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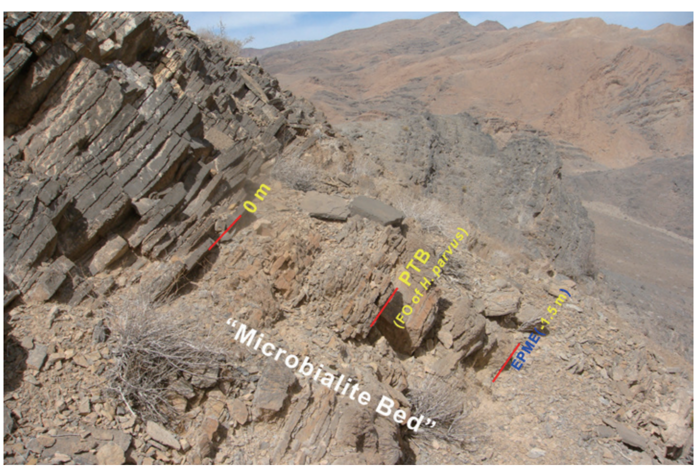

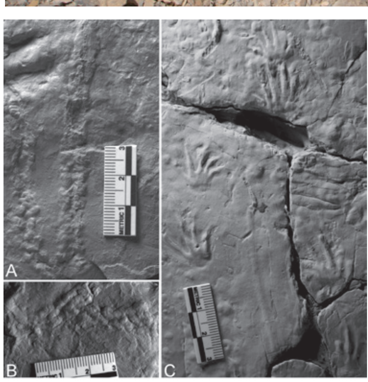

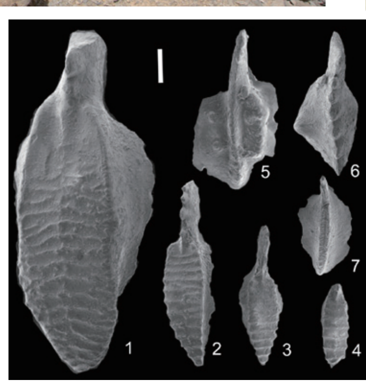

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Upper Pennsylvanian, Permian, and Lower? Triassic continental successions in SW Sardinia (Italy): a petro-sedimentological update of the molassoid Sulcis basin

Luca G. Costamagna
Dipartimento di Scienze Chimiche e Geologiche, Cittadella Universitaria, Blocco A, 09042 Monserrato (CA)

Introduction

In the SW Sardinia Sulcis-Iglesiente area, the continental late to post-Variscan upper Pennsylvanian, Permian, and Triassic successions are thin, fragmentary, restricted, and scattered (Fig.1). They are rarely superimposed on each other. So, the reconstruction of the sedimentary evolution of the basin as a whole depositional unit is difficult. More detailed stratigraphical-sedimentological analysis and investigations of historically known outcrops, and stratigraphic and thin section analysis of newly found outcrops have allowed the delineation of the history of the late to post-Variscan successions in SW Sardinia.

Fig. 1. Location of the upper Pennsylvanian to ?Lower Triassic outcrops in SW Sardinia. Overlapping circles mean the formational units superpose on each other conformably.

Geological Framework

In SW Sardinia over the Variscan basement, the succession starts unconformably with the upper Pennsylvanian limnic San Giorgio Fm. (Lower Rotliegend), formed mainly by alternations of coarse- to medium-grained siliciclastics. Fine siliciclastics are subordinated. Scattered intercalations of carbonates (mainly in the San Giorgio locality lower part) and volcanic rocks (in the Guardia Pisano locality upper part) are present (Barca and Costamagna, 2003a; Costamagna, 2019). The unit was deposited in a narrow warm-wet alluvial-to-lacustrine early collapse basin. The small 25 km-distant NW upper Pennsylvanian Tuppa Niedda outcrop (Barca et al., 1994) records a succession about 14 m thick made up of conglomerates and sandstones (Costamagna and Barca, 2008), and is lithologically similar to the San Giorgio Fm. This outcrop testifies to the presence of contemporaneous limnic basins in SW Sardinia, possibly evolving later in the nearbyTriassic Is Arenas basin (Costamagna and Barca, 2002).

The Lower – Middle (?) Permian red bed Guardia Pisano Fm. (Upper Rotliegend) follows: pelites, sandstones, and rare conglomerates are represented (Barca and Costamagna, 2006; Costamagna, 2019). Volcanic rocks occur in the coarser deposits as cm-sized pebbles of lavas and pyroclastic rocks. The unit was deposed in a warm-subarid alluvial, sinuous environment of mid- to low-energy.

The Guardia Pisano Fm. is followed by the Upper Permian - Lower Triassic red bed s.l. Rio Is Corras Fm. (Sardinian Buntsandstein Group?) (Costamagna and Barca, 2002; Barca and Costamagna, 2003b, Costamagna, 2019). This unit is formed by conglomerates and carbonates with rare sandstones, reddish pelites, and evaporites. The conglomerates contain dm-sized pebbles from the older upper Pennsylvanian-Permian deposits below. This unit was deposited in a warm(hot?)-arid fan-delta to lake environment of variable energy. The passage to the restricted marine Muschelkalk Campumari Fm. (Costamagna and Barca, 2002; Barca and Costamagna, 2003b) follows rapidly, marked by a possible weak unconformity (?). Stratigraphic type-sections have been described for all the mentioned units (Costamagna and Barca, 2002; Barca and Costamagna, 2003a, b, 2006).

In all SW Sardinia, scattered and isolated thin covers of pebbly to sandy red beds deposits referable to the Guardia Pisano Fm. or the Rio Is Corras Fm. are often unconformably deposited on the Lower Cambrian carbonates, these latter during Late Paleozoic times forming residual low reliefs all through the final peneplaning of the Variscan chain (Sinisi et al., 2014; Costamagna, 2019). Examples are known in all of SW Sardinia (e.g., from N to S: Planu Sartu mine, Baueddu, Sa Bagattu, Barega mine, Barbusi mine, Terraseo breccias: Pasci et al., 2016, and references therein). Their origin is variable, and sometimes even their age (Permian or Caenozoic?) is controversial (Moore McMahon, 1972). Some of them are red bed deposits filling partially through sinkholes and open fractures the upper karstic network developed underground in the Lower Cambrian carbonate rocks during late- to post-Variscan times (Bechstadt, 1983; de Waele et al., 2001). Others were simply part of a superficial alluvial cover that, due to the following tectonic events, are now squeezed and trapped between carbonate tectonic wedges of later age. A graphic history of those events in the collapsing Variscan chain frame is summarized in Costamagna, 2019 (Fig. 2).

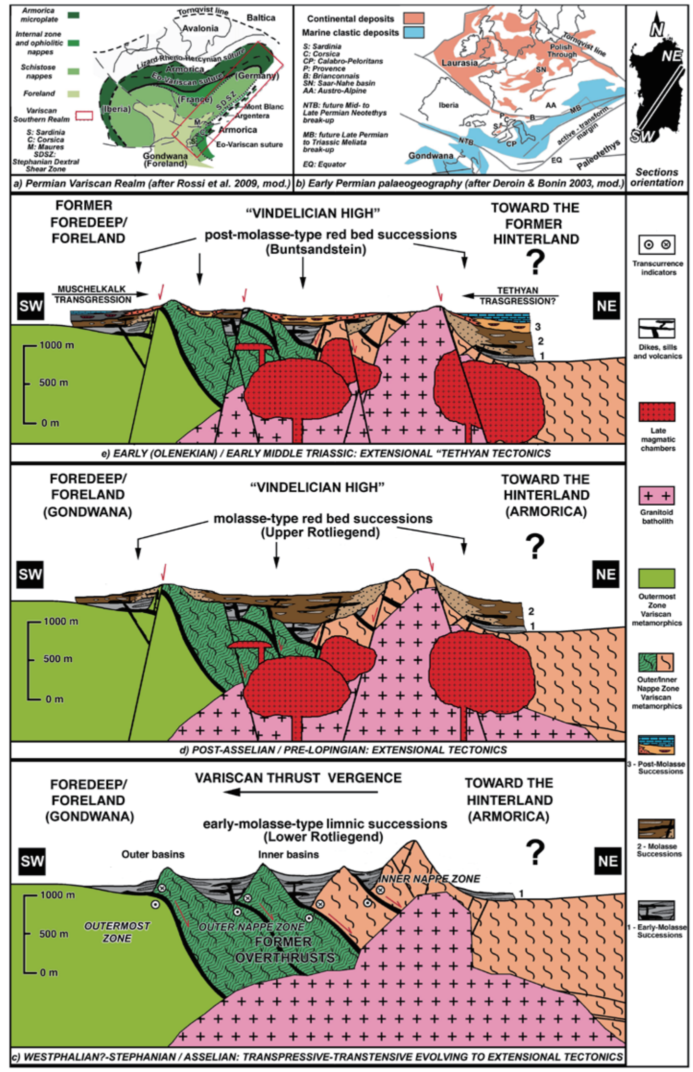

Fig. 2. Schematic comparison of the different evolutive stages of the Sardinian Pennsylvanian to lower Middle Triassic continental basin and their location in respect to the (a) general geodynamic and (b) palaeogeographic context. Scale and thicknesses are only indicative; the feeding of the late- extensional volcanic rocks is not fully represented in figures. (c) Pennsylvanian (?Westphalian–Stephanian) to Cisuralian (Asselian): limnic basins during transtensive/transpressive regime. Late-tectonic granitoids cut the former tectonic structures. (d) Guadalupian (post-Asselian) to Lopingian(?): red-bed basins. Basins open up, coalesce and their bottoms collapse: orographic barriers no longer exist and local climate changes from humid to dry. The Variscan peneplain develops. Post-tectonic intrusions take place. (e) Early Triassic (Olenekian?) – early Middle Triassic (late Anisian, Pelsonian–Illyrian boundary): Alpine red-bed basins, thin and rapidly submerged by the marine Muschelkalk transgression. From Costamagna, 2019, modified.

Key sections: sedimentology

Along the SS130 motorway by-pass circling the outskirts of Iglesias, a peculiar San Giorgio basin stratigraphic section about 8 m thick is exposed on the roadcut (Fig. 3). This section shows in its lowest part significant differences if compared with the typical San Giorgio Fm. succession. It rests unconformably over the Variscan basement, and it starts through about 1 m of petromict clast-supported conglomerates made of well-rounded cm-sized quartz pebbles and rare lydites, and crushed fragments of metamorphic rocks forming a false matrix: the mutual percentage of those components is about 50%. This basal level peters out W-ward and is followed by 6 m of well-bedded, locally wavy- and cross-bedded, grey-yellowish medium- to coarse-grained quartz-rich marly sandstones –sandy dolostones with rare intercalations of cm-thick beds of graded dolostone microbreccias with erosive base. The section is terminated by about 1.5 m of grey carbonate sandstones and microconglomerates-microbreccias in coarsening-upward beds with an erosive base. These rudites are frequently matrix-supported and texturally immature.

At Guardia Pisano the upper San Giorgio Fm. is finer than the lower one outcropping in the San Giorgio basin. The dark-grey limnic, thinly laminated, pelitic deposits with intercalated volcanic rocks, marl and carbonate bed of the upper San Giorgio Fm. are covered, through a weak but sharp unconformity, by the sandstones of the Guardia Pisano Fm red beds (Fig. 3, 4A). Nonetheless, the Guardia Pisano Fm. contains here still rare thin beds of grey-reddish siliciclastics.

The new red bed outcrops found in the San Giorgio basin area (Iglesias) represent a missing stratigraphic link (Fig. 3, 4B). Here at Case Massidda - Case Lai the Rio Is Corras Fm. carbonate pebbles-rich conglomerates embedding rare thin calcrete beds are conformably posed through a gradual, alternated boundary over red bed tight metric alternations of massive, rarely laminated pelites, microbial carbonates with fenestral structures, evaporites, and subordinated cm-to dm-thick beds of sandstones and matrix-rich microbreccias with no carbonate pebbles; mud cracks and halokinetic folds are also visible. The well-exposed thickness of the whole succession is about 30 m, but there remains about 30 meters more of the Rio Is Corras Fm., poorly visible due to the vegetation cover. These deposits represent the lower-energy upper phase of the alluvial red bed Guardia Pisano Fm. Pedogenization evidence is here present too. The lowest part of this succession is hidden by the Campo Pisano mine waste cover.

This transition from the Guardia Pisano Fm. red beds to the

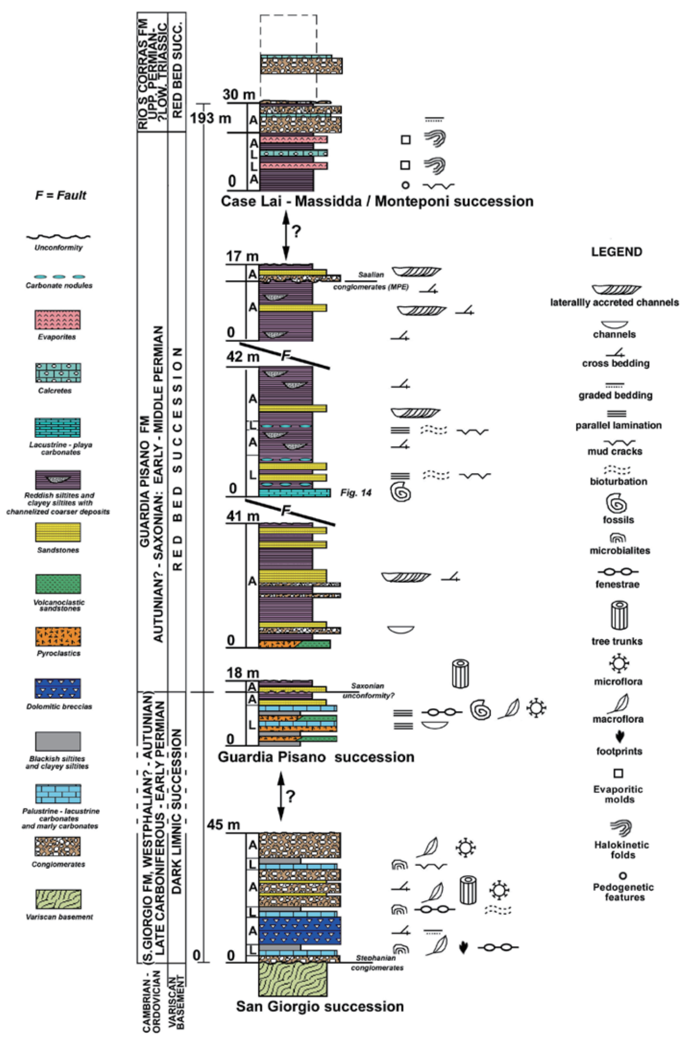

Fig. 3. Lithostratigraphic reconstruction of the late Pennsylvanian to ?Early Triassic Sulcis basin succession in SW Sardinia. A, alluvial deposits; L, lacustrine to playa deposits.

Rio Is Corras Fm. calcretes and oligomict conglomerates is also visible on a roadcut along the Iglesias-Gonnesa motorway, close to the Monteponi mine waste cover and the Laveria Mameli mining building (Fig. 4C): here, about 20 m of well-bedded alternations of red pelites, calcretes, evaporites, and very rare matrix-supported breccias rest unconformably over the Variscan basement and are followed conformably by not more than 3 meters of coarse carbonate pebbles-rich conglomerates and calcretes.

2 km E to Iglesias are small sparse outcrops of oligomict conglomerates formed by Cambrian carbonate pebbles and referable to the Rio Is Corras Fm. resting over the Variscan basement.

In the Planu Sartu mine area, in the Lower Cambrian carbonates (Bechstadt and Boni, 1994, and reference therein) is evident an extensive karstic network, whose chaotic filling framework is made of Lower Cambrian carbonate boulders and cobbles: they are interpreted as collapse breccias. The breccia internal cavities are filled by red bed parallel- to cross-laminated sandstones forming internal sediments. Upwards, the breccia framework decreases in volume and element size and conversely, the sandy matrix percentage grows up. Next to the Planu Sartu gallery crop out well-bedded to laminated reddish sandy to silty-clayey deposits, organized in fining-upwards couplets, and showing in the sandstones parallel laminations, flute-casts, groove-casts, and parting lineations (Fig. 4D). These deposits rest over a coarse poorly-sorted calcite-cemented breccia made of Variscan basement highly-weathered schist pebbles and cobbles. This breccia lies over the coarse carbonate cave speleothem formed by Lower Cambrian carbonate boulders. This red bed matrix-rich breccia setup is not uncommon in SW Sardinia (Baueddu, Terraseo).

Southwards, the Sa Bagattu outcrop (Brusca et al., 1968), resting unconformably over the Lower Cambrian carbonates, is very small (about 100 m2) and about two meters thick: it is formed mainly by oligomict heterometric breccias built of cm- to dm-sized angular fragments of carbonates, quartz, lidite, chert, and rare barite. The pebbles are embedded in a yellowish-gray to reddish dolomitic-sandy matrix and show a mainly quartzose cement: dolomite as cement is very rare. The carbonate-rich matrix may contain small cavities lined by acicular crystals (dissolution of former evaporitic minerals?). According to Brusca et al. (1968) these deposits cover the barite clast-rich red beds filling the carbonate karstic network and a limited, superficial thickness of Lower Cambrian silicitized carbonates. Above and laterally, the carbonate breccias pass to a coarse reddish-grey sandstone-petromict microconglomerate, thickly bedded and quartz-cemented. Pebbles of this lithofacies have been found in the Rio Is Corras Fm conglomerates.

One kilometer eastward, at Monte Barega, Bechstädt (1983) reports the finding of burrows (continental *Scoyenia* icnofacies) and *Equisetales* prints, in red bed sandstone boulders from karstic filling and showing mud-cracks. These sediments were supposed to have fallen from subaerial environments through wide fractures and were deposited in karstic cavities during the Permian-Triassic? surfacing of the Variscan basement (Bechstadt and Boni, 1994).

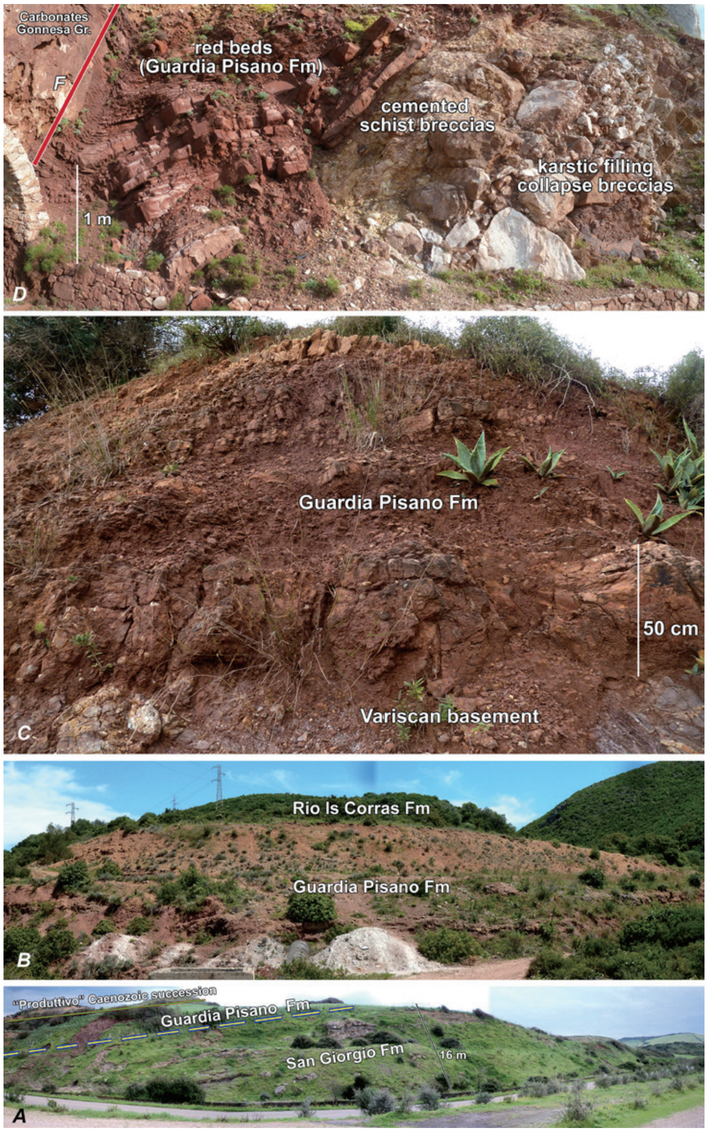

Fig. 4. Stratigraphic transition locations: A) San Giorgio Fm. - Guardia Pisano Fm., Guardia Pisano area; B) Guardia Pisano Fm. - Rio Is Corras Fm., San Giorgio area; C) Guardia Pisano Fm. pelites, calcretes and evaporites resting directly over the Variscan basement, Laveria Mameli, San Giorgio area; D) Guardia Pisano Fm. red bed outcrop resting over a breccia karstic filling, Planu Sartu mine. F: Fault.

Unconformably resting over the Variscan basement, suspected outcrops of Upper Permian-Lower Triassic Rio Is Corras Fm. petromict conglomerates have been described in the Piolanas area (Pasci et al., 2016), but the report is controversial; based on the composition of the pebbles, these outcrops could be the result of debris mixing with younger Mesozoic deposits in the following Monte Margiani Sandstones, that is the terrigenous base of the Caenozoic Sulcis Coal basin (Barca and Costamagna, 2000). So, they would not be genuine Rio Is Corras Fm. outcrops, although they suggest their presence nearby and dismantling at Early Caenozoic times.

In the Nuraxi Figus coal mine (Caenozoic Sulcis Coal basin, Fadda et al., 1994), at 500 m below sea level, the underground works crossed terrigenous to carbonate rocks referred to the Permian-Triassic succession (Murru and Salvadori, 1987), now attributable to the Guardia Pisano Fm. and Rio Is Corras Fm. red beds, and to the carbonate Campumari Fm. This at-times undifferentiated Permian-Triassic complex has been previously evidenced in the cores of the borehole 6/79 (Assorgia et al., 1992) by crossing 250 m of red bed terrigenous succession and 7 m of dolostones. The base of the red bed succession was never reached.

A new survey in the mine evidenced alternations of decimetric beds formed by red bed pelites, sandstones, and petromict conglomerates. The sandstones are parallel- to cross-bedded. The conglomerates are built of imbricated pebbles of cannibalistic sedimentary, igneous, and metamorphic nature and show a lower erosive boundary.

Key sections: petrographic notes

Preliminary modal analyses of the sandstone framework are informally represented in Fig. 5. The San Giorgio Fm. sandstones are litharenites, and specifically mainly phyllarenites. The metamorphic grains show a low-grade alteration. Carbonate–rich litharenites are frequent at the base of the San Giorgio Fm. stratigraphic section located along the SS130 motorway by-pass. Calclithites whose feeding is related to the Lower Cambrian carbonate extraclasts are present in the lower part of the unit, forming a monomict interval with scattered quartz tiny grains; they suggest times of almost exclusive detrital contribution from the Lower Cambrian carbonates. No defined maturity evolutionary vertical trend has been evidenced; several fluctuations are visible. In the upper part of the San Giorgio Fm., volcanic rocks fragments appear.

The Tuppa Niedda sandstones are phillarenites. The stratigraphic section is too short to allow any inference.

The Guardia Pisano sandstones are mainly litharenites with fragments of strongly weathered Variscan basement and volcanic rocks passing upwards locally to sublitharenites due to the growing contribution of K-feldspar from the erosion of coeval Permian volcanic rocks. A weak maturation trend upwards seems to be present, together with the replacement of the Variscan basement grains by the volcanic rocks and the feldspars grains.

The analysis of the Guardia Pisano Fm. sandstone samples collected underground in the Nuraxi Figus mine evidences a petrographic affinity with the lower part of the unit, given the abundance of Variscan basement grains.

The Rio Is Corras Fm. rare sandstones are all classifiable as calclithites and rare phyllarenites almost devoid of quartz. The sandstone beds are still now too scarce in the bulk of the succession to evidence any trend whatsoever.

At Sa Bagattu, oligomict microbreccias made only by partially silicitized angular carbonate pebbles with pervasive chalcedony cement are present.

At Planu Sartu, the red bed sandstones, both breccia void-filling and well-bedded sandstones alike are classifiable as litharenites.

Petro-sedimentological and stratigraphic results

The San Giorgio Fm., the Guardia Pisano Fm., and the Rio Is Corras Fm. rest conformably on each other, or directly and unconformably on the Variscan basement. The younger the unit, the wider its extent apparently could have been, as implied by the distribution of the remains (Fig. 1). The stratigraphic and the environmental relationships among the units in the diverse sectors of the late to post-Variscan Sulcis basin, suggest the size of the depositional basin gradually enlarged at times. Some thin red bed outcrops, organized in lithological couplets and short fining-upward sequences, and showing structures evidencing upper-regime flows, represent the final subtle cover mantling cave speleothems of karstic origins; these latter were ultimately filled by (colluvial?) red beds falling through dissolution fractures in the Lower Cambrian carbonates and featured by ephemeral high-energy depositional regimes. Depositional and erosive areas were activated alternatively in the basin according to their location, perhaps in respect to the tectonic collapse evolution and the following modification of the accommodation space. So the different stratigraphic units rested either over the older ones or unconformably over the Variscan basement. Based on this evidence, a progressive widening of this depositional continental basin in times is suggested, starting as a narrow (pull-apart?) basin in late Pennsylvanian times (Elter et al., 2020) and merging in the end with the wider extensional basins related to the W-Tethys rifting. Borehole subsurface data suggest at least 250 m of total thickness; this is comparable with the thickness of the coeval basins of E and NW Sardinia (Costamagna, 2019, and references therein).

The SS 130 by-pass San Giorgio stratigraphic section is significant. Here the intermediate key – level of carbonate breccias is closer to the Variscan basement; it is separated from it only by thin marly sandstones-sandy dolostones and quartz-rich conglomerates and sandstones that are singular in the area. These breccias correspond to the carbonate breccias located in an upper position in the other San Giorgio main stratigraphic sections. So, if compared to the main San Giorgio basin area (Barca and Costamagna, 2003a), this zone could represent a side depositional area, where sedimentation started later with lower-energy deposits. This supports further a gradual enlargement of the basin.

The almost undisturbed passage from the San Giorgio Fm. to the Guardia Pisano Fm. indicates a smooth climatic and environmental transition towards drier alluvial, more open environments (Costamagna, 2019).

Also, the gradual passage from the upper Guardia Pisano Fm to the Rio is Corras Fm. in the San Giorgio basin area (Fig. 3) marks a smooth passage from a low-energy playa environment with dominant fine pelitic deposits and evaporites (evolving from the previous alluvial sinuous environment of the lower Guardia Pisano Fm.) to a fan delta - lake environment. Pedogenization suggests interruptions in deposition. At Laveria Mameli, the Guardia Pisano Fm. lithological alternations rest directly over the Variscan basement; this again is evidence of the variable base of the Permian red bed succession and the gradual widening of the basin.

The progressive passage from the lower energy deposits of the Guardia Pisano Fm. to those of higher energy of the Rio Is Corras Fm. could be the response to a tectonic peak whose chronology is still undefined.

The red-bed well-bedded deposits locally covering the karstic network represent the final filling of the karstic network itself close to the topographic surface. As visible at the Sa Bagattu and Barega localities, the red bed facies karstic fillings can be sealed by a silicitized breccia facies of younger age. This younger age is also suggested by the presence of the Sa Bagattu lithofacies reworked pebbles in the Upper Permian-?Lower Triassic Rio Is Corras Fm. conglomerates. These quartz-cemented, partially silicitized deposits could be related to climatic (arid?) early silicretization processes (Summerfield, 1983) under stable tectonic conditions and might be of Early Triassic age, a renowned period with evidence of diffuse aridity (Bustillo, in Middleton et al., 2003; Boucot et al., 2013); they are associated with calcretes, dolocretes, and gypcretes under arid-semiarid and alkaline conditions.

In the limnic San Giorgio Fm., the debris source is essentially local. The sudden and ephemeral abundant feeding of extrabasinal carbonate grains giving place to the calclithites could be related to the development of active fault scarps in the surrounding Lower Cambrian carbonates due to the progressive widening of the basin. For the same process, later those same faults were buried under the debris.

There is still no clear explanation of the mixing of the mature and immature debris of the basal San Giorgio Fm. The rounded quartz grains and pebbles provenance are enigmatic. The contemporaneous presence of carbonate angular boulders and quartzose rounded pebbles (textural inversion phenomena: Pettijohn et al., 1987) suggests a mix from different feeding sources, and, possibly, one of them being an older molassic depositional cycle. The rounded quartz provenance could be provided by the complete dismantling of an older Westphalian mature-fed collapse basin, now totally dismantled.

In the Permian Guardia Pisano Fm., the replacing of the Variscan basement grains by the volcanic rocks and the feldspar grains seems to be in good accord with the enlargement of the basin and a progressively increasing distance from its Variscan shoulders.

The restart of a dominant carbonate source in the Upper Triassic-?Lower Triassic Rio Is Corras Fm. sandstones suggest a new uplift of the Lower Cambrian carbonate rocks, leading to a subsequent dismantling cycle.

So, recurring compositional and textural maturity trends at times (Fig. 5) suggest repeated uplifting cycles under a wet to dry (warm to hot?) climate.

Conclusive remarks

The joint analysis of new and revised stratigraphic, sedimentological, and petrographic data for the Sulcis late- to post-Variscan collapse sedimentary continental basin suggest a more complex and more persistent history than previously hypothesized, the basin being active almost continuously, although in different, shifting areas, from late Pennsylvanian at least until Late Permian-Early Triassic times. A more complete stratigraphic column has been reconstructed, and the evolution of the several continental environments from each other has been better delineated. The cyclical increase of the depositional energy suggests several tectono-magmatic spikes remodeling

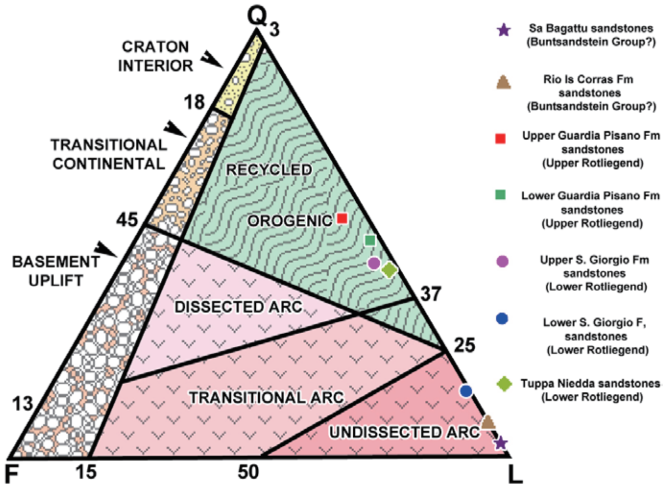

Fig. 5. Sketchy modal framework plot of the sandstones sampled in the upper Pennsylvanian to ?Lower Triassic succession in SW Sardinia. Discrimination fields after Dickinson et al. (1983).

the surrounding landscape. The feeding compositional and grain-size variation suggests too a gradual enlargement of the basin, repeated tectonic spikes, and consequent rejuvenations of the morphology. Based on the sedimentological evolution, a prevalently endhoreic behavior of the fluvial network can be hypothesized. The late to post-Variscan Sulcis continental basin, of which the San Giorgio basin could have been the starting point and later the closer point to the depocenter, at its climax was much more extended than previously thought.

The thick Permian-Triassic succession resting under the Sulcis Caenozoic coal basin supports further the presence of a previous wider extension and thickness of the upper Pennsylvanian-Permian-Triassic? basin and its function as an ancestor of the Palaeogene Sulcis coal basin (Arthaud and Matte, 1977).

Acknowledgements

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Digital geological modelling of the Tambach Formation around the Bromacker fossil-lagerstätte (Early Permian, Germany)

Frank Scholze
Friedrich Schiller University Jena, Institute for Geoscience, Burgweg 11, 07749 Jena, Germany
Email: Frank.Scholze@uni-jena.de

Introduction

The Tambach-Dietharz sedimentary basin of Early Permian (Artinskian [Schneider et al., 2020]) age is part of the superordinate Thuringian Forest Basin, which is exposed by numerous surface and subsurface outcrops in the Thuringian Forest mountain region (southern Thuringia, central Germany). Its tectonically uplifted Variscan basement is composed of metamorphic and plutonic rocks that became deeply incised by Upper Carboniferous–Lower Permian sediment fillings of the Gehren Subgroup and the Rotliegend Group, which are subdivided lithostratigraphically in multiple formations (for details see Lützner et al., 2012). In places, rhyolite and doleritic rocks intercalate with the sedimentary succession, allowing for high-precision (CA-ID-TIMS) U-Pb isotope geochronology for some of the rhyolitic volcanics (Lützner et al., 2021). Within the Rotliegend Group, distinctive changes in sediment rock colour from grey at its base to red at its top reflect a general trend from a semi-humid towards a semi-arid palaeoclimate (Roscher and Schneider, 2006). Semi-arid palaeoclimate conditions are indicated by characteristic red-bed deposits from the upper part

Fig. 1. Exemplified outcrop conditions of the Tambach Formation in the Tambach-Dietharz basin. A–B: The Tambach Sandstone Member exposed in the paleontological excavation site (A) and the present-day quarry section (B) at the Bromacker. C–D: The Bielstein Conglomerate Member at the Bielstein cliff section (C) and the Steinernes Tor section (D). E–F: The Finsterbergen Conglomerate Member at the Hainfelsen cliff section (E) and an uprooted exposure on the forested top of the Hainfelsen plateau (F). G: Abandoned quarry at the Hüllrod section, a formerly important outcrop in the northern part of the basin that is nowadays overgrown by vegetation. H–I: Kesseltal valley poorly exposing the lateral contact between the Tambach Sandstone Member (H) and the Finsterbergen Conglomerate Member (I).