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FACIES ANALYSIS, STRATIGRAPHY AND PETROGRAPHIC DATA FROM THE PERMIAN-MIDDLE TRIASSIC CALA BONA - IL CANTARO ROCK SECTIONS (ALGHERO, NW SARDINIA, ITALY): CONTRIBUTION TO THE POST-VARISCAN NURRA BASIN EVOLUTION

Abstract - New sedimentological, stratigraphical and petrographical data were collected on the post-Variscan rocks cropping out below the Quaternary cover along the northwestern Sardinian coastline immediately south of Alghero. Four stratigraphic sections were analyzed in detail at Cala Bona and Il Cantaro Rock: they were dated and correlated using widely known and well-defined lithostratigraphic markers. An about 85 m thick succession is present, from the Permian siliciclastic deposits via the Early - Middle Triassic «Buntsandstein» up to the Middle Triassic «Muschelkalk». The measured sections show the intra-Permian and Permian-Triassic unconformities, and the «Buntsandstein»-«Muschelkalk» gradual passage. Those latter features of the Permian-Triassic Nurra basin are described for the first time south of Alghero. The depositional characters show an evolution starting from continental environments of high-medium energy, in which deposition is interrupted during the Permian and at the Permian/Triassic boundary by important erosive phases; those environments pass suddenly in Triassic times first to a siliciclastic tidal flat and later, gradually, to shallow carbonate environments comprised between the tidal flat and the lagoon. The petrographic data from the most complete Cala Bona section confirm a growing maturity of the siliciclastics passing from the Permian to the Triassic units probably linked to the peneplanation of the landscape. The overlying Triassic siliciclastic deposits again grow immature upwards, possibly suggesting the start of the Alpine tectonic activity. The comparisons with other well-known Permian-Triassic successions located to the north (Cala Viola-Porto Ferro, Monte Santa Giusta) indicate the Cala Bona-Il Cantaro succession were deposited on a structural high possibly representing the southern margin of the Nurra basin: in this hypothesis, a symmetrical graben structure may be suggested for the basin.

Key words - Paleogeography, Permian, Post-Variscan basins, stratigraphy, sedimentology, Triassic.

Riassunto - *Analisi di facies, stratigrafia e dati petrografici delle sezioni permo-triassiche di Cala Bona e dello Scoglio del Cantaro (Alghero, Sardegna NW, Italia): contributo all'evoluzione del bacino post-varisico della Nurra.* Sono stati raccolti nuovi dati sedimentologici, stratigrafici e petrografici sui depositi post-Varisici affioranti lungo la costa della Sardegna nordoccidentale al di sotto della copertura sabbiosa quaternaria, immediatamente a sud dell'abitato di Alghero. Quattro sezioni stratigrafiche sono state esaminate nelle località di Cala Bona e dello Scoglio del Cantaro. Tali sezioni sono state datate e correlate usando noti e ben definiti marker litostratigrafici. Ne è risultata una successione stratigrafica dello spessore complessivo di circa 85 metri e costituita inizialmente da depositi permiani, che, tramite i depositi silicoclastici triassici del «Buntsandstein» passano ai carbonati medio-triassici del «Muschelkalk». La sezione mostra una disconformità intrapermiana, la disconformità permo-triassica ed il graduale passaggio fra il «Buntsandstein» ed il «Muschelkalk». La disconformità intrapermiana è verosimilmente correlabile con la discordanza di fase saaliana del Permiano medio. Questi elementi vengono per la prima volta messi in evidenza a sud di Alghero in affioramenti riferibili al bacino permo-triassico della Nurra. I caratteri deposizionali rinvenuti marcano un'evoluzione a partire da ambienti continentali di energia medio-alta, la cui continuità deposizionale viene interrotta, durante il Permiano ed al limite Permiano/Triassico, da importanti fasi erosive; tali ambienti nel Triassico passano bruscamente dapprima ad una piana tidale silicoclastica e successivamente, in maniera più graduale, a depositi carbonatici di bassa profondità compresi fra la piana tidale e la laguna. I dati petrografici provenienti dalla più completa sezione stratigrafica di Cala Bona confermano una crescente maturità dei depositi silicoclastici dal Permiano alla base del Triassico, probabilmente legata alla progressiva peneplanazione del paesaggio, ma per converso mostrano a partire dal Triassico l'aumento dell'immaturità dei depositi terrigeni verso l'alto, suggerendo l'esordio dell'attività tettonica alpina. Questi dati, insieme ai confronti con altre ben conosciute successioni localizzate più a Nord (Cala Viola-Porto Ferro, Monte Santa Giusta) hanno permesso di ipotizzare per la successione di Cala Bona-Il Cantaro una deposizione su un alto strutturale, forse identificabile con il margine meridionale del bacino della Nurra: in questa ipotesi, si potrebbe suggerire per il bacino una struttura a graben simmetrico.

Parole chiave - Bacini post-varisici, paleogeografia, Permiano, stratigrafia, sedimentologia, Triassico.

Introduction

In the Nurra area (NW Sardinia, Fig. 1) the continental post-Variscan basins Permian to Triassic in age were first studied in the last century (Oosterbaan, 1936; Pecorini, 1962; Vardabasso, 1966). During the last decades the well-exposed successions cropping out along the western coast stretching from Cala Viola to Porto Ferro (Gasperi & Gelmini, 1980; Cassinis *et al.*, 1996, 2000, 2003; Cassinis & Ronchi, 2002; Ronchi *et al.*, 2008) have been examined in detail. In these investigations attention was also given to minor outcrops at Baratz lake (Cassinis *et al.*, 2003; Gasperi & Gelmini, 1980) and Monte Santa Giusta (Neri *et al.* in Cassinis *et al.*, 2000; Fontana *et al.*, 2001; Sciunnach, 2002; Buzzi *et al.*, 2008;). The Cala Bona outcrops, located just south of Alghero, despite their early find-

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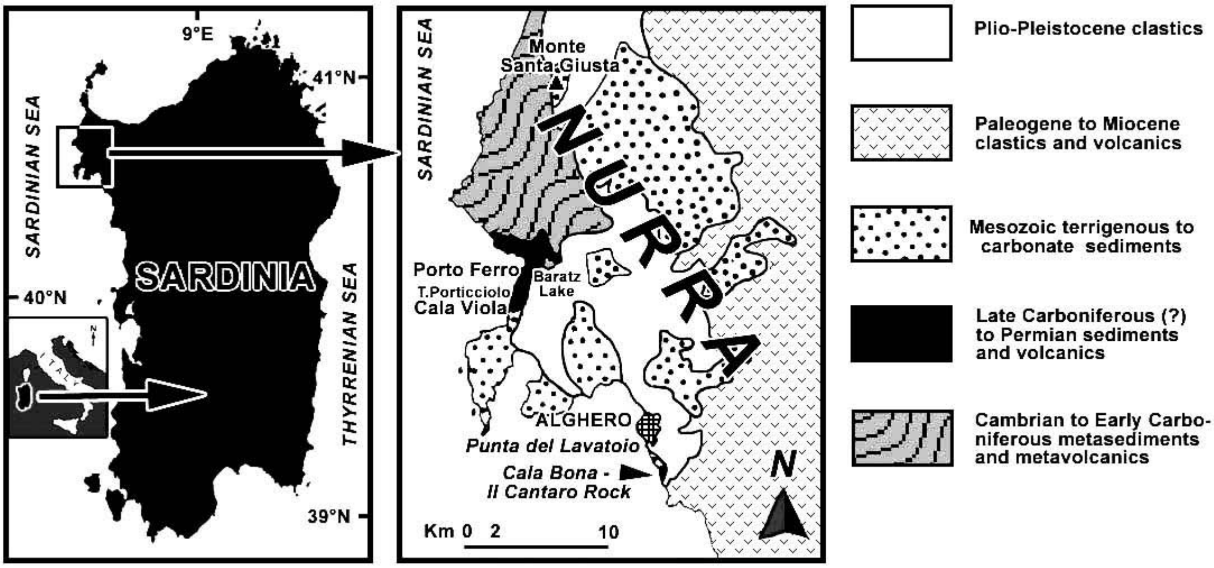

Fig. 1 - Location and geological sketch-map of the Nurra area (NW Sardinia).

ing and initial report (Oosterbaan, 1936), have been neglected but for terse descriptions (Gandin, 1978a; Gandin *et al.*, 1978; Gasperi & Gelmini, 1980; Sciunnach, 2001; 2002). Some of them (Il Cantaro Rock) were even never described. In this locality new, detailed investigations revealed well-exposed stratigraphical and sedimentological features that improved and detailed the knowledge on the Nurra Lu Caparoni-Cala Viola superposed basins of Permian to Triassic age. According to surface and drilling data (Lotti, 1930; Pomesano Cherchi, 1968), the depocenters of these basins were located close to the Torre del Porticciolo -Baratz lake area (Fig. 1).

Geological Framework

The investigated area is located in the southern Nurra territory of NW Sardinia (Fig. 1). Here the oldest rocks pertain to the northern part of the Sardinian segment of the Variscan chain (Carmignani *et al.*, 1979): they are low-medium (micaschists and paragneisses) to high grade (migmatites) metamorphic rocks. The protolithes were predominantly siliciclastic in composition and Cambrian to Early Carboniferous in age (Carmignani *et al.*, 1979; 1994).

During Late Carboniferous to Early Permian times, the gradual collapse of the Variscan chain led to development of extensional molassic basins (Cassinis & Ronchi, 2002; Cassinis *et al.*, 2003) The stratigraphic succession of these includes, from bottom to top: Lu Caparoni Fm., Pedru Siligu Fm., Porto Ferro Fm. and Cala del Vino Fm. All these units represent alluvial environments of variable energy (Cassinis *et al.*, 2003). The post-Variscan basins initially developed as a response to a right-lateral megashear system superimposed on the collapsing Variscan megasuture, and persisted in Europe during the Late Paleozoic, but changing gradually their kinematics towards an extensional mode (Arthaud & Matte, 1977; Vai, 1991, 2003; Ziegler & Stampfli, 2001) probably during the Middle Permian (Mid-Permian episode, Saalian Phase: Deroin & Bonin, 2003).

In Triassic times passive margin successions of the Neo-Tethys accumulated: they are related to the Pangea break-up (Ziegler, 1990; 1993; Ziegler & Stampfli, 2001). These successions belong to the «Germanic» Sephardic biofacies domain (Sardo-Provencal subdomain) of the northern margin of the arising Neo-Tethys (Hirsch, 1994 and references therein), and are formed by the typical three-folded Germanic facies succession: the siliciclastic Buntsandstein, the carbonate Muschelkalk and the carbonate-siliciclastic-evaporitic Keuper (Costamagna & Barca, 2002; Posenato, 2002). Nonetheless, for their marginal location with respect to the Neo-Tethys these successions underwent only a weak subsidence, so their thickness was limited to tens of meters for the Buntsandstein part, and to less than 300 m (Pomesano Cherchi, 1968; Costamagna & Barca, 2002) for the whole Triassic succession.

In detail, the Buntsandstein succession is formed by the siliciclastic Verrucano Sardo Fm. red bed unit, related to the Buntsandstein Sardinian Group (Costamagna & Barca, 2002) and unconformably lying over the Middle- to Late Permian Cala del Vino Fm. (Permian-Triassic unconformity, Cassinis *et al.*, 2003). The Verrucano Sardo Fm. at Cala Viola is at most 31 m thick

(Costamagna, submittted). It can be subdivided in two informal units described by Cassinis *et al.* (2003): the Conglomerato del Porticciolo Lithofacies (conglomerates and largely subordinated pebbly sandstones and sandstones) overlain by the Arenarie di Cala Viola Lithofacies (sandstones and subordinated siltites). The Verrucano Sardo Fm. has been supposed to lay down in alluvial environments of decreasing energy gradually evolving upwards to marine.

Costamagna & Barca (2002) discussed the usage of the term «Verrucano Sardo» introduced by Pecorini (1962) and Vardabasso (1966) and designated as «Verrucano sardo Fm.» all the thick red bed succession overlying the Autunian Punta Lu Caparoni Fm. (Gasperi & Gelmini, 1980). Cassinis *et al.* (2003) detached the Permian part (lithofacies 2 and 3 of Gasperi & Gelmini, 1980), restricting the Triassic Verrucano Sardo Fm. only to the upper part of the red bed succession (lithofacies 4 of Gasperi & Gelmini, 1980). In fact, the «Verrucano» term has been widely and properly used to mark the Triassic start of the Alpine depositional cycle in the Mediterranean area (Cassinis *et al.,* 1980): the reliability of an Alpine depositional cycle in this area is pointed out by the Pyrenean deformation phase in Western Sardinia (Barca & Costamagna, 1997; 2000; 2010).

The Muschelkalk is represented by the Punta del Lavatoio Fm. of the Sardinian Muschelkalk Group (Costamagna & Barca, 2002). The main section of this unit crops out at Punta del Lavatoio (Gandin, 1978b), in the town of Alghero. According to Costamagna & Barca (2002), its depositional context was connected to diverse carbonate ramp subenvironments.

The Upper Triassic, partially evaporitic «Keuper» is represented only by scattered small outcrops built of well-bedded carbonates, fine-grained siliciclastics and subordinate evaporites laid down in an arid peritidal to lagoonal environment (Costamagna & Barca, 2002).

During Jurassic to Cretaceous times, a large and continuous carbonate shelf developed on the northern Alpine Tethys margin, as shown by a shallow-water succession nearly 1000 m thick (Cherchi & Schroeder, 1985).

Following the latest Cretaceous emersion, Oligocene-Miocene magmatic rocks (Frezzotti *et al.*, 1992; Lecca *et al.*, 1997) and subordinate lacustrine deposits (Oligocene? Pecorini, 1961) were deposited. During the latest Oligocene-early Miocene a thick siliciclastic-carbonate sedimentation (Martini *et al.*, 1992; Brandano *et al.*, 2004) took place on the eastern side of the Nurra for the development of the NS-trending Sardinian Rift (Cherchi & Montadert, 1983). Such tectonic structure was due to the counterclockwise drifting of the Sardinia-Corsica block (Orsini *et al.*, 1980; Speranza *et al.*, 2002). Finally, a Quaternary sandy cover exposed along the Nurra western cliffs ends the stratigraphic record (Andreucci *et al.*, 2009).

Cala Bona - Il Cantaro Rock successions

The Cala Bona and Il Cantaro Rock coastal outcrops are easy accessible by short tracks running downhill from the main road Alghero-Bosa. Four stratigraphic sections from the Permian siliciclastics to the Middle Triassic carbonates were analyzed and correlated (Figs. 2, 3): they form a nearly 85 m thick succession altogether. The contact of the post-Variscan succession over the deformed Variscan basement is not exposed, although the mapping showed Variscan metamorphics cropping out close to the coast and to the Permian-Triassic deposits (Fig. 2). The metamorphics are green-grey metasandstones and metapelites of possible Ordovician age. The Permian-Triassic succession is intruded (and sometimes mildly thermo-metamorphosed) and displaced by the rising Tertiary Calabona «Porphyrite» dacitic body (Frezzotti *et al.*, 1992): still, their contact is usually obscured by the Quaternary Tyrrhenian sandy cover (Andreucci *et al.*, 2009).

Pyrenean tectonics tilted and rotated the post-Variscan deposits: now they dip strongly to NW (Cala Bona) or to SW (Il Cantaro Rock). They are also crossed by several fractures and faults. So, although many directional sedimentary indicators were measured, their combined use for the inference of the paleocurrent trend and paleogeography is problematical.

This study has been mainly conducted in neap-tide days, in order to having exposed the maximum outcrop surface. This was especially valid for the Cala Bona section, located basically along the shoreline.

The investigated stratigraphical sections are described below in detail for lithocorrelation purposes: in fact, lacking any biostratigraphic control, their age could be inferred only by use of lithostratigraphical markers recognized in other well-dated and well-known sections. Such inferred stratigraphic attributions, merely mentioned along the description, will be better justified in the following Discussion paragraph.

Il Cantaro Rock section 1

The lower stratigraphic section (n. 1, Figs. 2, 3) is located in the northwestern part of the Il Cantaro Rock. From bottom to top the succession is made of:

1) 7 m of reddish-brownish, moderately to well-sorted sandstones to rare pebbly microconglomerates with subordinated intercalations of red-green siltites to fine sandstones: they form a succession of fining-upward metric sequences showing at the base sharp erosive contacts. Coarser grained deposits show some trough cross-bedding and rare bioturbation, fine grained ones are thinly stratified, bioturbated (*Repichnia*: *Scoyenia* ichnofacies), and deformed at the top by load-casts protruding from the overlying bed. Rare lined-up calcrete nodules also occur. The pebbles, sub-rounded to rounded, rarely subangular, mostly some cm in size, are made of quartz, metamorphic rocks, lydites, Permian volcanics and reworked red sandstones in this order of abundance.

This interval is followed by Quaternary deposits obscuring 3 m of the succession.

2) 60 cm of structureless quartzose greyish, middle to fine sandstones.

Both intervals (1) and (2) may be ascribed to the Permian Porto Ferro Fm for its geometric position and lithological and sedimentological features.

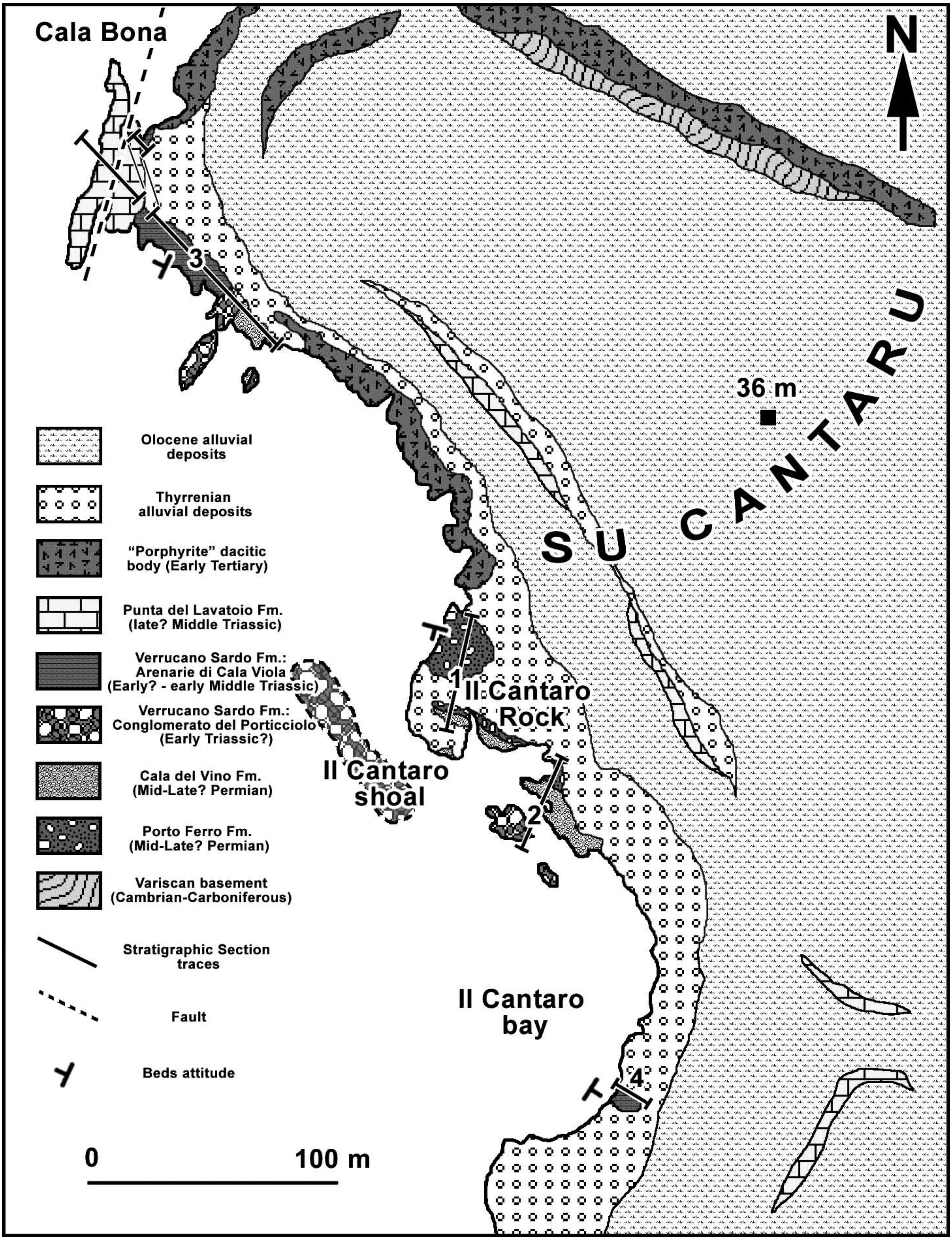

Fig. 2 - Geological map of the Cala Bona S - Il Cantaro Rock area with location of the stratigraphic sections.

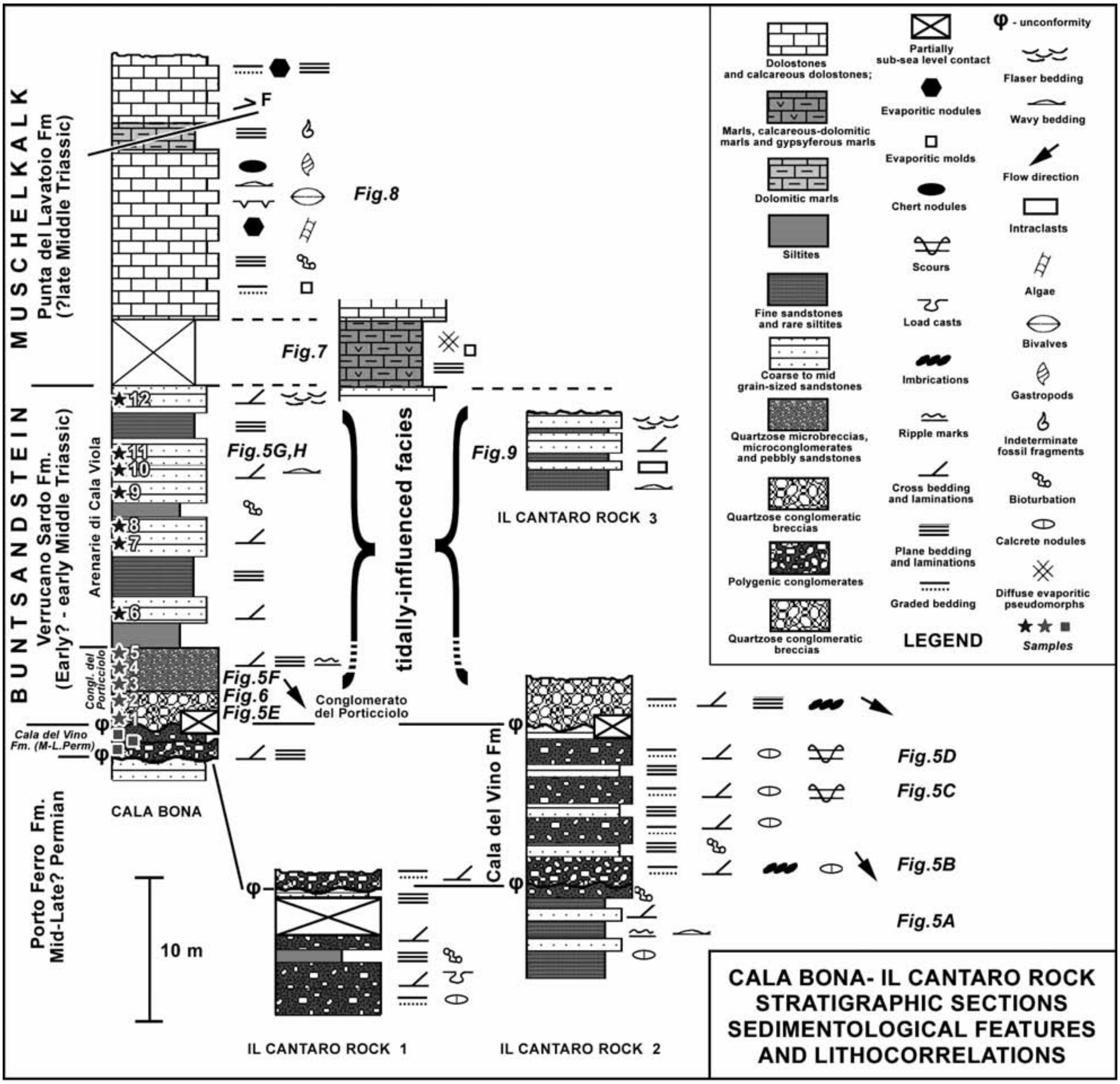

Fig. 3 - Cala Bona - Il Cantaro Rock stratigraphic sections. The stars mark the Verrucano Sardo Fm samples, the squares the Cala del Vino Fm samples.

These deposits are covered unconformably through an evident erosive surface by

3) 1.2 m of polygenic clast-supported conglomerates starting with a coarser (pebbles up to 10 cm) basal lag; the pebbles are the same type and shape formerly described in the interval 1, but meanly bigger in size.

Interval (4) may be ascribed to the Permian Cala del Vino Fm for being underlain by a significant unconformity possibly due to the Mid-Permian episode (see below; Cassinis *et al.*, 2003; Deroin & Bonin, 2003) identifiable as the intra-Permian Saalian unconformity and for lithological and sedimentological features. Upwards, the section is again obscured by Quaternary deposits.

Total thickness of this stratigraphic section is nearly 10 meters.

Il Cantaro Rock section 2

This section (n. 2, Figs. 2, 3), measured in the southernmost part of the Il Cantaro Rock, consists of (from the bottom):

1) About 7 m of reddish, rarely yellowish, well-stratified and laminated siltites and fine grained sandstones with rare decimetric beds of middle grain-sized sandstones; ripple cross laminations indicating a SE-directed paleoflow and faint cross bedding occur (Fig. 4A). Rare thin beds of greenish-

yellowish pelites are occasionaly intercalated. Clusters of calcrete nodules, gradually increasing in size and frequency upwards, are scattered in these sediments: their size and frequency gradually increase upwards. At the top bioturbation vertical structures (*Skolithos*: *Scoyenia* ichnofacies) occur.

2) 1.5 m of reddish, well-stratified alternations of polygenic clast-supported conglomerates and pebbly sandstones (Fig. 4B) organized in a single fining-upward sequence, locally displaying imbrications and a lateral decrease of the pebble grain-size along the same bed.

Intervals (1) and (2) may be referred to the Permian Porto Ferro Fm for their stratigraphic position and pebbles composition, featured by a higher content of volcanic and metamorphic rock pebbles in respect to the following units.

3) 3 m of reddish, well-stratified polygenic clast-supported conglomerates, minor conglomeratic breccias and sandstones arranged in metric fining-upward sequences with sharp erosive base and localized bioturbation. Interval 3 unconformably overlies interval 2. Its base is a flat, irregular surface (Fig. 5) cutting a dissolution/cementation altered up to 5 to 35 cm thick zone of possible pedogenic origin. Some sequences are more arkosic and, if traced laterally, lens-shaped, so figuring out narrow channels with low width/depth ratio. At the bottom of this interval a coarser pebbly basal lag occur. The well-organized conglomerates are built by lined-up, locally imbricated pebbles and small cobbles showing a paleoflow roughly oriented n. 140 to southeast. The pebbles, subangular to subrounded in shape, are formed by quartz, metamorphic rocks, Permian siliciclastics and volcanics. Flat bedding and trough, rarely tabular cross-bedding may occur. Sparse, reworked calcrete nodules can be observed. In the upper part bioturbation seldom occurs too.

4) 8 m of well-stratified polygenic conglomerates (made of the same types of pebble of interval 3 but smaller in size) to trough cross-bedded sandstones organized in fining-upward sequences with sharp erosive base. In this interval the conglomerates forming the base of the sequences are less coarse than those of the interval (3). Clusters or lined-up calcrete nodules (Fig. 4D) and calcretization crusts (Fig. 4C) are common, as well as shallow erosive scours with low relief (less than 3 dm deep, Fig. 4C) filled with pebbles including reworked calcrete (Fig. 4D).

Intervals (3) and (4) may be referred to the Permian Cala del Vino Fm for lithological and sedimentological features and for its geometric position between two significant unconformities identifiable as the intra-Permian Saalian unconformity (at the base) and the Permian/Triassic unconformity (at the top) respectively.

5) 4 to 6 m of whitish, well-bedded and well-sorted clast-supported quartzose conglomeratic breccias and subordinated quartzarenites with lined-up pebbles and grains (maximum grain size reaches nearly 10 cm). They contain only angular to minor sub-rounded quartz and scarce lydite pebbles. They are organized in irregular fining-upward sequences with or without separation erosive surfaces and show tabular and rare trough-cross bedding. This interval is represented by several tightly spaced big rocks emerging from the sea close to the coastline, and therefore is not observable directly from the shore, so a small boat was used. Nonetheless, the sharp passage from the interval (4) to (5) is still observable, being exposed on the shallow sea bottom. It can be furtherly and easily traced northwestward, still evident on the bottom just below the sea level (Il Cantaro shoal in Figs. 2, 3). This can be seen again using a boat and aerial photos.

Based on strict lithostratigraphic analogies with the unique quartzose horizon cropping out at Cala Viola (Cassinis *et al.*, 2003), interval (5) is attributable to the Conglomerato del Porticciolo Lithofacies, that is the lower lithofacies of the Triassic Verrucano Sardo Fm. Total thickness of the stratigraphic section is about 25 meters.

Cala Bona section

1) Basal, nearly 1.5 m of reddish sandstones and pebbly sandstones with poorly visible parallel bedding.

This interval may be referred to the Permian Porto Ferro Fm for its stratigraphic position. It is unconformably covered by:

2) 1 m of thickly stratified, moderately organized fining-upward coarse polygenic conglomeratic breccias with angular pebbles (quartz, metamorphic rocks, Permian siliciclastics, calcretes and volcanics) up to 10 cm in size: they are formed by four dm-thick fining-upward sequences separated from each other by thin microconglomeratic beds.
3) 1.5 m of reddish well-stratified pebbly sandstones.

Intervals (2) and (3) may be referred to the Permian Cala del Vino Fm based on its position between significant unconformities identifiable as the intra-Permian Saalian unconformity (at the base) and the Permian/Triassic unconformity (at the top), and for lithological and sedimentological features.

4) 1.8 m of well- to moderately sorted and thickly stratified quartzose conglomeratic breccias. They are organized in fining-upward sequences less than 0.5 m thick with sharp erosive base (Fig. 4E); the sequences are built of trough to tabular variously oriented cross-bedded sets separated by sharp surfaces and made of angular-subangular and subordinate sub-rounded quartz and rare lydite pebbles mainly cm-sized. The cross bedding foresets dip up to 25-30°. Rarely flat bedding occurs. Some sub-rounded quartz pebbles are clearly broken. The matrix, formed by silty to sandy quartz grains, ranges from scarce to abundant. This entire interval gradually tends to fine up.
5) Nearly 2.5 m of tabular to trough cross-bedded quartzose microconglomerates, pebbly sandstones and quartzarenites; in the lower part of the interval they show some sets of tangential trough cross-bedded medium grain-sized sandstones interspaced by subtle silty layers marking reactivation surfaces. In the upper part these deposits display thick foresets some dm thick (small/medium scale dunes) indicating a paleoflow direction oriented n. 130 to South-

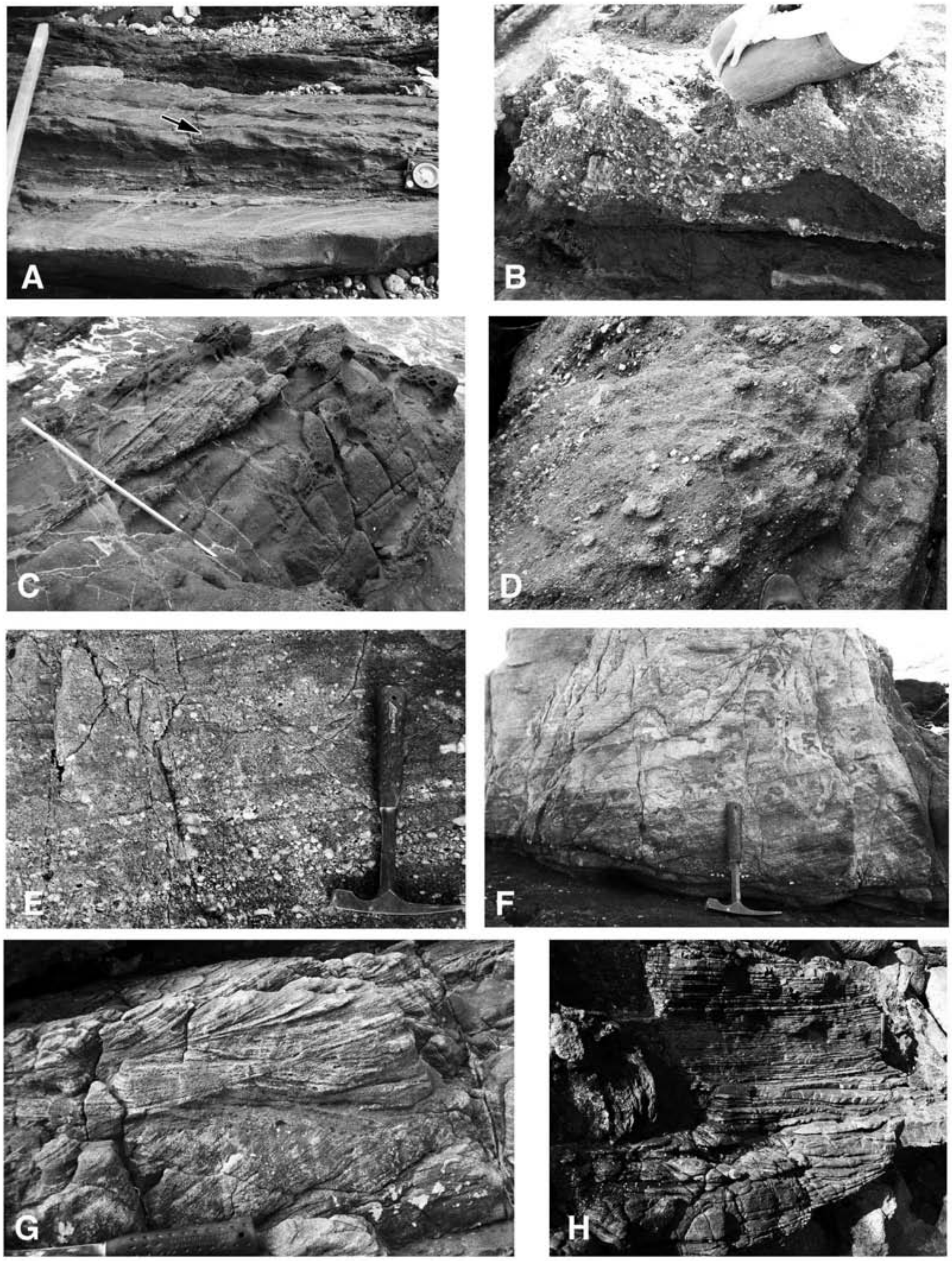

Fig. 4 - Some sedimentological aspects of the Permian-Triassic siliciclastics (in stratigraphic order). A) Porto Ferro Fm: Ripple marks (arrow) migrating to right in fine sandstones over a coarser cross-bedded sandstone layer; B) Polygenic conglomerates of the Cala del Vino Fm, base resting unconformably with a markedly irregular surface over the pelites of the Porto Ferro Fm (Middle-Permian unconformity, Saalian Phase unconformity); C) Cala del Vino Fm: base-event scour filled by a flat-laminated polygenic basal lag with calcrete crusts and reworked calcrete pebbles; the staff is 1.5 m long; D) Cala del Vino Fm: calcrete nodules (arrows) loosely disposed in polygenic conglomerates: the visible boot part is 11 cm long; E) Verrucano Sardo Fm, Conglomerato del Porticciolo Lithofacies: fining-upwards quartzruditic-quartzarenitic events with general fining-upward trend; F) Verrucano Sardo Fm, Conglomerato del Porticciolo Lithofacies: graded 45 cm-high foresets (alternations of eolian grain fall and grain flow deposits?) accreting over a one-pebble thick pebbly lag underneath supposed to be the actual channel sole (or a deflation pavement?); G) Verrucano Sardo Fm, Arenarie di Cala Viola Lithofacies: tidal bundles; trough cross-bedded sets divided by reactivation surfaces; H) Verrucano Sardo Fm, Arenarie di Cala Viola Lithofacies: waxing-waning-waxing sandstone bed trend with interspaced siltitic slack water stage laminae. The cross-bedding of the lower thickly-bedded interval possibly represents accretion processes in subtidal sandbars followed by back-bar plane-parallel tidal rhytmic deposits of lower energy. Way-up to the top.

east and accreting above one-pebble thick lags: here each foreset lamina is graded (Fig. 4F). Locally on the bed surfaces occur faint, possibly flat ripple marks oriented nearly ENE/WSW.

Based on strict lithostratigraphical analogies with the unique quartzose horizon cropping out at Cala Viola (Cassinis *et al.*, 2003), intervals (4) and (5) are referred to the Conglomerato del Porticciolo Lithofacies, that is the lower lithofacies of the Triassic Verrucano Sardo Fm.

6) 2 m of red, massive siltites to fine sandstones.
7) 17-18 m of gradually and weakly coarsening-upward reddish sandy to silty siliciclastics. They are arranged in irregular alternations formed by A) well-stratified dm-thick sets of tangential trough cross-bedded, medium grained sandstones; these sets are interspaced by thin, mm-sized silty layers marking mildly erosive surfaces (reactivation surfaces) (Fig. 4G); B) alternations of flat, thinly well-bedded sandstone layers showing thick-thin alternations in thickness (waxing-waning trend) regularly doubly interspaced by subtle fine sandy and/or silty reddish thin laminae (double mud drape - tidal rhytmites) (Fig. 4H), and C) thinly bedded, locally laminated and rarely bioturbated reddish to greenish siltites showing flaser and wavy bedding. These deposits are locally organized in fining-upward sequences.

Intervals (6) and (7) are referred to the Arenarie di Cala Viola Lithofacies, that is the upper lithofacies of the Triassic Verrucano Sardo Fm.

The gradual passage from the Buntsandstein Verrucano Sardo Fm to the thick- to medium-bedded carbonate beds of the Triassic Muschelkalk Punta del Lavatoio Fm is located along the right side of the Cala Bona promontory (Fig. 2). The carbonate succession is formed by:

8) 0.50 m of red fine sandstones with thin fractures filled by yellowish carbonates;
9) 1.60 m of thinly laminated, polychrome friable gypsiferous marls (Figs. 6A, C). The laminations are sometimes weakly convoluted due to the tectonics;
10) 1.80 m of well-bedded, dark brown to whitish marls and calcareous-dolomitic marls: the upper lighter part contains nodular evaporitic pseudomorphs and molds (Figs. 6B, C);
11) 0.50 m of dark carbonates rich of quartz veins (replacing former gypsum?).

Based on the increasing carbonate content, from the interval (9) the described deposits may be assigned to the «Muschelkalk» (Punta del Lavatoio Fm).

12) Nearly 20 m of thickly to medium-bedded dolomitic, rarely marly-dolomitic limestones arranged in generally incomplete peritidal cycles where the supratidal part is missing. Each cycle is commonly less than 1 m. The typical complete cycle (Fig. 7A) usually starts with dark grey, massive to thickly stratified, locally bioturbated, subtidal calcilutitic to fine calcarenitic deposits (Fig. 7B), changing towards the top from bioturbated («vermiculation» type *Auct.*) to bioclastic (algae fragments, bivalves, gastropods, echinoid spines) (Fig. 7C). These deposits grade rapidly into grey inter-supra(?)tidal, strongly bioturbated (*Callianassa* burrows? *Skolithos* ichnofacies) fine calcarenites containing rare cm-sized, evaporitic nodules (?). Finally, whitish calcilutites to fine calcarenites showing either fine plane laminations and faintly visible mud cracks or ripple laminations occur. Locally thin, whitish laminated fine calcarenitic beds may lie sharply over the supra(inter?)tidal muds or interspace with them: they sometimes con-

Fig. 5 - Il Cantaro 2 section: Porto Ferro - Cala del Vino Fm unconformity (Mid-Permian unconformity: Saalian phase unconformity). At the base of the Cala del Vino Fm an alteration zone of variable thickness occurs. The angle between the bedding surfaces of the two superposed units and the well-exposed lateral continuity of the surface are clearly visible. In the background some Quaternary sandstone boulders.

tain at the base graded mm-sized evaporitic molds concentrated in thin levels (Fig. 7B). The peritidal cycle terminates with a sharp surface over which dark-grey subtidal deposits rest again. In the middle of the carbonate succession a limited marly interval occurs. Scattered chert nodules are present too.

Total thickness of the Il Cantaro Section 2 is about amounts to 52-53 meters.

Il Cantaro section 3

This section (n. 4, Figs. 2, 3) is located along the southern side of the il Cantaro Rock bay: it is exposed in an erosion window through the Quaternary sandstones. On the whole it has a coarsening upward trend and is formed by:

1) 2-2.5 m of thinly laminated to massive fine sandstones passing upward to wavy - to flaser-bedded medium grained sandstones (Fig. 8.A);
2) 4-4.5 m of alternations of massive, middle grain-sized reddish sandstones and brownish cross-bedded medium to coarse grained sandstones whose sets are separated by sharp reactivation surfaces (Fig. 8C); the coarse sandstones increase up-section until becoming the dominating lithology. Their carbonate content also increases up-section. Sheet- to lens-shaped intercalations of intraclastic conglomeratic beds (Fig. 8B) with erosive base are present from the middle part of the interval. Thin, cm-thick levels of reddish pelites occur.

Total thickness of the described section, difficult to estimate with accuracy due to the inconvenient location, amounts to 6-7 meters.

Despite its limited thickness, based on close lithostratigraphic affinities with some peculiar deposits cropping out along the previously described Cala Bona section and along the Cala Viola section located 16 km to the northwest (Neri *et al.* in Cassinis *et al.*, 2000; Fontana *et al.*, 2001; Costamagna, submitted), these deposits can be referred to the upper part of the Arenarie di Cala Viola Lithofacies of the Verrucano Sardo Fm, near the transition to the «Muschelkalk» deposits.

The total thickness of the Permian-Middle Triassic succession amounts to almost 82 m (Fig. 3).

Petrography of the Cala Bona siliciclastics

Three samples of the Cala del Vino Fm and twelve samples of the Verrucano Sardo Fm were collected along the Cala Bona section (Fig. 3) for petrographic analysis.

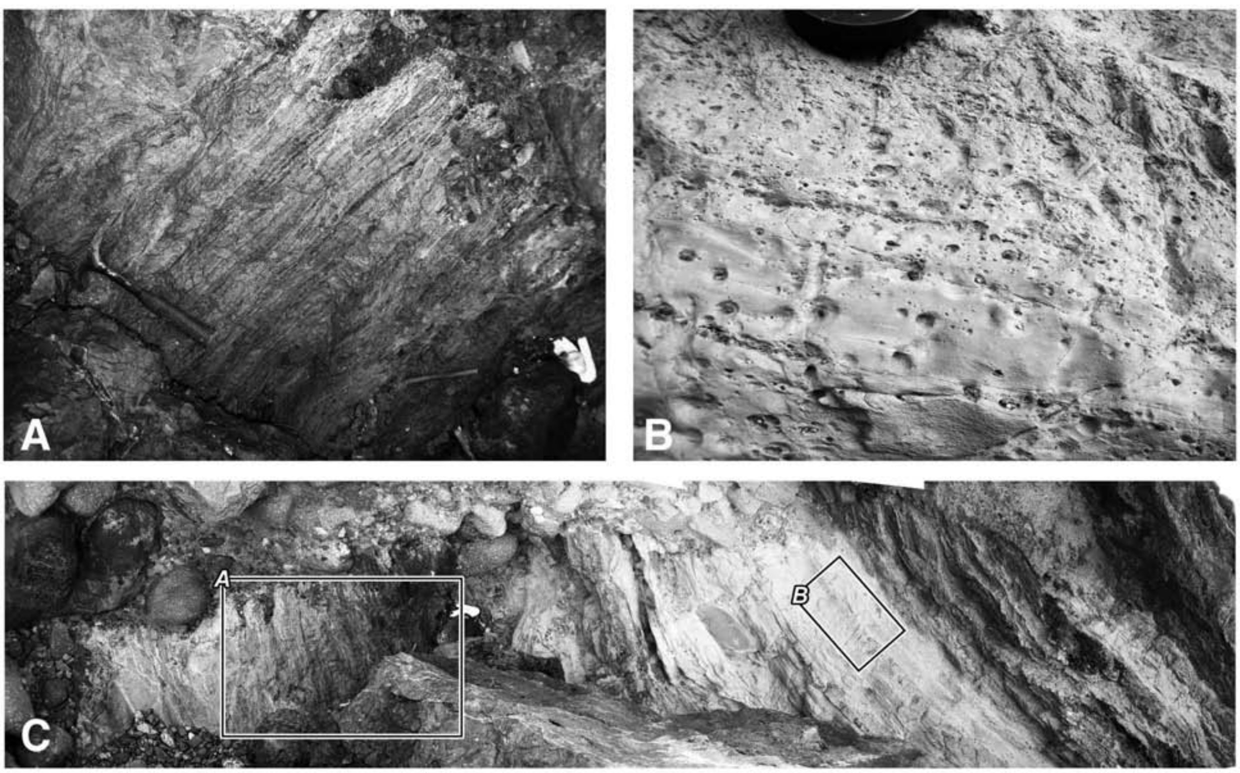

Fig. 6 - Some sedimentological aspects of the Triassic «Röt» lithofacies between the «Buntsandstein» and the «Muschelkalk» in the Cala Bona section. A) Tender, thinly laminated marls with scattered sulphates fine laminae. Way-up to low right; B) Calcareous-dolomitic marls with nodular evaporitic pseudomorphs; the camera cup visible in the topmost part is about 2.5 cm wide; C) Upper part of the «Buntsandstein»/«Muschelkalk» transition: the siliciclastic content of the carbonates decreases gradually to left. Way up to left; the dip of the beds is nearly 45°; thickness is 3.7 m; the camera field is about 4 m. The rectangles indicate the location of the close-up A and B.

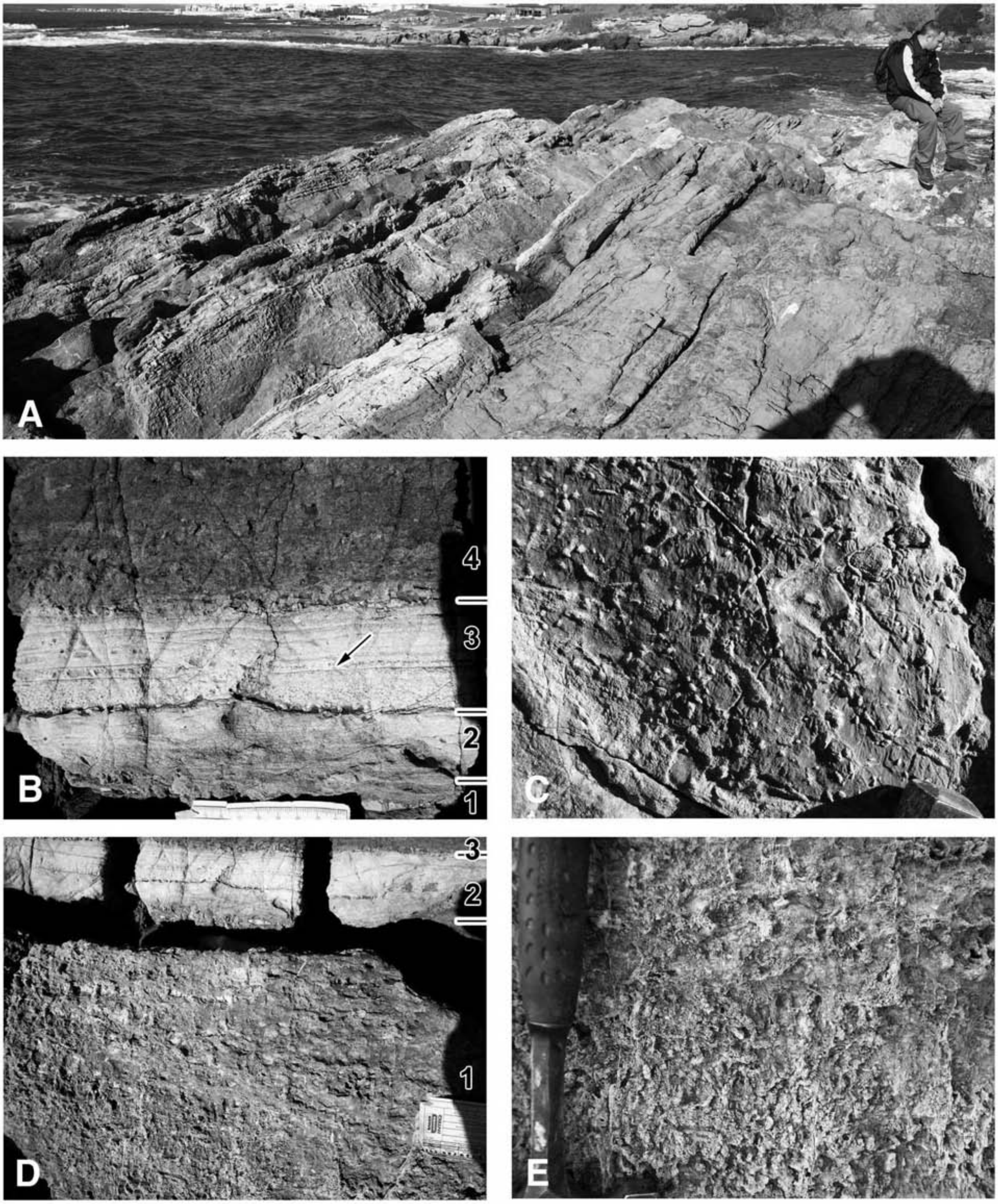

Fig. 7 - Some sedimentological aspects of the «Muschelkalk» in the Cala Bona section. A) Overview of some peritidal cycles; B) Detail of the top part of a peritidal cycle: over a last remain of the bioturbated intertidal sediments (1), a sandy storm tail with wavy lamination (2) is covered by flat-laminated decantation deposit (3) showing evaporitic molds at the base (arrow). A reworking surface marks the return to the dark grey, bioturbated subtidal muds (4); C) Subtidal deposits rich of bioclasts; little gastropods and bivalves are recognizable; D) Upper part of the peritidal cycle: inter(supra?)tidal bioturbated silty to muddy sediments (1) sharply covered by (inter?)supratidal deposits (2): at the extreme top right the passage to the dark grey muds of the next cycle (3) are visible; E) Strongly bioturbated intertidal deposits.

In every thin section three hundred points were considered. Data recalculation was made following the QFR method (Folk, 1974) and the Gazzi-Dickinson QFL (Dickinson, 1970; Zuffa, 1985). Only these latter normalized data are reported in the final plot.
Given the shortness of the Permian section, the Cala del Vino Fm three samples were collected merely for comparison with former papers (Cassinis *et al.,* 1996; Sciunnach, 2002) and calibration purposes with the remaining «Buntsandstein» upper part of the section. All the samples were classified using the Folk's scheme (1974). The Permian Cala del Vino Fm sandstones are moderately sorted litharenites with average mode Q55 F4 L41 and rich of little quartz pebbles. The grains are subangular to subrounded. The lithics are formed by equal amounts of volcanics and low- to high-grade metamorphic rocks. Biotite crystals and their alteration products are common. Some grains are coated by iron oxides. The five samples taken from the Triassic Conglomerato del Porticciolo Lithofacies are moderately to well-sorted quartz-cemented sublitharenites (Fig. 9A) averaging Q78 F2 L20. The grains are angular to subrounded. Angularity and average grain size increase upsection. A weak but steady increment of lithics (mainly formed by low- to high-grade, prevalently pelitic metamorphosed rocks) and perhaps of feldspars was detected upward. A complex cementation with multiple quartz overgrowths is displayed (Fig. 9B). Femic minerals are episodic: chlorites filling the residual porosity are likely the result of the alteration of former biotite crystals, or less frequently of metamorphic rock fragments.
Conversely, the samples from the Arenarie di Cala Viola Lithofacies are mainly well-sorted litharenites (Fig. 9C), although episodic intercalated arkoses (Fig. 9D) and subarkoses/sublitharenites occur. In this case the total average mode would not be significant for the extreme dispersion of the investigated samples: thus only the homogeneous litharenites were taken in account. They gave values of Q63 F4 L33. The feldspars are usually cloudy and medium- to highly altered. The lithics are usually highly altered and mainly consist of low- to high-rank siliciclastic metamorphic fragments. A deformed pseudomatrix is diffuse. A significant, growing upward content of femics (amphiboles, muscovite, biotite) with variable degree of alteration occurs. Also here different cements are present: the

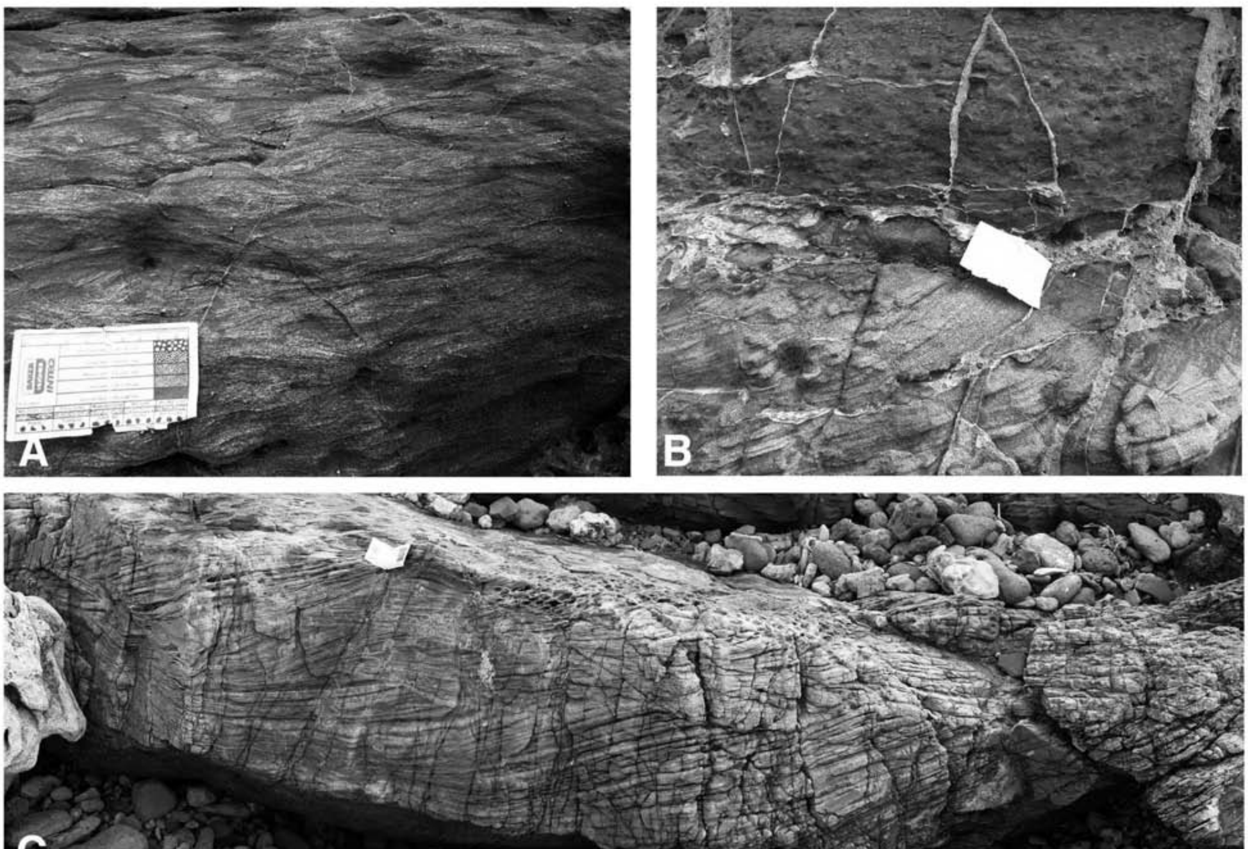

Fig. 8 - Some sedimentological aspects of the Triassic siliciclastics (Verrucano Sardo Fm, Arenarie di Cala Viola Lithofacies) in the Il Cantaro Rock section 3: A) Wavy- to flaser-bedding in medium to fine grain-sized sandstones; B) Intraclastic level resting over cross-laminated sandstones; C) Cross-bedded coarse sandstones sets separated by reactivation surfaces. The width of the scale is 10 cm.

quartz cement is subordinate; isolated clots of iron oxide and carbonate cement appear upward, where they fill at least partially residual voids.

Discussion

Stratigraphic analysis and correlation

Fossils are absent in the investigated successions and therefore the stratigraphic correlations are based on lithostratigraphic marker levels. The peculiar lithostratigraphic features of the conglomeratic breccias horizon described at the top of the Il Cantaro Rock section 2 (interval 5) and close to the base of the Cala Bona section (intervals 4 and 5) allow to identify it as the Conglomerato del Porticciolo Lithofacies. This is a marker horizon of regional importance (Cassinis & Ronchi, 2002; Cassinis *et al.*, 2003), which represents the base of the Early- early Middle Triassic Verrucano Sardo Fm (Costamagna & Barca, 2002) of the Sardinian Buntsandstein Group in the typical Cala Viola area (Cassinis *et al.*, 2003) and in the Monte Santa Giusta area (Fontana *et al.*, 2001). Accordingly, the deposits resting over it can be ascribed respectively to the upper finer red bed siliciclastics of the Sardinian Buntsandstein Group (Arenarie di Cala Viola Lithofacies) and to the overlying carbonates of the Sardinian Muschelkalk Group (Costamagna & Barca, 2002). The Arenarie di Cala Viola Lithofacies show also some peculiar lithostratigraphic features (e.g. tidal rhytmites, the intraclastic

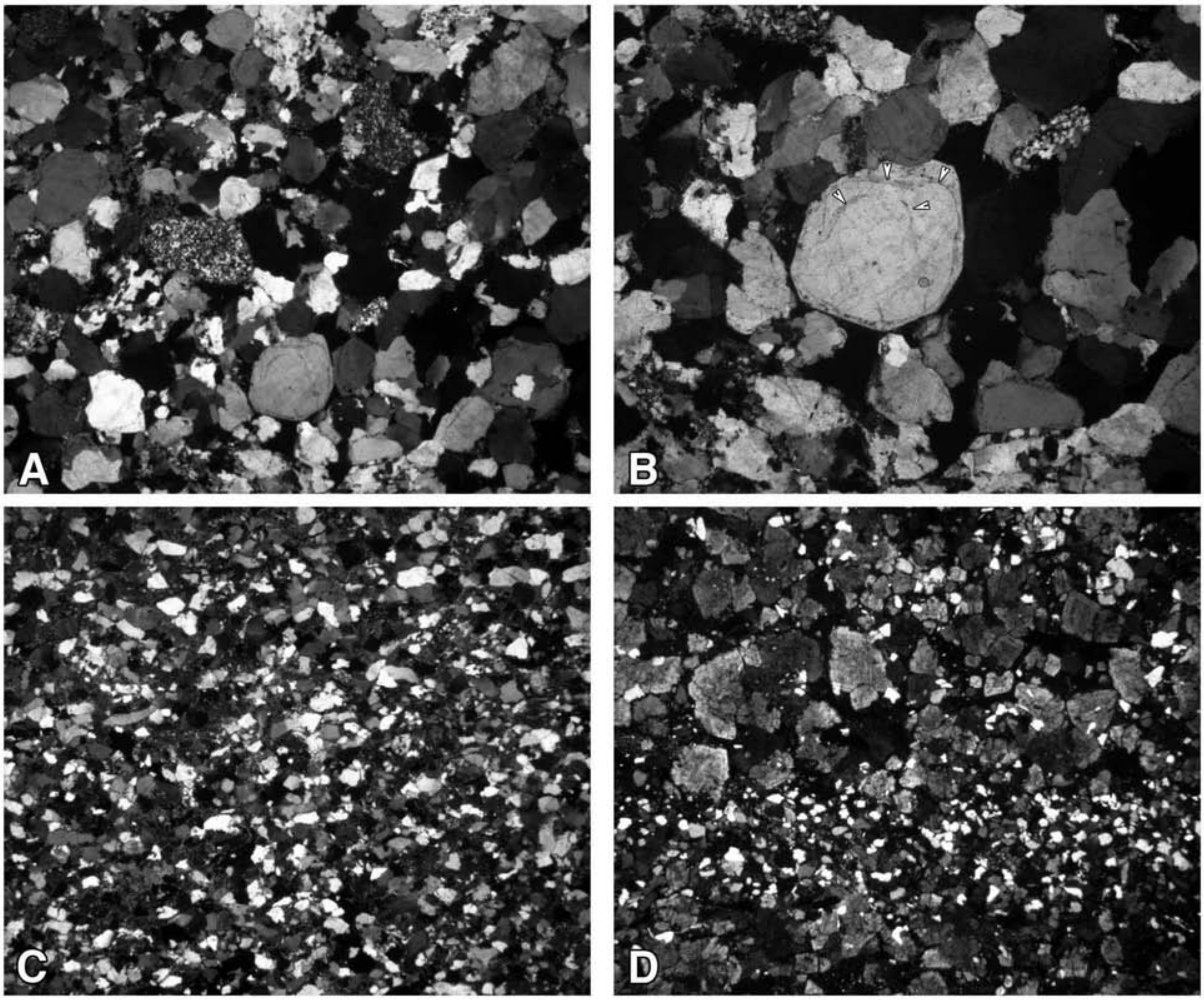

Fig. 9 - Photomicrographs of thin sections of the Cala Bona «Buntsandstein» sandstones (cross- polarized light): A) Sample 1 – Moderately sorted sublitharenite with quartz grains and rock fragments. Conglomerato del Porticciolo Lithofacies, 1.25X; B) Close-up of the former section: quartz grain with two-generation overgrowth (cement) evidenced by arrows. Conglomerato del Porticciolo Lithofacies, 2.5X; C) Sample 7 – Well-sorted litharenite composed of quartz and rock fragments: these latter, being in part weak pelitic metamorphics, contribute to form a pseudomatrix. Arenarie di Cala Viola Lithofacies, 1.25X; D) Sample 8: Moderately to well-sorted arkose: in its middle a thin lamina rich of little quartz grains is evidenced. Arenarie di Cala Viola Lithofacies; 1.25X.

horizons and the carbonate-rich coarse sandstones) that permit to distinguish it from the Permian units exposed in the studied area. Also their mineralogical composition matches well those of the Triassic sandstones cropping out at Cala Viola (Costamagna, submitted). The red bed rocks unconformably covered by the Conglomerato del Porticciolo Lithofacies has likely to be Permian in age. They can be correlated on the whole to the «Sequence II» (Cassinis & Ronchi, 2002; Cassinis *et al.*, 2003. In particular, they might correspond to: A) the Porto Ferro Fm; B) a coarse, lower pars of the Cala del Vino Fm; C) a reduced succession where the Porto Ferro Fm. is unconformably covered by a thin remain of the basal, coarse part of the Cala del Vino Fm., that in its turn is deeply eroded and overlain by the Triassic Verrucano Sardo Fm. Several evidences point to hypothesis C: lithological composition, calcrete abundance, apparent overall diverse energy degree, and conglomerate composition.
The coarse conglomerate horizon described in the Permian part of the Il Cantaro Rock section n. 1 (interval 4), n. 2 (interval 3), and in the Cala Bona section (interval 2) (Fig. 3), locally overlying a significant alteration zone (Fig. 5), can be traced laterally (nearly 300 m) and it cannot be considered as a channel coarse basal lag. It may mark instead a significant fall of the base level and evidences the Porto Ferro Fm/ Cala del Vino Fm unconformity (again in agreement with case C) (Cassinis *et al.*, 2003), probably referable to the Mid-Permian tectono-magmatic episode (Deroin & Bonin, 2003), correlatable with the Saalian unconformity. Thus, the Cala del Vino Fm would thin out laterally (Fig. 3), suggesting a transgressed rough landscape. The petrographic data hereby presented (see also below) and from the bibliography (Cassinis *et al.*, 1996; Sciunnach, 2002) support these interpretations.
Over the Buntsandstein Verrucano Sardo Fm, the passage to the Muschelkalk Punta del Lavatoio Fm is evidenced by transitional, marly gypsiferous lithologies, which may be referred to a Germanic-like Röt facies (Pittau, in Cassinis *et al.*, 2000).

Sedimentological analysis
The NW Sardinia Permian red bed succession was interpreted by Cassinis *et al.* (2003) as deposited in braided to meandering stream environments of variable energy. At Cala Bona - Il Cantaro Rock this succession is featured by fining-upward braided stream fluvial sequences (*sensu* Campbell, 1976). Every sequence is produced by a depositional event evidenced by channels filled by sandy-pebbly bars. At their base, erosive surfaces punctuated by scours and smoothed out by following basal lags suggest very wide channels and/ or unchannelized turbulent flows (sheet-floods). Every depositional event was related to a stream-flow. The calcretes increase above the unconformity, thus suggesting a rising aridity, typical of the Permian evolution (Roscher & Schneider, 2006) and being a further clue to the identification of the intra-Permian Saalian unconformity. The embedded volcanic and red bed sandstone pebbles point to a coeval reworking of the basin itself due to synsedimentary tectonics. Besides, the presence of reworked calcrete nodules filling shallow scours also suggests concentrated high erosion rate. The bioturbation in fine and coarse deposits as well improve the existence of bottom life also in high-energy streams (Mader, 1985). The strongly different mean grain-size between the superposed Permian units indicates important tectonic movements and a rejuvenation of the landscape occurred during the Mid-Permian episode (Deroin & Bonin, 2003) or Saalian unconformity.
The following Conglomerato del Porticciolo Lithofacies (Fig. 4E) at the base of the Verrucano Sardo Fm starts the Triassic sedimentation after an erosive phase of uncertain duration (10-15 Ma, sub-Triassic unconformity: Durand, 2006): it was deposited probably as a small, short-lasting depositional body built of medium to fine gravelly lobes. These lobes (possible wadi-like deposits) have been modeled as fining-upward longitudinal bars formed by few, thin sheet-floods and deposed by diverse, high- to medium energy turbulent events. Sometimes, superposed fining-upwards sequences lack of clear bounding surfaces. This may be interpreted in two different ways: it may mean amalgamation of superposed, diverse events or, alternatively, different current pulses developing in the same depositional event. Here, indications of a precocious tidal influence (tangential trough cross-bedding, reactivations surfaces, reversing flow) were found too. Pebbles and grains are made of quartz from the Variscan basement (vein quartz); scarce broken rounded quartz pebbles indicates a partial sedimentary recycling; lydite (Paleozoic black microquarzites) and metamorphic rock pebbles are very rare. Upwards, the almost sudden passage to microconglomerates and pebbly sandstones modeled in mesoforms *sensu* Jackson (1975) (small dunes, megaripples, unit bars *l.s.*) marks the development of channel-bar island foresets. A weak tidal influence cannot be entirely excluded. The straight one-pebble lag underneath is supposed to be the actual channel sole over which the bedforms step on. Some beds show faint evidences of a minor aeolian deposition: while normal and reverse graded laminae suggest alternations of grain-fall and grain-flow processes, discontinuous lineations of pebbles may be interpreted as deflation pavements. The sudden passage upwards from the Conglomerato del Porticciolo Lithofacies to the Arenarie di Cala Viola Lithofacies evidence a swift stop of the coarse feeding: this has been described also by Cassinis *et al.* (2003) at the Cala Viola-Torre del Porticciolo Buntsandstein outcrops. At a basin scale, hypothetically it may be due to the disappearing of the topographic irregularities due to the smoothing of the relieves surrounding the basin. Going up-section, the irregular alternations of medium- to fine grained red bed siliciclastics of the Arenarie di Cala Viola Lithofacies (upper Verrucano Sardo Fm) are here interpreted as tidal bundles and rhytmites indicating marine tide-influenced shallow environment with limited depth variations. The sharp-based intraclastic levels apparently are the filling of shallow tidal channels, or possible washouts. Tidal evidences have been reported in the upper part of the succession also in the Cala Viola area (Neri *et al.*, in Cassinis *et al.*, 2000; Fontana *et al.*, 2001).

Thus, in the Verrucano Sardo Fm the continental environment, even just interested by a mild, episodical tidal influence, turns in the upper part definitely to a transitional coastal one. This sharp and early settlement of a tidal environment (Arenarie di Cala Viola Lithofacies) supports the progressive ingression over a flat, previously smoothed Early Triassic landscape.
The sharp appearance and the rapid increase of the carbonate content, together with the scattered embedded evaporites and the stop of the terrigenous input, mark the progressive passage to an initially restricted shallow carbonate environment before the transition to the following more open marine domain. In fact, the succeeding peritidal cycles point to a carbonate shelf with shallow lagoon to carbonate subarid tidal flat sub-environments. Storm events deposited their tail fines over the tidal flat, so leaving behind thin cross-laminated fine sands and laminated carbonate muds: the stagnation of the storm water surge over the tidal flat may depose evaporitic crystals forming the lag of the storm layer (Aigner & Bachmann, 1989). The scattered marly events may suggest either a temporary deeper lagoon or a slowing down of the carbonate deposition. Furthermore, the features, the geometric position and the geographic location of this carbonate succession suggest its pertinence to the lower part of the «Muschelkalk» succession and so to the lower, unknown continuation of the Punta del Lavatoio stratigraphic section (Fig. 1) (Gandin, 1978b; Costamagna & Barca, 2002): this section, located less than 600 m to the NW, is the main reference section of the Punta del Lavatoio Fm (Costamagna & Barca, 2002; Knaust & Costamagna, 2012).

Petrographic analysis

Despite the relatively few samples analyzed, their precise collection sites along the Cala Bona section display their petrographic evolution and allow their modal analysis can be usefully compared with other data from investigations carried by authors (Cassinis *et al.*, 1996; Sciunnach, 2001) on the NW Nurra Buntsandstein. The Cala del Vino Fm samples modal composition is in good accord with the values reported by the previous authors. Conversely, for the overlying «Buntsandstein» deposits, the values are in agreement only for the Conglomerato del Porticciolo Lithofacies, while the Arenarie di Cala Bona Lithofacies occupies a different field. Besides, both lithofacies show altogether also a clear different evolving trend. In fact on average from the sample 1 to the 12 the maturity decreases gradually (Fig. 10). As pointed out by Cassinis *et al.* (1996), the passage from the Cala del Vino Fm (designed as lithofacies 3) to the Verrucano Sardo Fm (lithofacies 4) show increasing textural and mineralogical maturity, probably linked with the peneplanation of the landscape under an aggressive weathering. The data presented here confirm this statement but also show that the Verrucano Sardo Fm – and particularly the Arenarie di Cala Viola Lithofacies – gradually evolves to more immature terms, closer to the less mature composition of the Permian units found in this study (and even superposing on the values of Cassinis *et al.*, 1996), so marking a rejuvenation of the landscape.

Thus, somewhat sharp evolution of the mineralogical composition from the Conglomerato del Porticciolo Lithofacies to the Arenarie di Cala Viola Lithofacies evidenced in the plot of Dickinson *et al.* (1983) (Fig. 10) may suggest that, after the leveling of the Variscan landscape, and following the erosion of a quartzose mature cover, the sediment source area for the Verrucano Sardo Fm was uplifted leading to a renewed exhumation of the Variscan chain probably due to a limited tectonic phase without significant magmatism; alternatively, a minor sea level drop may achieve the same results. Sciunnach (2002) suggested possible relations between Buntsandstein deposition and an early Eo-Alpine weak tectonic phase (Recoaro phase of De Zanche & Farabegoli, 1981) consisting only in the reactivation of local fault scarps. Besides, in the Arenarie di Cala Viola Lithofacies the strongly variable composition of sandstones (from litharenites to arkoses) could mean sudden, drastic but ephemeral changes in feeding areas.
Petrographically the transition from the lower to the upper lithofacies of the Verrucano Sardo Fm is quite sharp. The significant and abrupt increase in detrital femic minerals underscores the notion of a different source area for the lower and the upper Verrucano Sardo Fm lithofacies and perhaps under different climatic conditions. The frequency of unaltered femic minerals in areas of slow sedimentation rate suggests a subarid-arid climate for the Arenarie di Cala Viola Lithofacies, although the alteration of intercalated feldspar-rich arkoses could hint wetter, ephemeral phases. Furthermore, basing on the frequent double overgrowth of the outer rim, the Conglomerato del Porticciolo Lithofacies quartz stock at least partially comes from the reworking of previous undeformed coarse sedimentary deposits (Permian and/or even Carboniferous conglomeratic horizons?).

Geometry and structural setting of the Nurra Permo-Triassic basin: some remarks

Well-defined and recognizable marker levels and unconformity surfaces in the studied sections, (i.e. the Conglomerato del Porticciolo Lithofacies marking the Permian/Triassic unconformity and the Mid-Permian unconformity) are important stratigraphic key-points in the post-Variscan molassic Nurra basin (Fig. 3). In fact, these same markers were studied at Monte Santa Giusta (Gasperi & Gelmini, 1980; Neri *et al.* in Cassinis *et al.*, 2000; Fontana *et al.*, 2001) and along the cliffs of the Nurra coastline (Cassinis *et al.*, 1996; 2000; 2003). Buzzi *et al.* (2008) synthesized a large array of data of the Permian-Triassic Nurra basin and proposed a general tectonic scheme, suggesting a half-graben setting with a structural high in the Monte Santa Giusta area. The possible depocenter could be roughly close to the Cala Viola-Torre del Porticciolo-Baratz area (Fig. 1). A Variscan basement horst in the Monte Santa Giusta area during Permian age was just previously supposed (Gasperi & Gelmini, 1980). Moreover, this horst could have persisted through the Permian, so keeping to play that role during Triassic times: the peculiar Monte Santa Giusta petrofacies (subarkoses to arkoses: Cassinis *et al.*, 1996; Sciunnach, 2002), richer in feldspars in

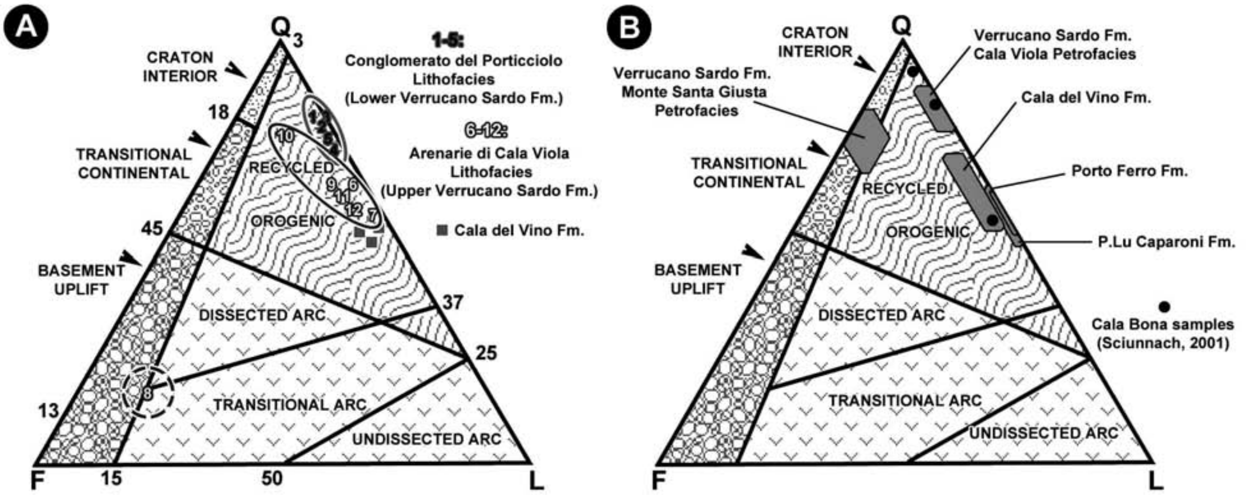

Fig. 10 A) Modal framework of the sandstones sampled in the Cala Bona stratigraphic section and comparison with B) a simplified and modified plot of the Permian-Triassic petrofacies after Cassinis et al. (1996), and Sciunnach (2001). Discrimination fields after Dickinson et al. (1983). The Sciunnach's Lower «Buntsandstein» Cala Bona litharenite dot (falling in the Cala del Vino Fm field) has been sampled in deposits attributed in this paper to the Cala del Vino Fm.

respect to other Verrucano Sardo Fm petrofacies, may be explained as the dismantling product of the basement uplift due to the Triassic Eo-Alpine tectonics.
However, on the basis of the stratigraphic and sedimentological data presented in the previous paragraphs, a tectonic high of the Nurra basin can be hypothesized for the Cala Bona-Il Cantaro Rock succession: this might represent only a minor tectonic structure or, alternatively, even the southern basin margin. In fact, such a short red bed succession, where Mid-Permian and Permian/Triassic disconformities are so close (2.5 m in the Cala Bona section, Fig. 3) can be justified only by a reduced succession due to the location on higher ground in respect to the Cala Viola-Torre del Porticciolo area, where the probable depocenter of the Permian-Triassic basin has been located (Gasperi & Gelmini, 1980; Buzzi *et al.*, 2008).
A try to restore the paleodirectional indicators (imbrication, cross-bedding) to their original orientation has been made using the Wulff stereonet: the results gave a mean flow paleodirection of n. 140° to SE for all the Permian-Triassic red bed succession: this value is in good accord with Sciunnach's results (2001) and paleogeography.
So, by supposing here a southern structural high of the basin, a full graben structure oriented nearly E-W may be proposed: nonetheless, it has to be pointed out that, differently from the Monte Santa Giusta northern high, the missing Permian volcanics and the lower feldspar content may imply here a less marked tectonic activity.

Comparison with other neighbouring coeval successions: different sedimentological interpretations and regional consequences

According to the interpretation presented here, the Cala Bona-Il Cantaro succession records the evolution of the southern (marginal?) part of the Nurra Permo-Triassic basin. That in turn represented the southern part of a wider single basin including the Provençal area (Cassinis *et al.*, 2003; Durand, 2006, 2008). Strong stratigraphic and evolutionary analogies have been evidenced between Provence and NW Sardinia. This basin was then fragmented by the Tertiary shift of the Corsica-Sardinia block (Orsini *et al.*, 1980; Speranza *et al.*, 2002).
The results presented here substantially confirm the depositional hypothesis suggested for the Permian units by previous authors whereas they are in contrast with the foregoing paleoenvironmental interpretations of the Triassic Buntsandstein.
Cassinis *et al.* (2003) and Durand (2006, 2008) suggest a deposition in a braided environment for the Conglomerato del Porticciolo Lithofacies («Poudingue de Port Issol» in Provence), and a terminal fan context for the Arenarie di Cala Viola Lithofacies («Grés de Gonfaron» in Provence). According to Cassinis *et al.* (2003) and Durand (2006; 2008), these lithofacies are separated by an unconformity. Nonetheless, for the Conglomerato del Porticciolo Lithofacies the braided pattern and the early rising tidal influence should be considered together for reconstructing the depositional environment: so, a possible explanation may be the fluvial braided environment gradually passing to a transgressive braid delta (McPherson *et al.*, 1987) characterized by low subsidence and low relief conditions. This would agree with the next marine tidal passage. The terminal fan model was recently questioned in its very existence (North & Warwick, 2007). Anyway the prevalence of channelized sands over interchannel pelites in the Arenarie di Cala Viola Lithofacies would account only for the inner, feeder zone of the typical terminal fan model (Kelly & Olsen, 1993), and the lacking of the intermediate and outer terminal fan zones contrasts with the rapid passage to the marine «Muschelkalk» deposits. Besides, the terminal fan model is characterized by an overall

fining-upward succession (Kelly & Olsen, 1993), while the Cala Bona succession shows a weakly coarsening-upward one, probably compatible with a tidal environment evolution in a trasgressive context (Ginsburg, 1975; Dalrymple, 1992). Still, a terminal fan would develop under a strong evaporation rate that would be marked by calcretes abundance that actually does not exist in the investigated outcrops. Besides, undisputable tidal influences were found also in the Buntsandstein Cala Viola outcrops (Costamagna, submitted): here they were first mentioned by Fontana *et al.* (2001).

Generally in Central Europe the passage from Buntsandstein to Muschelkalk is marked by transitional, coastal to lagoonal-deltaic deposits indicating a mixed, locally evaporite-bearing, sedimentation (Röt) (Gall, 1985; Grunert, 1985; Niedermayr, 1985; Douringer & Gall, 1987). Nonetheless in the Iberian area (united to the Corsica-Sardinia Block during Permian-Triassic times) a tidal influence has been suggested (Ramos *et al.*, 1986; Morad *et al.*, 1989; Garcia-Gil, 1991). The presence of a siliciclastic tidal system in the upper part of the Sardinian Buntsandstein fits well with the previous location of the Corsica-Sardinia block in front of the Neo-Tethys, providing significant tides during the Triassic. The Upper Anisian Escalaplano Fm (Costamagna *et al.*, 2000) of the Buntsandstein Group in Southeastern Sardinia may represent a similar depositional unit with tidal influences: in fact, on a mudflat a cyclical coarser sedimentation with faintly cross-bedded sandstone layers took place immediately before the «Muschelkalk» transgression.

The unconformity between the Conglomerato del Porticciolo Lithofacies and the Arenarie di Cala Viola Lithofacies (Durand, 2006, 2008; Linol *et al.*, 2009) is not visible in the Cala Bona section for the exiguity of the outcrop. Nonetheless a sharp transition (sample 5 to 6: Figs. 3, 10) with the sudden vanishing of the quartz pebbles and the quick change in sand composition and color (increase of the not-quartzose content) can be noticed. However, accurate reviews of the Cala Viola sections and photomosaics located 20 km northward evidenced the presence of an important unconformity between these lithofacies (Costamagna, submitted).

Conclusions

The results of this study, although representative of a small area, improve the geology of a previously poorly known sector and so gave a further contribution to the knowledge of the NW Sardinia post-Variscan successions of Permian-Triassic age. The Cala Bona - Il Cantaro stratigraphic successions can be used for fruitful comparisons, since some data and interpretations are significantly different from those presently acknowledged for the Cala Viola-Torre del Porticciolo Buntsandstein areas. So, this evidences that further investigations are needed also on the well-studied Buntsandstein deposits located northward.

In the investigated area Permian and Triassic marker beds and units were precisely identified. Besides, Permian deposits were mapped southward of Alghero for the first time. So, almost all the units of the post-Variscan basin succession are here represented. Besides, tidal precocious influences on the Early to Middle Triassic siliciclastic continental to transitional environments were here pointed out. A minor aeolian contribute to the sedimentation is suspected. Moreover, the first «Buntsandstein»-«Muschelkalk» outcropping passage shows the gradual sedimentological evolution from marine siliciclastic to carbonate environment under mildly confined conditions. The possible regional implication of the tidal influences on the NW Sardinia upper «Buntsandstein» was discussed. The initial steps and the stacking pattern of the Middle Triassic carbonate shelf in a peritidal context were delineated. Petrographic classifications and evolutionary trends of the siliciclastics were evidenced: they confirmed a gradual peneplanation during the Permian-Triassic transition, but also suggested, in contrast with previous authors (Cassinis *et al.*, 1996, 2003; Fontana *et al.*, 2001; Sciunnach, 2001), a landscape rejuvenation during Early to Middle Triassic times perhaps due to the Eo-Alpine tectonics. This should be further confirmed by more detailed petrographic investigation in other Buntsandstein areas as the Cala Viola-Torre del Porticciolo-type outcrops. Finally, the evolution and the paleogeography of the Nurra Permian-Triassic basin has been more detailed, evidencing a southern structural high, possibly representing the southern edge of the basin. In this view, a full-graben structure cannot be excluded at all.

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