays a wide range of siliciclastic sediments, over 250 m thick, intercalated with volcaniclastic products. The succession can be subdivided into at least two tectonosedimentary cycles. The oldest cycle, which is developed for a maximum of 15 m only, is the Lu Caparoni Fm., rich in the lower part of Autunian plants. This Unit begins with alluvial and lacustrine sediments, above which we find some explosive products, which have been interpreted as kaolinized cinerites. Subsequently, this volcano-tectonic activity generated coarser-grained fluvio-deltaic deposits. However, thin clastic intercalations persisted within these massive deposits, again in the presence of tuffaceous material.

The upper cycle is made up of siliciclastic sediments, showing frequent facial and geometrical changes. It has been subdivided into four Units, of which the total thickness ranges up to about 250 m. Coeval volcanism is documented by a few scattered products extending into the two lower Units, and perhaps into the the basal part of Unit 3. These products are represented by acidic volcaniclastic deposits, where a possible alkaline-potassic affinity (already advanced by previous authors) is partly obscured by pervasive secondary mobilization. In particular, the gray-greenish and reddish succession of Units 3 and 4

Cuadernos de Geología Ibérica, núm. 21, pp. 149-169.
Servicio de Publicaciones. Universidad Complutense, Madrid, 1996.

recalls the typical Buntsandstein of Europe. On the basis of past microfloristic research, this Buntsandstein persisted up to the early Middle Triassic times.Lithologic and sedimentologic aspects, together with thickness changes, lead us to interpret this upper cycle as due to alluvial environments, which acted within extensional swell and basin structures. During Buntsandstein development, the deposits were formed in a coastal plain environment and, in proximity with the marine Muschelkalk transgression, also in a littoral environment.

Key words: Permian-Triassic, continental deposits, stratigraphy, sandstone petrography, volcanics, Nurra, Sardinia.

RESUMEN

La sucesión continental post-hercínica de Nurra, en el oeste de Cerdeña, está compuesta por unos 250 m de sedimentos siliciclásticos con intercalaciones de productos volcanoclásticos. Esta sucesión puede subdividirse en, al menos, dos ciclos tectono-sedimentarios. El ciclo mas antiguo, es la llamada Fm. Lu Caparoni. Tiene un espesor máximo de solo 15 m y en su parte inferior, existen abundantes plantas autunienses. Esta Unidad comienza con sedimentos aluviales y lacustres, por encima de los cuales se encuentran algunos productos explosivos que han sido interpretados como cineritas caolinizadas. Posteriormente, esta actividad volcano-tectónica dio lugar a la sedimentación de series fluvio-deltaicas de grano grueso. No obstante, dentro de estos depósitos masivos, persisten delgados niveles de sedimentos clásticos finos asociados con material tobaceo.

El ciclo superior esta compuesto por sedimentos siliciclásticos con frecuentes cambios de facies y de geometría. Puede subdividirse en cuatro Unidades, con un espesor total cercano a los 250 m. El volcanismo coetáneo viene determinado por la presencia de unos pocos productos dispersos dentro de las dos unidades inferiores y quizá en la parte basal de la tercera unidad. Estos productos están representados por depósitos volcanoclásticos ácidos, en los que una posible afinidad alcalino-potásica (ya mencionada por autores previos) está enmascarada parcialmente por una movilización penetrante secundaria. La sucesión de las unidades 3 y 4 de colores grises, verdes y rojos, recuerda al Buntsandstein típico de Europa. Teniendo en cuenta investigaciones microflorísticas anteriores, este Buntsandstein llega hasta la parte inferior del Triásico medio. Las características litológicas y sedimentológicas, junto con los cambios de espesor, permiten interpretar este ciclo superior como formado en ambientes aluviales, dentro de una cuenca de fondo extensional. En su evolución vertical, el Buntsandstein, pasa a depósitos de llanura costera. También corresponden a un ambiente litoral los sedimentos inmediatamente anteriores a la transgresión marina del Muschelkalk.

Palabras clave: Pérmico-Triásico, depósitos continentales, estratigrafía, petrografía de areniscas, volcanismo, Nurra, Cerdeña.

INTRODUCTION

As is known, palaeomagnetic, stratigraphic and structural research shows Hercynian and post-Hercynian Sardinia as having been linked to stable Europe. On the basis of the present geographical scenario, Sardinia presumably occupied an area between Provence and the northeastern sector of Spain. The former block only spread towards the Tyrrhene during subsequent geological events, and assumed its present position through a counterclockwise rotation that mostly took part in Miocene times (Westphal, Orsini & Vellutini, 1976, and others).

As a consequence, up to the Middle Triassic marine transgression, the post-Hercynian succession is represented in the isle, as in the above-mentioned contiguous regions, by continental sedimentary and igneous, intrusive and extrusive deposits. Substantial research has been dedicated to these deposits, which have often revealed significant data. However, many problems remain unsolved, so that general reconstructions and interregional correlations are very elusive.

This paper, which deals with a stratigraphic and petrographic examination carried out by the authors on some Permian and Triassic sequences in the Nurra area, is a first step towards such reconstructions and correlations.

STRATIGRAPHIC RECORD

The deposits investigated crop out in a traditional area to the north of Alghero, between Cala Viola, Lake Baratz and Punta Lu Caparoni (Fig.1). The deposits are widespread and, at thicknesses of up 250-300 m, well developed.

About 15 Km to the north of this area, the small post-Hercynian redbeds of Mount Santa Giusta also attracted our attention for their distinct petrographic characteristics.

Lower Permian deposits.—The basal part of the Permian-Triassic continental succession of Nurra is clearly exposed along the western side, a little below the peak, of the aforementioned Punta Lu Caparoni (Fig.1). The peculiar lithology of this lower section generally led previous authors to recognize a new Unit. Gasperi and Gelmini (1980) suggested that it should be defined as «Formazione di Punta Lu Caparoni», and the Unit is currently known as such in the literature.

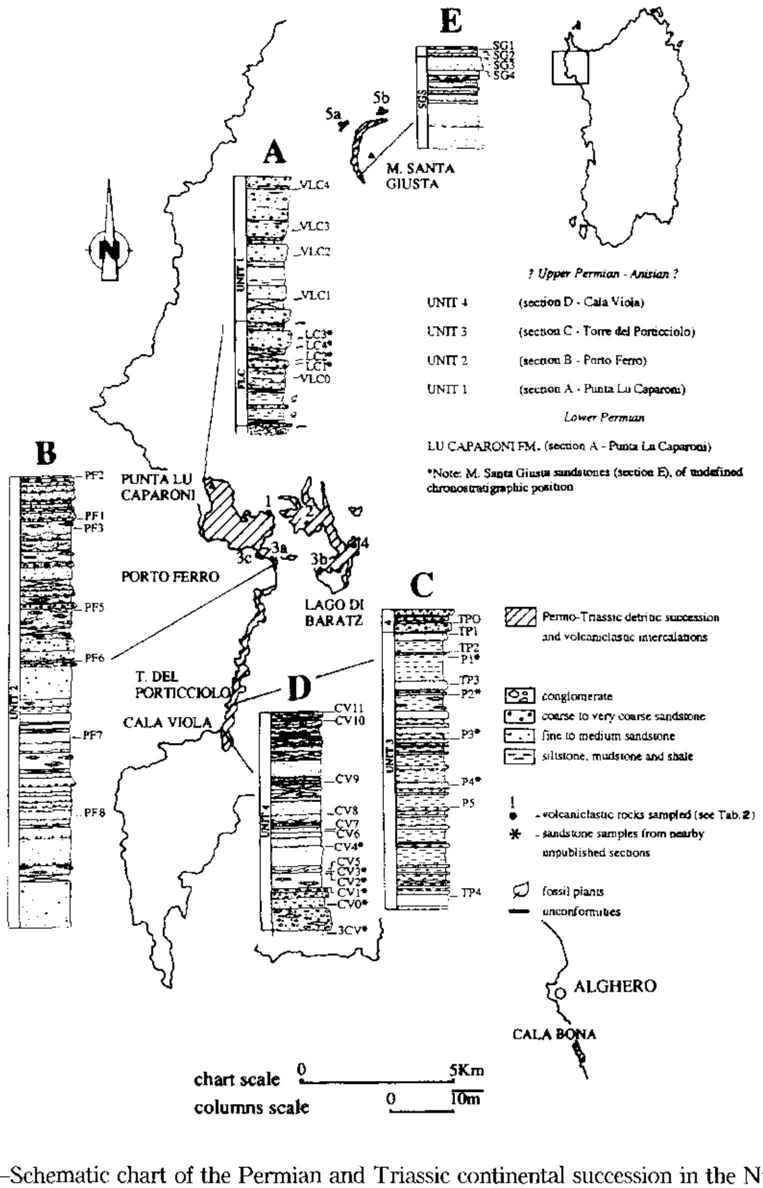

Fig. 1.—Schematic chart of the Permian and Triassic continental succession in the Nurra area (after Moretti, 1959, modified). Stratigraphic columns (scale 1:200), drawn up by A.Ronchi, only show some representative detritic sequences of single detritic Units.

Fig. 1.—Esquema de situación de la sucesión continental del Pérmico y Triásico en el área de Nurra (modificado de Moretti, 1959). Las columnas estratigráficas (escala 1:200), levantadas por A. Ronchi, muestran solo algunas secuencias detríticas representativas de Unidades detríticas simples.

The Lu Caparoni Fm. begins with a conglomeratic unit, about 1m thick, that bears rock fragments derived from the metamorphic Hercynian substrate. The boundary with this complex is marked by a pronounced unconformity, and by the presence of a palaeosol. Upwards of these basal conglomerates, there are 4-5m of grey-dark, laminated, sandstones, siltstones and shales, all rich in plant fossils. These deposits are intercalated with a conglomeratic bank, which contains quartz- metamorphic lithics. Some small ochreous, very thin beds of still uncertain nature (tuffaceous products?) occur locally.

The vegetal remains indicate an Autunian assemblage (Pecorini, 1962; Gasperi & Gelmini, 1980). Recently, this attribution has also been admitted by Broutin (pers. comm.), who determined a lot of specimens collected by Ronchi at the same levels.

A unit of 3-4m of light weathered massive strata crops out above. Minute inspection by Cortesogno and Gaggero led to the interpretation of these rocks as kaolinized cinerites. Their scattered ochreous crusts, which show volcanic quartz and rare metamorphic fragments, could have been formed in a pedogenetic environment. In the past, these volcaniclastic sediments were generally defined as calcareous deposits, and in particular by Gasperi and Gelmini (1980) as silicified carbonates. However, because these beds have also been signalled in other close sections of the investigated area, preliminary exclusion of such an origin is not possible. Silicified limestones inside some post-Hercynian sequences of Sardinia are indeed well known, e.g. in the Perdasdefogu basin of Ogliastra.

Upwards of these volcaniclastic products, the Lu Caparoni section displays abundant coarser-grained, detrital sediments that are rich in polygenic lithoclasts. However, small sandstone and siltstone siliciclastic lenticular bodies are again intercalated. The highest of these deposits also yields slightly reworked and thin-bedded tuffaceous material, which was subjected to kaolinisation and illitisation phenomena. The red-brownish crusts are probably linked to the presence of palaeosols. Contact between the above-mentioned conglomeratic bodies and these fine-grained intercalations is generally marked by synsedimentary erosion surfaces.

Throughout the section examined, the Lu Caparoni Fm. is overlain by light-coloured massive conglomerates and sandstones. A slight unconformity marks the boundary.

? Upper Permian-Anisian ? deposits.—The related clastic sediments lie between the Lu Caparoni Fm. and the Germanic Muschelkalk facies. Thus, their chronostratigraphic position extends from the Autunian of the first Unit up to the marine deposits of the second one, of which the beginning was tentatively assigned to Anisian on the basis of microfloristic data (Pittau Demelia & Flaviani, 1982). However, the possibility of a hiatus at the boundary with the underlying formation, along with the conspicuous lithologic and ge-

ometric changes in these younger deposits, impede a detailed understanding of their chronostratigraphic evolution. Further impediment derives from the paucity of existing palaeontological data, and from the doubts attached to their interpretation.

Gasperi and Gelmini (1980) subdivided this succession into four Units (Fig.1), which are characterized by (from bottom to top): 1) quartz withish massive conglomerates, with variable amounts of sandy matrix, and white sandstones, with horizontal bedding and bioturbation. This Unit essentially consists of metamorphic and volcanic quartz; the latter is connected with a more or less coeval volcanic activity, and is mixed with kaolinized products (30-40m thick); 2) alternation of reddish conglomerates and sandstones, both characterized by tabular and trough cross-stratification, channel fills, and intercalated with vivid red siltstone lenses. The conglomerates range in thickness from 2 to 15 m, and are composed of quartz, red volcanic and basement fragments (c. 150 m thick); 3) gray-greenish sandstones, from centimetrical to metrical in thickness, alternated with intense red siltstones. The sandstones show tabular and trough cross-stratification, mud cracks, as well as ripple marks (c. 50m thick); 4) reddish fine and medium-grained sandstones, in decimetrical beds, with tabular and trough cross-stratification and, at the top, ripple marks and bioturbation. A very coarse white quartz conglomerate, 3-6m thick, with red matrix, crops out at the lowermost part of the Unit (50-60m thick).

On the basis of their general properties (colour, structures etc.), only Units 3 and 4 are correlatable with typical Buntsandstein; the characteristics of Unit 1 tend strongly to preclude correlation. Accordingly, the denomination of all these deposits as «Verrucano Sardo» seems inappropriate, not least because the isle did not take part in the Permo-Triassic history of the Alpine and Apennine domain, where the Verrucano originated.

The above-mentioned stratigraphic Units (1and 2, and perhaps the basal part of 3) are mixed or intercalated with igneous, extrusive products. These crop out in reduced and scattered bodies, and generally exhibit a clastic nature which led some authors (Lombardi, Cozzupoli & Nicoletti, 1974) to the interpretation of these rocks as rhyolitic tuffs and ignimbrites. In this paper, Cortesogno and Gaggero, however, prefer to use the term «welded tuffs» in place of «ignimbrites» as a result of their unclear evidence on the field.

SANDSTONE PETROGRAPHY

The sandstones of the Permian-Triassic succession of Nurra were analysed in order to investigate their composition and provenance.

The sampling was conducted both within the Punta Lu Caparoni Fm. (FLC) and in the overlying succession, divided into four Units, in accordance with lithologic, sedimentologic and textural characteristics by Gasperi and

Gelmini (1980). The study also examined the clastic red facies underlying the M. Santa Giusta Middle-Triassic carbonate succession (Fig.1).

The Nurra sandstones are classified as metamorphic litharenites, volcanic litharenites, sublitharenites and subarkose (Folk, 1974), following the detailed petrographical analysis. This defines seven different petrofacies (Fig.2). Mineralogical maturity and textural trends record the evolution from lacustrine-alluvial to transitional-marine environment, from bottom to top, as confirmed by field evidence.

Detrital modes reflect composite source areas represented by low-grade metamorphics (Hercynian basement) and by a large amount of acidic volcanites. The M. Santa Giusta sandstones have been fed by different sources (mostly volcanic units).

METHODS OF STUDY

Fifty-eight unaltered samples (43 from measured sections and 15 from sparse outcrops), from Fine to Very Coarse grain size were studied microscopically. Three hundred points were counted on each thin section. Data recalculation (Tab.1) was conducted according to the Gazzi-Dickinson QFL method (Zuffa, 1985) and QFR (Folk, 1974). In the first method the L parameter conventionally represents only the afanitic lithics in order to limit the dependance of the detrital mode from grain size (Dickinson, 1970).

The widespread presence of pseudomatrix (Dickinson, 1970), derived from the alteration of volcanic grains and of kaolinite (derived by feldspar and glass alteration), counted in separate categories, led to substimed the lithic and feldspatic detrital fraction both in FLC and in Units 1 and 2.

STRATIGRAPHIC DISTRIBUTION OF PETROFACIES

The modal analysis indicates the existence of 7 different petrofacies (Fig.2).

Punta Lu Caparoni Formation (FLC)

Although moderate (< 15m) in thickness, the FLC shows two different petrofacies: P1LC (Q21 F0 L79) and P2LC (Q58 F0 L42).

P1LC is made up of poorly-sorted litharenites, dominated by metamorphic lithics, which characterise the lowermost detritic beds. This petrofacies has a high quartz percentage, mostly of the polycrystalline type (C/Q >0,84), and widespread low grade philladic fragments; this indicates erosion of the underlying Hercynian basement.

Sample	Units	Petrof.	Q	F	L	C/Q	P/F	V/L
Punta Lu-Caparoni								
VLC0	FLC	P1LC	29.4	0	70.5	0.89	—	0.20
LC1	FLC	P1LC	13.7	0	86.2	0.91	—	0.40
LC2	FLC	P1LC	20.3	0	79.6	0.84	—	0.35
LC3	FLC	P2LC	57.4	0	42.5	0.3	—	0.90
LC4	FLC	P2LC	59.0	0.8	40.1	0.24	—	0.81
VLC1	U1	PU1	67.3	0	32.6	0.34	—	0.98
VLC2	U1	PU1	50.7	0.3	47.8	0.4	0.5	0.94
VLC3	U1	PU1	54.3	0	45.2	0.48	—	0.91
VLC4	U1	PU1	61.5	0	37.5	0.45	—	0.91
Porto Ferro								
PF1	U2	PU2	59.7	0	40.2	0.65	—	0.86
PF2	U2	PU2	61.0	0	38.9	0.62	—	0.85
PF3	U2	PU2	59.3	1.9	38.7	0.77	—	0.89
PF5	U2	PU2	61.3	0.5	38.1	0.68	—	0.83
PF6	U2	PU2	64.6	0	35.3	0.68	—	0.81
PF7	U2	PU2	48.8	1.4	49.7	0.64	0.5	0.92
PF8	U2	PU2	55.6	0	37.5	0.72	—	0.89
Torre del Porticciolo								
TP4	U3	PU3	58.5	3.0	38.3	0.6	—	0.86
P5	U3	PU3	67.7	4.3	27.8	0.7	—	0.65
P4	U3	PU3	54.6	4.6	40.6	0.53	—	0.79
P3	U3	PU3	71.6	6.1	22.2	0.66	—	0.82
P2	U3	PU3	56.0	2.6	41.2	0.8	—	0.98
TP3	U3	PU3	71.4	8.4	20.1	0.64	—	0.88
P1	U3	PU3	55.8	0.9	43.1	0.51	—	0.88
TP2	U3	PU3	58.3	6.4	35.2	0.76	—	0.89
TP1	U3	PU3	80.1	3.4	16.4	0.63	—	0.71
TP0	U4	PU4	95	0.9	3.9	0.58	—	0.62
3CV	U3	PU3	45.7	6.4	47.8	0.31	—	1.00
Cala Viola								
CV0	U4	PU4	84.0	0.4	15.5	0.62	—	0.91
CV1	U4	PU4	76.6	1.0	22.3	0.39	—	0.93
CV2	U4	PU4	77.4	0	22.5	0.47	—	0.97
CV3	U4	PU4	88.0	0.4	11.5	0.56	—	0.96
CV4	U4	PU4	88.0	0	11.9	0.41	—	1.00
CV5	U4	PU4	89.2	2.1	8.6	0.63	—	0.84

Sample	Units	Petrof.	Q	F	L	C/Q	P/F	V/L
Cala Viola								
CV6	U4	PU4	76.4	2.1	21.3	0.37	—	0.79
CV7	U4	PU4	85.1	5.7	9.1	0.42	—	0.68
CV8	U4	PU4	88.2	6.7	4.9	0.25	0.4	0.63
CV9	U4	PU4	87.5	5.0	7.5	0.22	—	0.83
CV10	U4	PU4	75.1	4.2	20.6	0.24	0.25	0.96
CV11	U4	PU4	85.7	2.5	1.6	0.24	—	0.88
M. Santa Giusta								
SG1	SGS	PSGS	79.4	18.4	2.1	0.11	0.38	0.04
SG2	SGS	PSGS	66.4	22.7	10.7	0.2	0.1	0.58
SG3	SGS	PSGS	72.7	25.5	1.7	0.6	0.66	0.06
SG4	SGS	PSGS	84.1	14.2	1.6	0.41	0.11	0.16

Table 1.—Point counting data for 58 sandstone samples of the Permian-Triassic continental succession in the Nurra area. Units: Punta Lu Caparoni Fm. (FLC); Unit 1 (U1); Unit 2 (U2); Unit 3 (U3); Unit 4 (U4); Santa Giusta sandstones (SGS). Petrofacies: P1LC (petrofacies 1-Lu Caparoni); P2LC (petrofacies 2-Lu Caparoni); PU1 (petrofacies Unit 1); PU2 (petrofacies Unit 2); PU3 (petrofacies Unit 3); PU4 (petrofacies Unit 4). Q = quartz; F = feldspar; L = aphanitic lithic fragment; C/Q = polycrystalline/total quartz ratio; P/F = plagioclase/total feldspar ratio; V/L = volcanic fragments/total lithics ratio.

Tabla 1.—Datos del contaje de puntos en 58 muestras de areniscas, de la sucesión continental del Pérmico-Triásico en el área de Nurra. Unidades: Fm. Punta Lu Caparoni (FLC); Unidad 1 (U1); Unidad 2 (U2); Unidad 3 (U3), Unidad 4 (U4); Areniscas de Santa Giusta (SGS). Petrofacies: P1LC (petrofacies 1-Lu Caparoni); P2LC (petrofacies 2-Lu Caparoni); PU1 (petrofacies Unidad 1); PU2 (petrofacies Unidad 2); PU3 (petrofacies Unidad 3); PU4 (petrofacies Unidad 4). Q = cuarzo; F = feldespato; L = fragmentos líticos afaníticos; C/Q = relación policristalinos/cuarzo total; P/F = relación plagioclasas/feldespato total; V/L = relación fragmentos volcánicos/líticos totales.

P2LC consists of litharenites, dominated by volcanic lithics, which characterise the medium and upper clastic parts of the Lu Caparoni Fm. This petrofacies suggests that the input of volcanic grains has became dominant. Petrographical changes are gradual within P1LC, but abrupt passing from P1 to P2. This is shown by a dramatic increase of both the monocrystalline quartz grains (often embayed) and the volcanic fragment percentages.

Permian-Triassic succession

The petrofacies of *Unit 1* (PU1) shows a Q59 F1 L40 composition and can be distinguished from the underlying P2LC by its different C/Q ratio

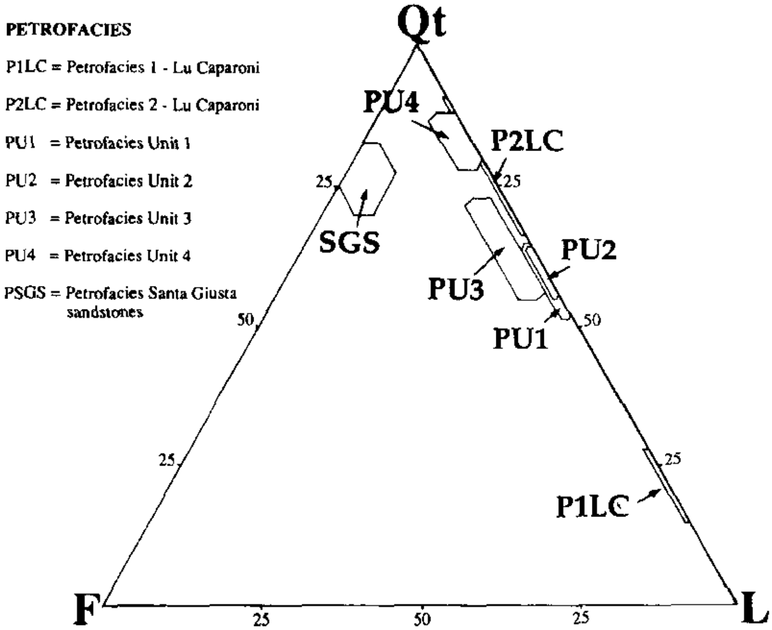

Fig. 2.—Compositional ternary diagram of the Nurra Permian-Triassic sandstones. Qt = total quartz; F = feldspars; L = aphanitic lithic fragments. The seven petrofacies are indicated by polygons: individual polygons show one standard deviation on both sides of the mean value of each parameter. In petrofacies P2LC, PU1 and PU2, both feldspathic (F) and lithic (L) percentages are underestimated because of their abundant content of secondary matrix (pseudomatrix) and replacive kaolinite.

Fig. 2.—Diagrama ternario composicional de las areniscas permo-triásicas de Nurra. Qt = cuarzo total; F = feldespatos; L = fragmentos líticos afaníticos. Las siete petrofacies están indicadas por polígonos: los polígonos individuales muestran una desviación estandar a ambos lados del valor medio de cada parámetro. En las petrofacies P2LC, PU1 y PU2, los porcentajes de feldespatos (F) y líticos (L), están subestimados a causa de su abundante contenido en matríz secundaria (pseudomatríz) y caolinita de remplazamiento.

(between 0,34 e 0,5) and V/L ratio (>0,9). Sorting is moderate-poor. Quartz fragments are of two types; those polycrystalline are well rounded, whereas those volcanic are more prevalent, frequently embayed and are angular in shape.

The petrofacies of *Unit 2* (PU2) has Q59 F1 L40 grain proportions. Secondary parameters show an increase of polycrystalline quartz (C/Q > 0,6) and a decrease of volcanics (V/L < 0,9). Sandstone sorting is poor. The lithic fragments, as well as the authigenic carbonates (averaging 6-8% of total rock) and the Fe opaques are commonly altered and the rock itself exhibits a reddish colour.

The overlying Units 1 and 2 show detrital modes similar to the P2PC and indicate a mixed crystalline and volcanic source area. In these petrofacies the volcanic fragments are usually vitric and porphyric, but sometimes they show ignimbrite-like flow textures; kaolinite «booklet» crystals of secondary origin are pervasively developed. The presence of opaques (iron and titanium oxides) is widespread.

Unit 3 is characterised by litharenites and sublitharenites moderately-poor to moderately-well sorted. The petrofacies of Unit 3 (PU3) exhibits an average mode Q64 F4 L32. These sandstones differ markedly from the previous ones in their higher compositional maturity, with an increase in quartz content, frequently with authigenic overgrowths, associated with a parallel decrease of the lithic constituents (average V/L ratio = 0,82). Polycrystalline quartz prevails on monocrystalline quartz. The alkaline feldspars, sometimes perthitic and always kaolinized, reach their relative maximum.

The high quartz percentage and the abundance of heavy minerals (zircon, tourmaline, rutile and titanite) as well as white mica, suggest a more selective environment (littoral). Authigenic calcitic, dolomitic and ferroan patchy carbonates are widespread; in some samples they represent one third of the rock.

Unit 4 is made up of orthoquarzites, moderately to well sorted and therefore represents a distinct petrofacies (PU4). The detrital mode is Q83 F3 L14; quartz fragments always show large syntaxial overgrowths (averaging 20% of total rock) and C/Q ratio decreases from 0,6 at the section's base to 0,2 at its top.

Primary porosity has also been reduced by authigenic carbonates enucleating initially from the fine matrix and also replacing the framework grains with a patchy appearance. A similar textural feature is found in baritic cement present locally.

Rock fragments are very poorly represented; among them, those volcanic, sometimes kaolinized, prevail. Enrichments of heavy minerals (zircon, tourmaline, titanite and rutile) often concentrated in laminae are present, as well as hematitic and titaniferous opaques. Complex diagenetic recrystallization occurs expecially in interstitial ferruginous and carbonatic matrix.

At the very base of this Unit, in association with quartz conglomerates, sandstones show a very low percentage of both feldspar and authigenic carbonate.

The *M. Santa Giusta sandstones* (SGS) are moderately-poor sorted, with an arkose-subarkose composition Q76 F20 L4. They represent a markedly different petrofacies (PSGS), showing high percentage of quartz and feldspar (rare microcline with cross-hatched twinning and frequent orthoclase-sanidine with Carlsbad twinning), together with scarce rock fragments. Monocrystalline quartz generally prevails over the polycrystalline type; their roundness varies from the well rounded to the angular class. The authigenic pervasive calcite (averaging 20%), of late origin, replaces all mineral phases.

Permo-Triassic succession

1. *Pedru Siligu* (LC2-2): near the boundary between the Lu Caparoni Fm. and the overlying unit 1.
2. *Casa Satta* (ARCS 18-19-20-21-22): between units 1 and 2.
3a. *Torre Bianca* (LC 2-17): lithoclast from a channelled massive conglomeratic body, along the beach.
3b. *Lago di Baratz* (LC 2-12): lithoclast from unit 2, at the side of lake.
3c. *Torre Negra* (ARTN/1): lithoclast from unit 2, to the north of the tower.
4. *Ponte Crabolu* (PC 14): tuffaceous rocks from the lower part of unit 3, at the side of the road. (After Gasperi & Gelmini, 1980).

M. Santa Giusta

5a. *Mancineddu* (ARSG 23-24): below the red sandstones, which underlie the Middle-Triassic Muschelkalk.
5b. *Pozzo San Nicola* (ARSG 26): below the red sandstones, which underlie the Middle-Triassic Muschelkalk.

Table 2.—Location and indicative stratigraphic position of the volcaniclastic rock samples analysed (see Fig.1).
Tabla 2.—Localización y posición estratigráfica de las muestras de rocas volcanoclásticas analizadas. (ver Fig. 1).

Even if these sandstones seem to pass gradually to the overlying Muschelkalk carbonates, they do not show similarities with those present in the uppermost part (PU4) of the clastic southern sequence.

VOLCANIC ACTIVITY

Petrographic features

The Permian-Triassic volcanism in Nurra is shown by pyroclastic deposits, or by reworked pyroclastic products (Fig. 1 and Tab. 2). Some widespread petrographic features are common to all volcanites and suggest a possible common origin: phenoclasts are represented by corroded quartz, sanidine and biotite; zircon and apatite are accessory phases; Fe-Ti oxides are common, at least in part replacing biotite. Fragments of welded hyaloclastic tephra and pumices are frequent. Cavities and bubbles are frequently filled by quartz, and/or calcedony, sometimes with zeolites.

In the predominant welded tuff from *M. Santa Giusta* , broken crystals and streaked glass lie in a matrix of bubble fragments affected by planar lamination (Figs. 3 and 4).

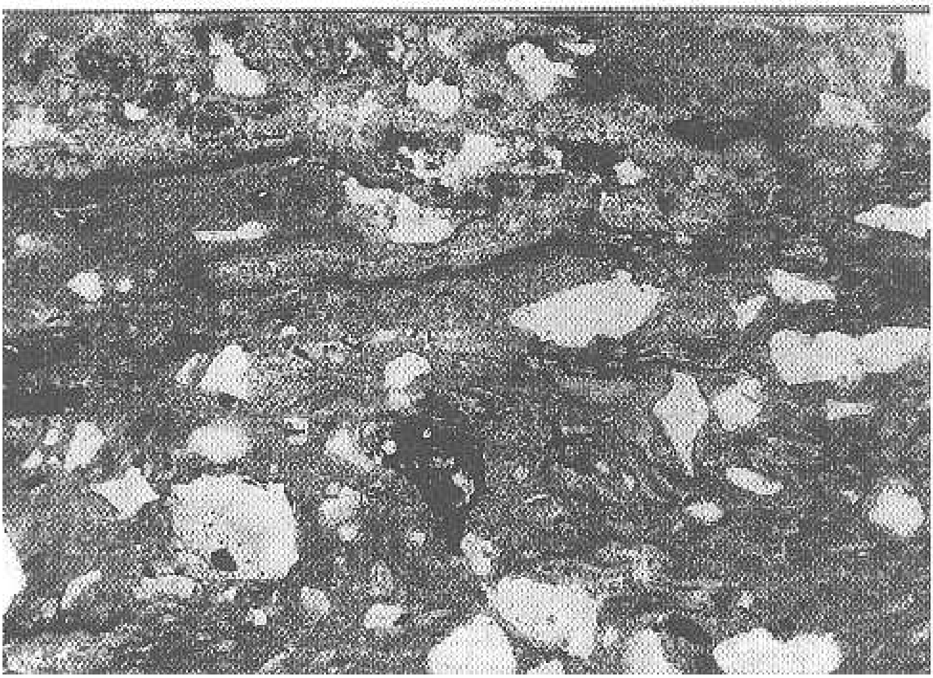

Fig. 3.—K-feldspars, quartz, biotite phenoclasts and pumiceous fragments in eutaxitix vitroclastic matrix. Polarized light, scale: photo lenght 4.5 mm.
Fig. 3.—Feldespato potásico, cuarzo, fenocristales de biotita y fragmentos de pumita en una matríz vitroclástica eutaxítica. Luz polarizada, escala : longitud de la fotografía 4,5 mm.

The mesostasis is extensively replaced by kaolinite, illite and Fe-hydroxides. Porosity is filled by aggregates of radiating kaolinite, calcedony, fibrous zeolites and microcrystalline to granoblastic quartz. K-feldspar is generally preserved, whereas biotite is in part affected by dehydration processes during magma uprise or altered to secondary phyllosilicates (celadonite, kaolinite, illite) and opaque oxides. K-feldspar and biotite are largely preserved, and secondary alteration is moderate.

At *C. Satta* tuffs with fall deposit textures are dominant, whereas welded tuffs are subordinate. Some pyroclastites contain clasts of quartzmicaschists derived from the metamorphic basement; angular fragments occur locally with coarse-grained mosaic calcite and Fe-hydroxide pigmentation. Biotite is generally altered to secondary phyllosilicates (white mica and illite), whereas K-feldspar is largely replaced by kaolinite. The matrix mostly contains broken bubbles replaced by aggregates of predominant microcrystalline quartz, with kaolinite, calcedony and Fe-hydroxides.

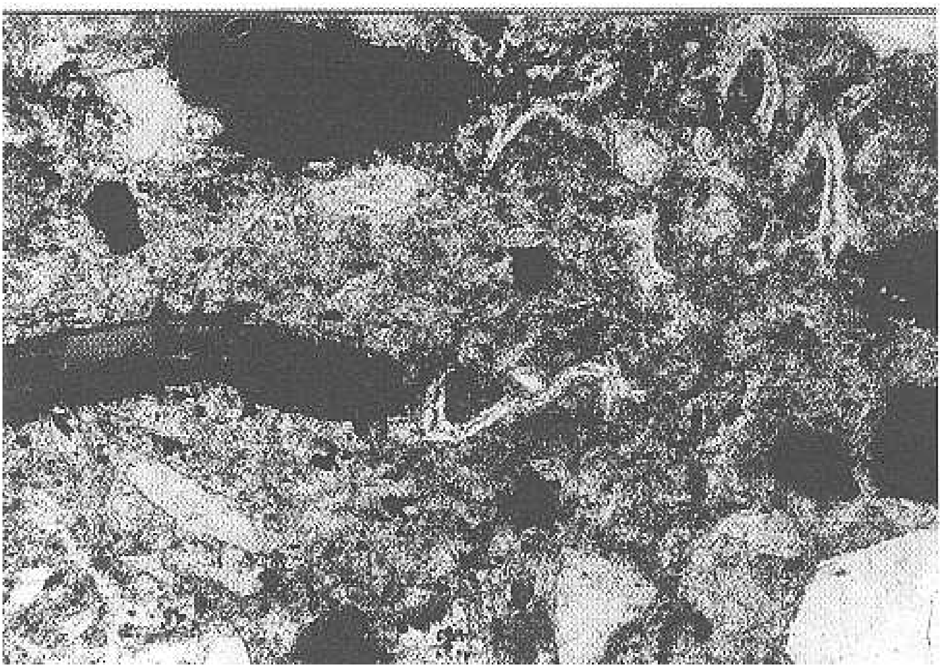

Fig. 4.— Broken bubbles texture in completely devitrified matrix; K-feldspar and partially dehydrated biotite phenoclasts. Polarized light, scale: photo length 1.5 mm.
Fig. 4.—Textura de burbujas rotas en una matríz completamente desvitrificada; feldespato potásico y fenocristales de biotita parcialmente deshidratados.

At *C. Pedru Siligu* and at *Ponte Crabolu*, volcanites are well sorted tuffitic sandstones, including clasts of volcanic quartz, fragments of vitric volcaniclastites and basement lithoclasts in varying amounts.

Volcanic lithoclasts in conglomerates from *Torre Negra*, *Torre Bianca* and *Lake Baratz* contain: 1) Welded tuffs with phenoclasts of quartz, biotite (altered to secondary phyllosilicates), and K-feldspar (pervasively kaolinized); vitric components are altered to quartz, calcedony, Fe-hydroxide aggregates. Kaolinite, illite, celadonite and barite are widespread. Radiating to spherulitic aggregates of K-feldspar, albite, quartz, calcedony with hydroxide pigmentation are the result of devitrification; for increasing hydrothermal alteration they are associated or replaced by kaolinite, illite, celadonite, chlorite. 2) Fall out tuffs with quartz, K-feldspar and biotite phenoclasts. The vitric lithoclasts and the vitroclastic matrix are altered to kaolinite and microcrystalline quartz.

Occurrence	Casa Satta	Casa Satta	Casa Satta	Casa Satta	Casa Satta	C. Pedru Siligu	Lago Baratz	Torre Bianca	Ponte Crabolu	M. Santa Giusta Nurra N	M. Santa Giusta Nurra N	M. Santa Giusta Nurra N
Sample	CS1 8	CS1 9	CS20	CS21	CS22	LC2-2	LC2-12	LC17	PC14	SG23	SG24	SG26
Oxides wt%												
SI02	83.13	85.07	80.65	80.93	78.81	86.68	85.91	82.88	64.70	72.81	70.67	69.98
TI02	0.14	0.12	0.15	0.09	0.16	0.10	0.28	0.25	0.58	0.19	0.26	0.25
AI203	10.66	9.59	12.70	13.15	10.72	9.33	7.51	9.22	21.59	14.02	15.60	16.19
Fe203	2.42	1.94	2.12	1.40	2.27	1.52	3.02	3.78	2.78	1.94	2.45	3.10
Mn0	0.03	0.03	0.06	0.01	0.14	0.00	0.01	0.04	0.01	0.03	0.03	0.02
Mg0	0.12	0.00	0.03	0.04	0.90	0.00	0.30	0.12	1.25	0.36	0.75	0.51
Ca0	0.13	0.06	0.10	0.03	1.79	0.03	0.05	0.13	0.03	0.34	0.56	0.28
Na20	0.03	0.02	0.03	0.02	0.04	0.01	0.01	0.16	0.12	0.12	0.49	0.37
K20	0.55	0.34	0.59	0.73	0.88	0.32	1.49	0.87	3.85	8.38	6.65	7.21
P205	0.06	0.06	0.08	0.03	0.03	0.04	0.03	0.04	0.06	0.26	0.24	0.08
L.O.I.	2.74	2.77	3.49	3.57	4.25	1.96	1.37	2.51	5.12	1.55	2.31	1.99
K20/Na20	18.33	17.00	19.67	36.50	22.00	32.00	149.00	5.44	32.08	69.83	13.57	19.49
Trace ppm												
Ba	327	365	379	179	253	192	314	2076	269	649	655	550
Co	22	27	18	19	22	35	21	32	14	14	31	15
Cr	11	7	8	6	22	11	14	8	39	7	8	7
Cu	3	<2	<2	<2	27	<2	16	4	11	10	4	13
Nb	6	6	7	10	6	5	7	11	17	6	6	7
Nd	18	13	17	20	13	25	15	30	39	23	24	18
Ni	<2	<2	<2	<2	7	<2	<2	<2	17	<2	<2	23
Pb	7	5	6	3	6	41	17	7	11	8	16	9
Rb	25	14	21	29	47	10	77	40	230	132	142	171
S	277	31	51	74	88	156	115	1770	126	145	570	105
Sc	<5	<5	5	5	8	<5	7	<5	16	<5	<5	6
Sr	48	38	42	41	33	98	31	86	89	23	33	55
Y	15	12	15	18	17	17	26	41	39	19	17	21
Zn	10	8	15	10	16	8	18	12	55	24	26	19
Zr	91	72	87	71	72	83	118	185	275	125	158	157

Table 3.—Bulk rock analyses of the Nurra volcanites.

Tabla 3.—Conjunto de análisis realizados de las volcanitas de Nurra.

Analytical techniques

Whole rock major and trace element abundances in the Nurra volcanites (Tab.3) were determined by XRF techniques using a Philips PW 1480 XR spectrometer at the Dipartimento di Scienze della Terra, Università di Genova. Intensities were examined according to Franzini, Leoni and Saitta's (1975), and Leoni and Saitta's (1975) methods. Loss on ignition (L.O.I.) was determined by the gravimetric method.

Petrochemical features

Whole rock analyses were carried out on 12 samples of Permian-Triassic volcanites from Nurra. In Tab.3 selected representative compositions are reported.

In Casa Satta volcanites and in the volcanic clasts of Lake Baratz and Torre Bianca, the high SiO_2 contents (up to 77 wt%), and apparent alkalis depletion are a consequence of silicification and kaolinization. The low Al_2O_3 and TiO_2 and high Fe_2O_{3tot} contents are in accordance with the pervasive silicification and impregnation by Fe-oxides (Fig. 5).

On the classificative Total Alkalis-Silica diagram (Cox, Bell & Pankhurst, 1979, not reported) M. Santa Giusta volcanites are in accordance with data in Lombardi *et al.* (1974), and fall within the alkali-rhyolite field near the subalkaline-alkaline boundary; on the whole, the result is a potassic affinity. Part of trace elements are only affected to a minor extent by secondary mobilizations. Chlorite and kaolinite in the matrix (Ponte Crabolu) and the occurrence of clasts of the metamorphic basement (C. Pedru Siligu) account for the scattered chemical data of tuffites.

However, Ponte Crabolu volcanites show anomalous high Cr, Ni, Nb, Rb, Sc, Y and Zr, and are probably a consequence of some degree of sedimentary reworking. Conversely, the silicified clasts from Torre Bianca show high Ba, Sr and Y (Fig.6).

In spite of the pervasive secondary mobilizations evidenced by petrography and chemistry, the alkaline affinity of the Nurra volcanites (already hypothesized by Lombardi et al., 1974) is confirmed by the normalized Rock/MORB spiderdiagrams (Pearce, 1983; Fig. 7). On the other hand, Casa Satta volcanites are remarkable for a calcalkaline-type pattern; this can be either primary or induced by important secondary depletion of mobile elements.

CONCLUDING REMARKS

The Permian-Triassic continental succession of the Nurra area, near Alghero, consists of a number of stratigraphic Units, which can be subdivided

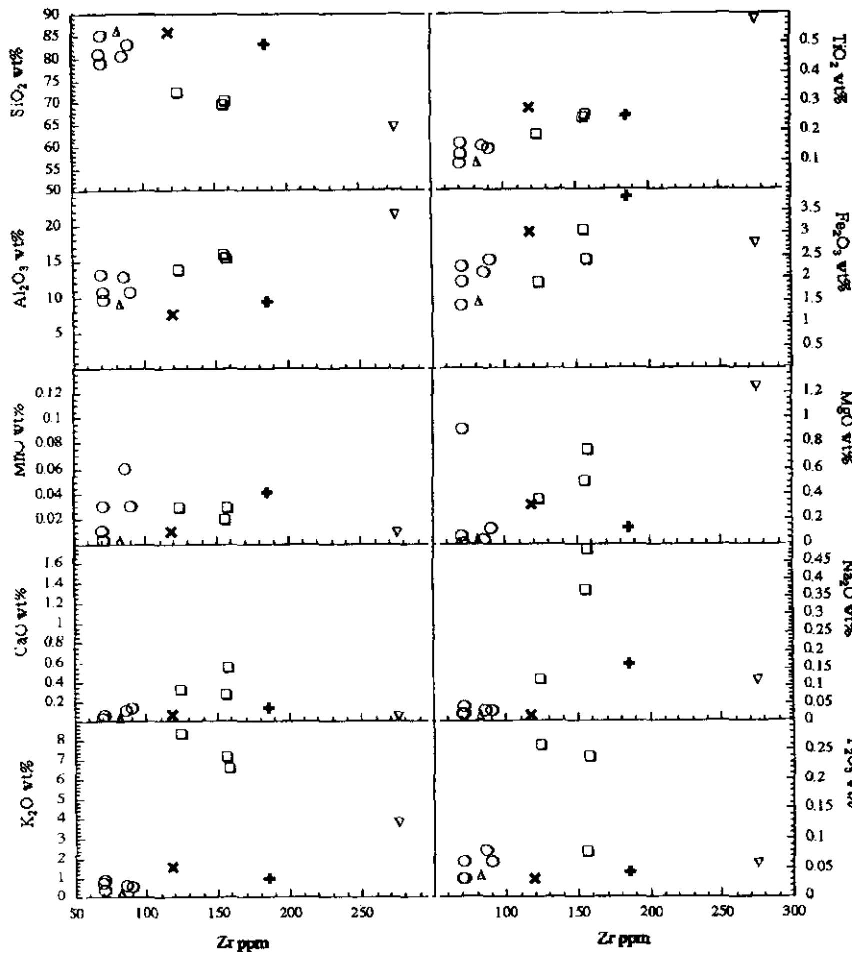

Fig. 5.—Major elements vs. Zr for Nurra volcanites. Symbols. Square: M. Santa Giusta; Circle: Casa Satta; Triangle C. Pedru Siligu; Inverted triangle: Ponte Crabolu; Cross: Torre Bianca; Asterisk: Lake Baratz.

Fig. 5.—Elementos mayores vs. Zr de las volcanitas de Nurra. Símbolos; cuadrados: M. Santa Giusta; *círculos*: Cassa Satta; *triángulos*: C. Pedro Siligu; *triángulos invertidos*: Ponte Crabolu; cruces: Torre Bianca; asteriscos: Lago Baratz.

into at least two tectonosedimentary cycles. The lower cycle (1) is represented by the alluvial-lacustrine deposits of Lu Caparoni Fm., rich in Autunian plants. These deposits, whose thickness does not exceed 15 m, rest unconformably upon the Hercynian crystalline basement. However, some sediments, which in the past have been interpreted as silicified limestones, along with

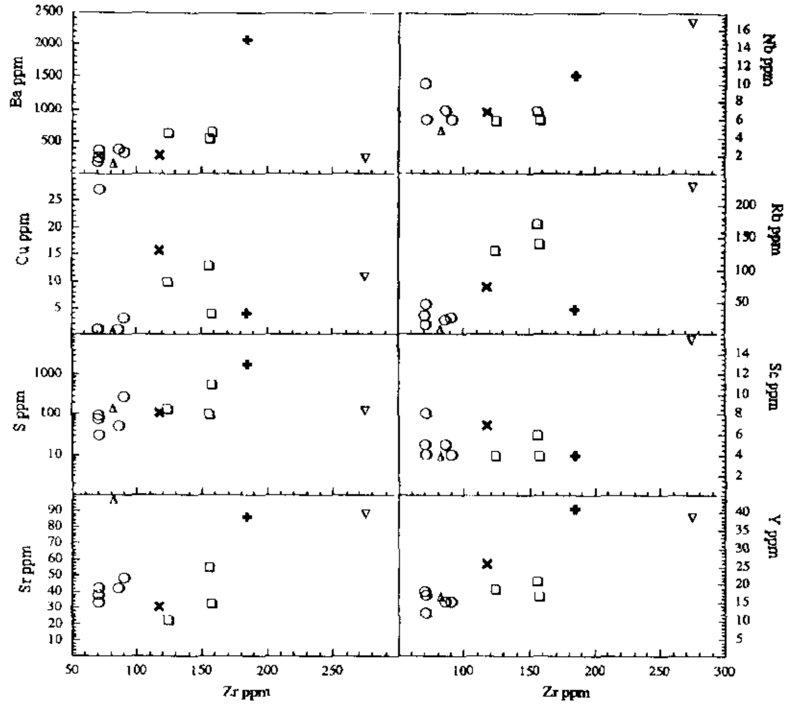

Fig. 6.—Trace elements vs. Zr for Nurra volcanites. Symbols as in Fig. 5.
Fig. 6.—Elementos traza vs Zr de las volcanitas de Nurra. Símbolos como en Fig. 5.

some sandstones are evidence of coeval volcanism. This igneous, extrusive activity started with the emission of cinerites.

The upper cycle (2) is made up of a detritic succession which, at thicknesses of 250-300 m, is decidedly more developed than the lower cycle. The succession is characterized by continuous alternation of conglomerates, sandstones and siltstones of prevalent reddish colour, subjected to frequent facial and geometrical changes. This detritic succession could be assigned to a generic Upper Permian to Middle Triassic (presumably Anisian in age), because of the palaeontological data from the stratigraphic boundaries with the Lu Caparoni Fm. and the overlying Muschelkalk, combined with petro-chemical analysis of contemporaneous volcanic deposits.

The co-existing volcanic rocks are composed of pyroclastics and ignimbrites (welded tuffs), acidic in composition. More or less reworked tuffaceous products also occur.

The sandstones of Units 1 and 2 show a rather uniform petrofacies, which is similar to that of the upper part of Lu Caparoni Fm. Clasts derived from the

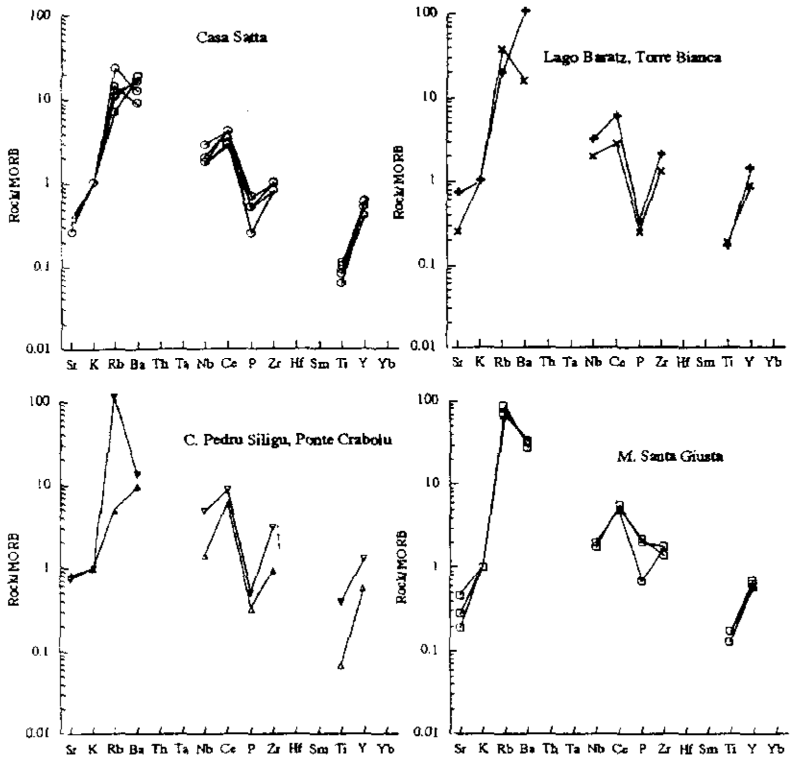

Fig. 7.—Rock-MORB (Pearce, 1983) spiderdiagram for Nurra volcanites. Symbols as in Fig. 5.
Fig. 7.—Diagrama «Rock-MORB» (Pearce, 1983) de las volcanitas de Nurra. Símbolos como en Fig.5.

Hercynian basement and the aforementioned volcanics have features in common.

The peculiar petrofacies of the Mt. S. Giusta red sandstones, near the boundary with the overlying Muschelkalk, is in part linked to the erosion of volcanic rocks. The high percentage of quartz, feldspars and the scarse amount of rock-fragments, markedly differ from those observed in the sandstones of the Alghero area. As a consequence, new research on these uppermost rocks is necessary in order to ascertain their chronostratigraphic position and to reconstruct the still doubtful geological evolution of the local sector.

All these volcaniclastic sediments, which have been subjected to pronounced and coeval erosion, probably took place during the Permian. This is suggested by their alkaline affinity (mostly evident in the very few weathered products of M. Santa Giusta), which is widely evident in the Upper Permian of Corsica and Provence, i. e. in regions countiguous to Sardinia at that time.

Units 3 and 4, which mark the beginning of typical Buntsandstein, introduce new geological situations. Conglomerates, sandstones and siltstones are mostly rich in basement quartz-clastics, probably due to the extinction of volcanic activity and to a renewed structural setting. Step by step, the swell and basin extensional framework, which generally received alluvial deposits, underwent a continuous levelling and, during the Middle Triassic marine transgression, gave rise to coastal plain and littoral deposits.

ACKNOWLEDGEMENTS

This work was supported by grants from MURST (40%, 60%) and CNR. A. Ronchi is grateful to M.Gaetani, E.Garzanti and D.Sciunnach for their help during a first examination of the sandstone petrofacies described in the text.

This paper is dedicated to the memory of our friends Rodolfo Gelmini and Amparo Ramos, who carried out a great and important research activity on the Permian and Triassic successions of the western Mediterranean areas.

REFERENCES

Cox, K.G., Bell, J. D. & Pankhurst, R. J. (1979), *The interpretation of igneous rocks,* Allen & Unwin, London, 450 pp.

Dickinson, W. R., (1970), «Interpreting detrital modes of graywacke and arkose», *Journ. Sed. Petrol.*, 40, 695-707.

Folk, R. L. (1974), *Petrology of sedimentary rocks*, Hemphill's Bookstore, Austin, Texas, 182 pp.

Franzini, M., Leoni, L. & Saitta, M. (1975), «Revisione di una metodologia analitica per fluorescenza-X basata sulla correzione completa degli effetti di matrice», *Rend. Soc. Ital. Mineral. Petrol.*, 31, 365-378.

Gasperi, G. & Gelmini, R. (1980), «Ricerche sul Verrucano. 4. Il Verrucano della Nurra (Sardegna nord-occidentale)», *Mem. Soc. Geol. Ital.*, 20, 215-231.

Leoni, L. & Saitta, M. (1975), «X-ray fluorescence analysis of 29 trace elements in rocks and mineral standards», *Rend. Soc. Ital. Mineral. Petrol.*, 32, 497-510.

Lombardi, G., Cozzupoli, D. & Nicoletti, M. (1974), «Notizie geopetrografiche e dati sulla cronologia K-Ar del vulcanismo tardopaleozoico sardo», *Period. Mineral.*, a. 43, 221-312.

Moretti, A. (1959), *Carta geologica d'Italia alla scala 1:100.000, F.179 «Porto Torres»,* Servizio Geologico d'Italia, Roma.

Pearce, J.A. (1983), «The role of sub-continental lithosphere in magma genesis at destructive plate margins», in Hawkesworth, C.J. & Norry, M. J. (eds.), *Continental basalts and mantle xenoliths*, Nantwich, Shiva, 230-249.

Pecorini, G. (1962), «Nuove osservazioni sul Permico della Nurra (Sardegna nord-occidentale)», *Atti Acc. Naz. Lincei*, Rend. Cl. Sc. fis., mat. e nat., s. 8, 32 , 377-380.

PITTAU DEMELIA, P. & FLAVIANI, A. (1982), «Aspects of the palynostratigraphy of the Triassic Sardinian sequences (Preliminary Report)», *Rev. Palaeobot. Palynol.*, 37, 329-343.

WESTPHAL, M., ORSINI J. & VELLUTINI, P. (1976), «Le microcontinent Corso-Sarde, sa position initiale: données paléomagnétiques et raccords géologiques», *Tectonophysics* , 30, 141-157.

ZUFFA, G. G. (1985), «Optical analyses of arenites: influences of methodology on compositional results», in Zuffa, G. G. (ed.), *Provenance of Arenites*, NATO-ASI Series, Reidel, Dordrecht, 165-189.

Manuscrito recibido: 8-4-1996
Manuscrito aceptado: 12-6-1996