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The Permo-Triassic clastics of Nurra: sedimentology, heavy mineral provinces and palaeogeography

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Introduction

Palaeogeographic reconstructions of Sardinia in the late Paleozoic have great bearing to unravelling the ancient geological scenarios of post-Variscan southern Europe. Until recently, detailed reconstructions in this area have been largely hampered by the poor exposure of Permian sedimentary rocks, the scarcity of biostratigraphic checkpoints, and the disruption of the Hercynian range during the Alpine evolution of the Western Mediterranean, which since the Early Miocene has rotated the Corso-Sardinian Block counterclockwise with respect to stable Europe.

At the end of the Paleozoic, Sardinia was close to the continental platform bordering the western edge of the Tethys Ocean (Golonka *et al*., 1994). Post-orogenic clastic sedimentation in a continental setting started in the Westphalian (Fontana *et al*., 1982) but was confined to small fault-bounded basins up to Saxonian-Kungurian times (Broutin *et al*., 1994). Intercalations of intermediate to acidic volcanics occur at various levels in the Permian succession, documenting post-orogenic magmatism coeval with sedimentation.

In the Nurra region, Lower Permian clastics occur as small, scattered outcrops, whereas mid-Permian to Anisian clastics are better exposed in two distinct outcrop areas, from Porto Ferro to Cala Viola near the Torre del Porticciolo village, and at Monte Santa Giusta. In the present paper, sedimentological observations and quantitative heavy mineral data from the considered succession are interpreted in the framework of the available regional and stratigraphic information.

Regional and stratigraphic framework

Similarities between the post-Variscan sedimentary successions of Sardinia and the classical Permo-Trias of Germany were recognised more than a century ago (Lovisato, 1884; De Stefani, 1891). However, above the oldest clastic deposits, unconformably overlying the metamorphic basement (Rotliegend), no Zechstein evaporites are found in Sardinia. Instead, a thick clastic succession of fossil-barren red beds passes upwards to a more characteristic Buntsandstein (Vardabasso, 1966). The Middle and Upper Triassic of Sardinia are widely held as displaying a typical Germanic facies, with well represented Muschelkalk carbonates and Keuper evaporites; actually, the Muschelkalk facies of mid-Carnian age in Sardinia (Carrillat *et al*., 1999) would find no analogue in Germany, where the Muschelkalk/Keuper boundary falls well into the Ladinian (Aigner & Bachmann, 1998). This interpretation has been recently questioned in Costamagna & Barca (2002), who ascribe the topmost "Muschelkalk" carbonates according to Carrillat *et al*. (1999) to the Keuper, based on the finding of evaporite crystals to pseudomorphs. In this view, the Carnian part of the carbonate succession would largely fit in the classical Germanic triad.

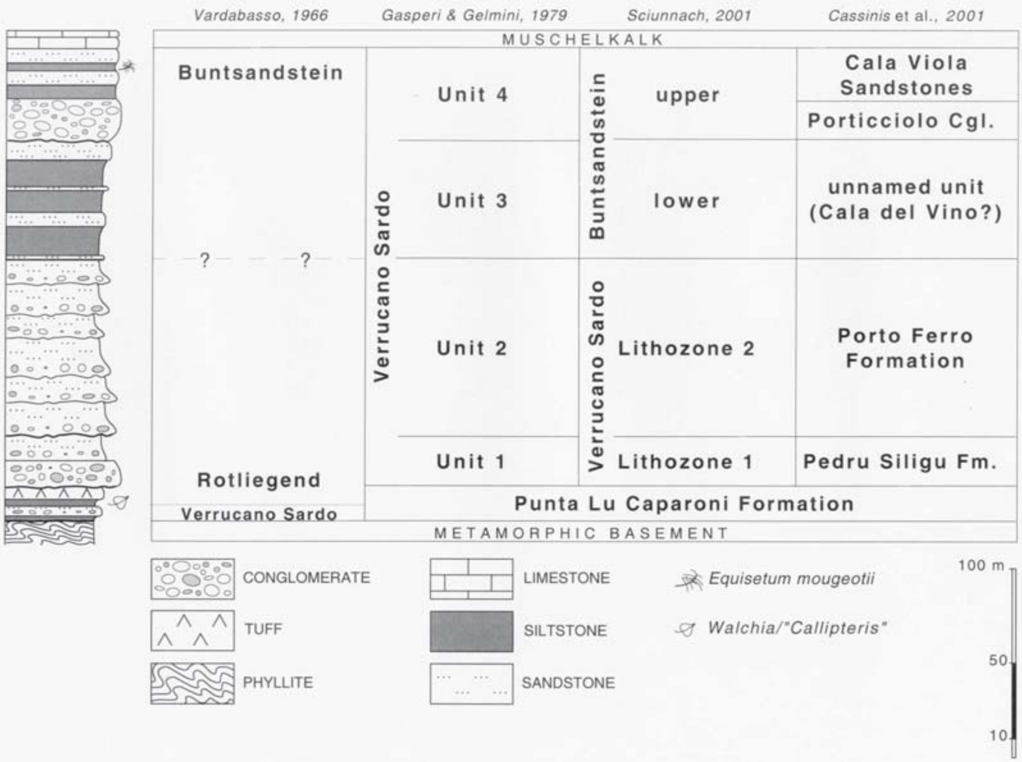

Fig. 1 - Stratigraphic framework for the Permian-Triassic clastic succession of Nurra, bracketed between the Hercynian metamorphic basement and the Middle Triassic transgressive carbonates in Muschelkalk facies. A simplified sketch of the thickest and most complete section, from Punta Lu Caparoni to Cala Viola, is displayed to the left.

Clastic sedimentation after the Variscan metamorphism began in north-western Sardinia with lacustrine fanglomerates to mudrocks, up to 15 m-thick (Punta Lu Caparoni Formation) overlain by alluvial red beds, up to 250 m-thick ("Verrucano Sardo") and subdivided into four informal units of lesser rank, numbered 1 to 4 in ascending stratigraphic order (Gasperi & Gelmini, 1979). Although new names have been recently proposed for the four lithozones (Sciunnach, 2001; Cassinis *et al.*, 2001), and one of them has been split in two (Cassinis *et al.*, 2001), this scheme has undergone only minor changes to date (Fig. 1).

Within the whole clastic succession, the only valuable biostratigraphic data are reported from the Punta Lu Caparoni Formation, where upper Autunian (~ Artinskian) macro- and microfloral remains occur (Pecorini, 1962; Broutin *et al.*, 1996; Ronchi *et al.*, 1998), and from the upper part of the "Verrucano Sardo" at Cala Viola, where abundant remains of the Triassic *Equisetum mougeotii* Brongt occur in a "white-greenish, arenaceous-shaley intercalation" in cross-bedded red sandstones, also containing *Estheria* (Pecorini, 1962). At Cala Viola, a greenish shale facies occurs only in the uppermost three metres of the Cala Viola Sandstones. Although the *Equisetum* remains were regarded as strictly Early Triassic in age by Pecorini (1962), they might be Middle Triassic as well (R.H. Wagner, pers. comm.).

The taxonomic nomenclature of the Autunian flora described - but, unfortunately, not illustrated - by Pecorini (1962) has been recently updated as follows (R.H. Wagner, writt. comm. 2000):

Original	Updated
Lebachia (*Walchia*) *piniformis* Florin (Schloth. pars)	*Walchia piniformis* (Schloth. pars) Sternberg
Lebachia (*Walchia*) cfr. *gallica* Florin	*Hermitia* cfr. *gallica* (Florin) Kerp & Clement-Westerhof
Lebachia (*Walchia*) cfr. *laxifolia* Florin	*Culmitzschia* cfr. *laxifolia* (Florin) Clement-Westerhof
Walchia linearifolia Goepp.	*Walchia linearifolia* Goeppert
Ernestiodendron (*Walchia*) *filiciforme* Florin (Schloth. pars)	*Ernestiodendron filiciforme* (Schloth. pars) Florin
Callipteris nicklesi Zeill.	*Lodevia nicklesii* (Zeiller) Haubold & Kerp
Callipteris conferta Sternb.	*Autunia conferta* (Sternberg) Kerp
Callipteris bergeroni Zeill.	*Sphenocallipteris bergeronii* (Zeiller) Haubold & Kerp
Callipteris lyratifolia Goepp.	*Rhachiphyllum lyratifolium* (Goeppert) Kerp
Callipteris cfr. *flabellifera* Zeill.	*Dichophyllum* cfr. *flabelliferum* (Weiss) Kerp & Haubold
Callipteris cfr. *raymondi* Zeill.	*Sphenocallipteris* cfr. *raymondi* (Zeiller) Haubold & Kerp
Taeniopteris multinervis Weiss	*Taeniopteris multinervia* Weiss
Odontopteris subcrenulata Rost.	*Mixoneura subcrenulata* (Rost.) Zeiller
Annularia stellata Schloth.	*Annularia stellata* (Schlotheim) Wood
Annularia sphenophylloides Zenk.	*Annularia sphenophylloides* (Zenker) von Gutbier
Linopteris cfr. *brongniarti* Gutb.	*Linopteris gangamopteroides* (De Stefani) Wagner?

A datum plane fixing an upper boundary for the age of the "Verrucano Sardo" is provided by the major marine transgression causing encroachment of the shallow-shelfal Muschelkalk carbonates onto the underlying continental to transitional clastic succession. The available biostratigraphic data constrain this transgression as not younger than the early Fassanian (Gandin, 1978; Carrillat *et al*., 1999) and probably not older than the Illyrian (TST of the 3rd order sequence UAA-2.2 of Haq *et al*., 1987).

Sedimentology

Lithozone 1 of the "Verrucano Sardo" (over 20 m-thick; Pedru Siligu Fm., Cassinis *et al*., 2001) consists of fining-upward cyclothems 4 to 6 metres-thick, comprising massive paraconglomerates in lenticular beds passing upwards to moderately to poorly sorted, whitish coarse-grained sandstones, arranged in amalgamated bedsets and displaying parallel and cross-bedding. A proximal alluvial fan environment, incised by high-energy braided streams, is indicated.

Lithozone 2 (over 75 m-thick; Porto Ferro Fm., Cassinis *et al*., 2001) consists of red beds arranged in metric to decametric cyclothems, representing a distal alluvial fan to high-energy braided stream environment. Depth of the fluvial channels and the absence of mudclasts strongly suggest that the braided streams were not ephemeral.

Lithozone 3 = lower Buntsandstein (45÷50 m-thick) consists of alternating intervals of grey-greenish sandstones and deep red, micaceous siltstones. A delta plain to delta front environment is indicated, with mouth bar sands, deposited during flooding stages, cyclically prograding onto coastal marshes to lower shoreface mudrocks.

Lithozone 4 = upper Buntsandstein (over 36 m-thick) starts with a conglomerate bank, very rich in milky quartz pebbles (Porticciolo Conglomerate, Cassinis *et al*., 2001). An overall fining-upward succession follows, in which channelised lens-shaped beds of pebbly sandstones are overlain by pinkish coarse-grained sandstones exhibiting widespread high-angle and parallel to cross-lamination, as well as climbing sets of asymmetrical current ripples, clay plugs and oversized mudclasts (Cala Viola Sandstones, Cassinis *et al*., 2001). Lithozone 4 marks a new stage of fan progradation, after which distal braidplain to meandering river plain environments took over. The aeolian structures reported in Gasperi & Gelmini (1979) are questionable and can be also interpreted as fluviatile in origin.

Palaeocurrent indicators document fluvial transport largely towards the ESE, corresponding to a prevailing southerly direction if Sardinia is restored to its Permian palaeoposition by a clockwise rotation of 50÷60° with respect to stable Europe (Zijderveld *et al*., 1970; Westphal *et al*., 1976).

Subordinate antithetic palaeocurrent indicators might be, at least in part, interpreted as backset beds. A tidal influence (Neri *et al*., 2000) would be consistent with upper delta plain settings and with carbonate content increasing upsection, but should have been subordinate because the red bed facies persists even in the upper part of the section, where plant debris and fresh-water crustaceans are found.

Heavy minerals analysis

Heavy mineral (HM) analysis can provide useful information for sediment provenance, correlation of unfossiliferous clastic units, and distinction of drainage areas ("HM provinces").

The HM suites of the studied sandstones (7 samples from the Cala Viola Sandstones, 5 from Monte Santa Giusta) comprise dominantly tourmaline, zircon and rutile, along with variable amounts of apatite, garnet, chloritoid, staurolite, epidotes, amphiboles,

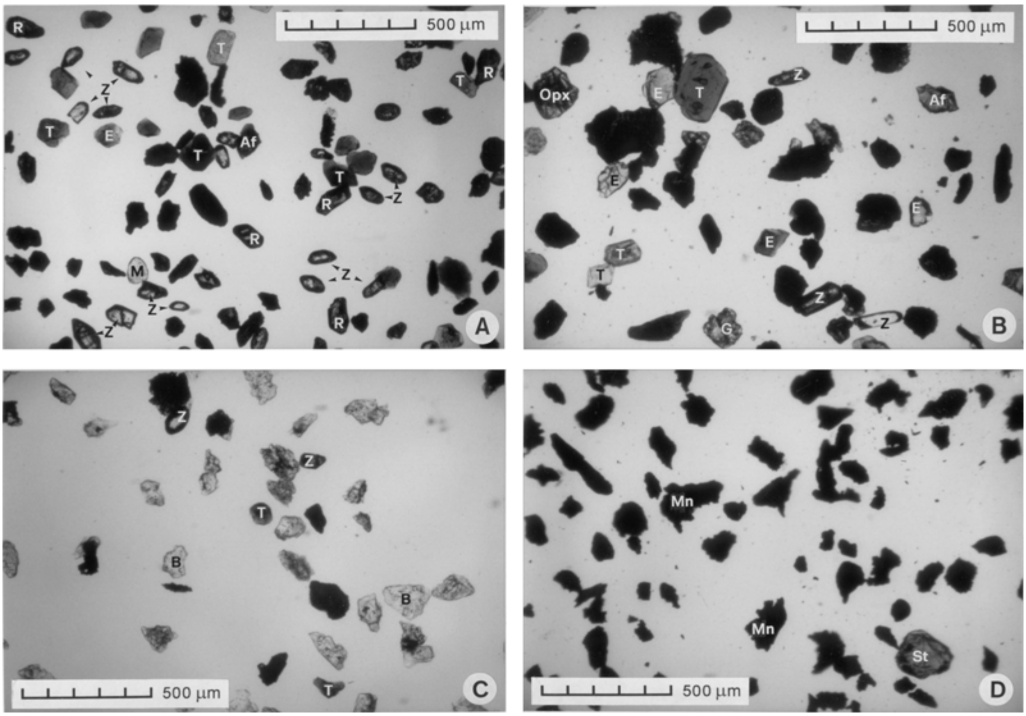

Fig. 2 - Heavy mineral suites from the Torre del Porticciolo and Monte Santa Giusta provinces. A) High-ZTR index suite from the Torre del Porticciolo province (Z = zircon, T = tourmaline, R = rutile, Af = amphibole, E = epidote, M = monazite); B) low-ZTR index suite from the Monte Santa Giusta province (G = garnet, Opx = orthopyroxene); C) authigenic baryte (B) from the Torre del Porticciolo province; D) authigenic hydrous Mn-oxides from the Monte Santa Giusta province (St = staurolite).

pyroxenes, monazite and sphene; other HMs, such as spinel, andalusite, xenotime, dumortierite, vesuvianite, anatase and brookite are very minor, whereas detrital phyllosilicates (biotite, muscovite and chlorite) are widespread. Authigenic baryte and dolomite are the most abundant transparent HMs in some samples, and hydrous Mn-oxides (largely romanechite) locally dominate the opaque suite at Monte Santa Giusta.

Differences in the HM suites from the two outcrop areas are remarkable, allowing to identify a Torre del Porticciolo HM province as distinct from a Monte Santa Giusta HM province (Fig. 2).

In the Torre del Porticciolo province, composition of the HM suites is dominated by both "neovolcanic" and recycled zircon, along with tourmaline and rutile, and is therefore consistent with provenance from mostly volcanic and intrusive to metamorphic basement rocks, incorporating significant amount of recycled detritus from older sediments. In the Monte Santa Giusta province, the HMs were derived essentially from low to medium-grade metamorphic (epidotes, staurolite, pyriboles) and intrusive (pyriboles, monazite) basement rocks, with minor contribution from volcanic and sedimentary successions. The preferred explanation for the observed compositional differences (Sciunnach, 2001) is that the Monte Santa Giusta arkoses were deposited by a local alluvial fan, flowing into the Torre del Porticciolo distal floodplain, which was fed by a larger and more complex drainage system, receiving detritus from distant northern sources. First-cycle detritus from basement source rocks, similar to those feeding the Monte Santa Giusta fan, would have been diluted by overwhelming quantities of volcanic detritus from the Permian volcanics (mostly represented by fresh euhedral zircon and apatite) and by polycyclic detritus from older sediments (brownish abraded zircon and, possibly, some tourmalines and rutile). Uniform geochemistry of detrital staurolite (Sciunnach, 2001) supports the model of provenance of the Monte Santa Giusta clastics from a single, local source.

The ZTR index decreases upsection in the Cala Viola section; this trend can hardly be explained by more severe diagenetic effects at depth (Morton, 1985) because of the small differences in burial depth of the studied samples and the overall low diagenetic grade of the Permian to Lower Triassic clastics of Nurra. Therefore, decreasing ZTR index values can be interpreted as a provenance signal, recording increasing flux of first-cycle detritus from the progressive unroofing of basement lithologies, paralleled by decreasing contribution from both volcanics, providing fresh zircons, and older sediments shedding recycled grains. The latter are particularly well represented in the lowermost sample from Cala Viola, where zircons are dominantly rounded with pitted surfaces, and "neovolcanic" crystals are negligible.

The unroofing sequence model is consistent with increasing amounts of accessory minerals from acidic igneous rocks (monazite, apatite) from the middle part of the Cala Viola section, and then increasing proportions of pyroxenes in the upper part. It is noteworthy that a similar unroofing sequence is not recorded by sandstone detrital modes within the upper Buntsandstein (Ronchi, 1993), although it is evident at the scale of the whole "Verrucano Sardo".

Palaeogeographic implications

Contrasting with views of a world-wide hot and arid climate throughout the Early to Middle Triassic, data obtained from the Buntsandstein of Nurra support the hypothesis of a more humid climate – at least seasonally - during these epochs.

In fact, locally abundant authigenic hydrous Mn-oxides in possibly Lower Triassic to Anisian sandstones are likely to have formed as a result of sediment weathering in hot and humid climatic conditions favourable to lateritisation; moreover, sedimentary features and dimensions of the permotriassic fluviatile channels suggest that they were seasonal to perennial rather than ephemeral. The local occurrence of *Equisetum* does not point unambiguously to humid climates, as it might be expected by looking at present-day forms (R.H. Wagner, pers. comm.).

Global evidences for humid palaeoclimates in the Triassic might be accounted for by a supposed Pangean megamonsoon (Parrish *et al.*, 1982; Parrish, 1993), causing high seasonal rainfall in coastal regions, extending to continental interiors not shielded by mountain ranges.

Palaeocurrent indicators suggest a Permian to Early Triassic southerly transport for the alluvial sediments. This might be consistent with the occurrence of uplifted basement areas within the Hercynian range in the present-day central to southern France (Dercourt *et al.*, 1993), where a dominantly southerly-directed fluvial system is often suggested during the post-Hercynian. Modal palaeocurrent indicators also correspond well to the regional tectonic trends as documented by the major Cévennes (Languedoc), Nîmes (Provence) and Campidano (Sardinia) faults (Broutin *et al.*, 1994), once restored to the Permian palaeoposition of Sardinia with respect to stable Europe. In this view, the inference of a Permian inheritance controlling the major Campidano trough gains support (Gasperi & Gelmini, 1979).

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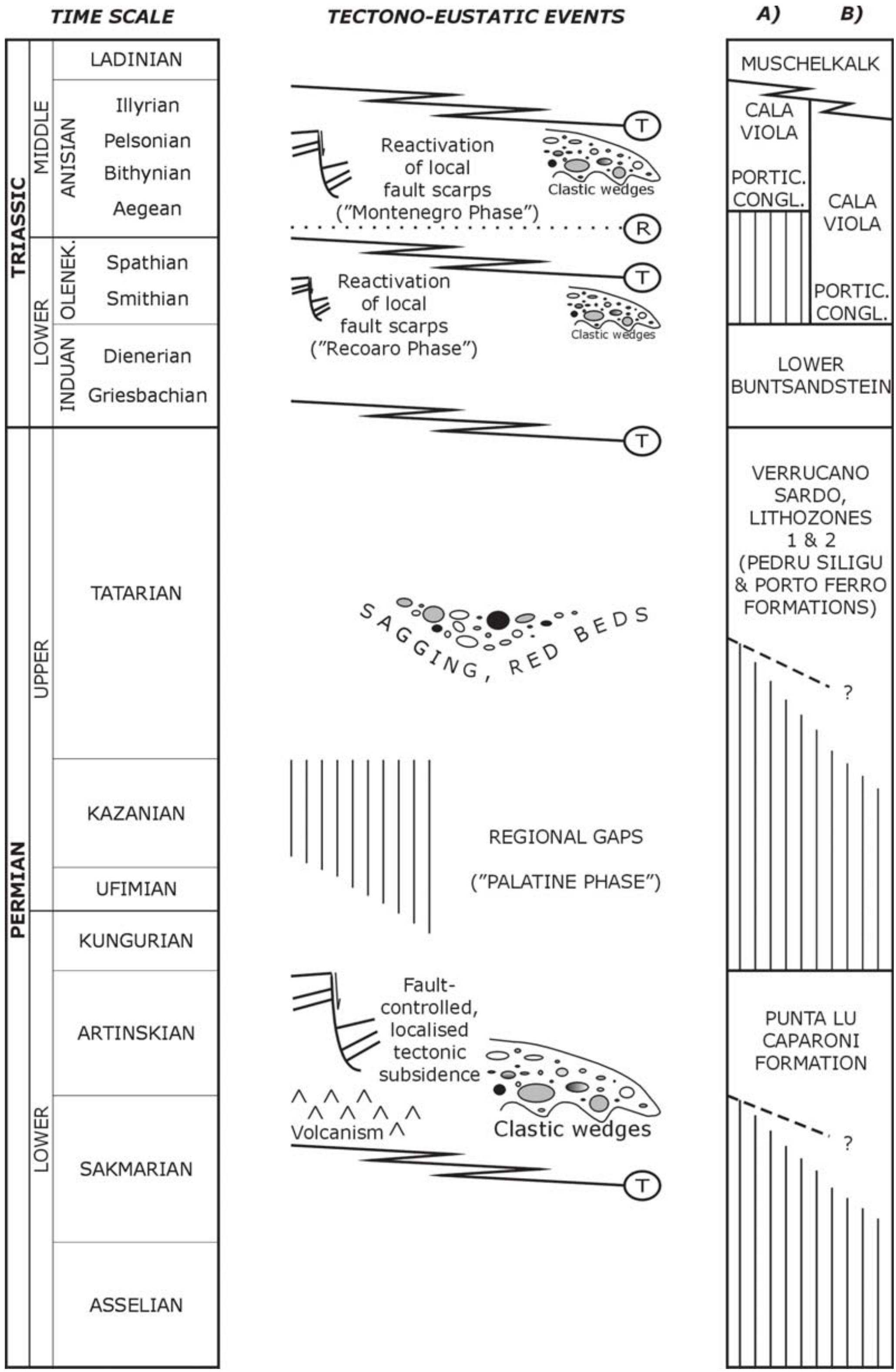
Fig. 3 - Tentative chronostratigraphic scheme for the Permian to mid-Triassic clastic succession of Nurra. Due to the scarcity of biostratigraphic age constraints, much about the position of the studied units is inferred from their correlation with major eustatic transgression and tectonic pulses, as recognised regionally in the south-Hercynian borders. Lithozones 1 and 2 of the "Verrucano Sardo" can be tentatively ascribed to the uppermost Lower to Upper Permian, but the widespread stratigraphic gaps in the mid-Permian, from central Europe to the present-day Mediterranean area, suggest to shift the two units towards the Upper Permian. A relative sea-level rise is documented, beginning at the base of the lower Buntsandstein, by encroachment of deltaic facies onto a high-energy continental braidplain. This may correspond to the major eustatic rise at the onset of the Triassic (Sequence UAA-1.2 of Haq *et al.*, 1987; Holser & Magaritz, 1987). If so, the lower Buntsandstein should represent most of the Lower Triassic and the upper Buntsandstein (Porticciolo Cgl. and Cala Viola Sandstones) at least part of the Anisian, when tectonic control on sedimentation was widespread over a large part of the present-day Mediterranean area.
Option A), implying the occurrence of a stratigraphic gap between the lower and upper Buntsandstein, would be consistent with their distinctive petrographic compositions and would not result in an exceedingly long time span for the deposition of the relatively thin Cala Viola Sandstones – see option B); however, option A) fails to record the widespread Spathian transgression.
Duration of the P-Tr stages after Menning (1995) and Gradstein *et al*. (1995). T = transgression, R = regression.



TIME SCALE
TECTONO-EUSTATIC EVENTS
A)
B)
TRIASSIC
MIDDLE
ANISIAN
LADINIAN
Illyrian
Pelsonian
Bithynian
Aegean
LOWER
OLENEK.
Spathian
Smithian
INDUAN
Dienerian
Griesbachian
PERMIAN
UPPER
TATARIAN
KAZANIAN
UFIMIAN
LOWER
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSELIAN
T
Reactivation of local fault scarps ("Montenegro Phase")
Clastic wedges
R
T
Reactivation of local fault scarps ("Recoaro Phase")
Clastic wedges
T
SAGGING, RED BEDS
REGIONAL GAPS
("PALATINE PHASE")
Fault-controlled, localised tectonic subsidence
Volcanism
Clastic wedges
T
MUSCHELKALK
CALA VIOLA
PORTIC. CONGL.
CALA VIOLA
PORTIC. CONGL.
LOWER BUNTSANDSTEIN
VERRUCANO SARDO, LITHOZONES 1 & 2 (PEDRU SILIGU & PORTO FERRO FORMATIONS)
?
PUNTA LU CAPARONI FORMATION
?

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