The Anisian continental-marine transition in Sardinia (Italy): state of the art, new palynological data and regional chronostratigraphic correlation

L. Stori1 · J. B. Diez2 · M. Juncal2 · R. De la Horra3 · V. Borrueo-Abadía4 · J. Martín-Chivelet3,5 · J. F. Barrenechea2,6 · J. L. López-Gómez5 · A. Ronchi1

Received: 3 October 2021 / Accepted: 22 December 2021 / Published online: 16 February 2022
© The Author(s) 2022

Abstract

The scarce evidence of paleontological records between the upper Permian and the Anisian (Middle Triassic) of Western Europe could reflect (1) large stratigraphic gaps in the continental successions and/or (2) the persistence of disturbed conditions after the Permian–Triassic Boundary extinction event and the succession of ecological crises that occurred during the Early Triassic. In this context, the study of palynological associations, integrated with the stratigraphical and sedimentological data, plays a key role in dating and correlating the successions of the Western European domain and improves our understanding of environmental and paleoclimatic conditions. In some cases, pre-Anisian paleontological evidence is lacking, as in Sardinia (Italy), where a long gap encompasses the middle Permian (pars) to late Lower Triassic successions. Although fragmented and disseminated, the continental Lower-Middle Triassic sedimentary successions (Buntsandstein) of Sardinia have proved crucial to our understanding of the evolution of the southern edge of the Paleo-Europe and the different timings of the Tethys transgression (Muschelkalk facies) in some of these areas. Various paleogeographic reconstructions were attempted in previous works, without providing any consensus on the precise position of Sardinia and its surrounding seaways in the Western Tethys domain during this time interval. At present, the configuration and distribution of the subsiding and emerging landmasses and the temporal development of the transgressions of the Western Tethys during the Middle Triassic remain unclear. This work focuses on the stratigraphical, sedimentological and palynological aspects of three Middle Triassic continental-marine sedimentary successions in Sardinia, with particular attention to the analysis of the palynological associations sampled there, and it also provides a detailed review of all previous palynological publications on the Sardinian Anisian. The studied successions are: Su Passu Malu section (Campumari, SW Sardinia), Arcu is Fronestas section and Escalaplano section (Escalaplano, Central Sardinia). These sections were also correlated to other significant sections in the SW (Scivu Is Arenas) and NW (Nurra) parts of the island.

Keywords Palaeogeography · Palynology · Triassic · Buntsandstein · Biostratigraphy · Muschelkalk

Resumen

El escaso contenido paleontológico en el registro sedimentario entre el Pérmico superior y el Anisiense (Triásico Medio) del oeste de Europa estaría relacionado con 1) una prolongada ausencia de registro continental y/o 2) la persistencia de

© Springer
conditions ambientales alteradas tras la crisis de la extinción del límite Pérmino-Triásico (PTB) y posteriores crisis asociadas durante todo el Triásico Inferior. En este contexto, el estudio detallado de asociaciones palinológicas integrado con datos estratigráficos y sedimentológicos juega un papel destacado para datar y correlacionar las sucesiones del registro sedimentario de esta edad en el dominio occidental de Europa, así como para conocer mejor los ambientes deposicionales y la evolución climática. En algunos casos no hay datos paleontológicos del Triásico previos al Anisiense, como es el caso de Cerdeña (Italia), donde la ausencia de registro sedimentario incluye desde parte del Pérmino medio hasta el Triásico Inferior. Aunque los afloramientos del Triásico Inferior y Medio (en facies Buntsandstein) de Cerdeña son incompletos y están separados entre sí, sin embargo, han mostrado proporcionado una información crucial para comprender la evolución del eje meridional de Paleo-Europa, así como para precisar las diferentes etapas transgresivas (en facies Muschelkalk) en estas áreas del Tethys occidental. Se han publicado diferentes trabajos intentando reconstruir el escenario paleogeográfico de Cerdeña y de sus diferentes corredores interiores durante el intervalo de tiempo señalado, aunque no se ha alcanzado ningún consenso en cuanto a su posición ni en la configuración de zonas elevadas y depresivas durante el citado intervalo de tiempo. El presente trabajo se centra en el estudio detallado de la estratigrafía, sedimentología y asociaciones de polen en tres secciones con una evolución de ambientes que incluyen desde el continental hasta el marino. Se hace un especial hincapié en el estudio de las asociaciones palinológicas muestreadas en este trabajo, así como en la revisión de otras asociaciones de edad Anisiense estudiadas por otros autores. Las secciones estudiadas aquí son: Su Passu Malu (Campumari, SO Cerdeña), Arcu Is Fronestas and Escalaplan (Escalapiano, Cerdeña Central). Estas secciones han sido también correlacionadas con otras conocidas de distintas áreas de la isla, como Scivu Is Arenas y Nurra, al SO and NO de Cerdeña, respectivamente.

**Palabras clave** Anisiense · Palinología · Cerdeña · Buntsandstein · Bioestratigrafía · Muschelkalk

### 1 Introduction

The late Palaeozoic era witnessed the formation of the Pangaea supercontinent, derived from the collision of Gondwana, Laurussia and several other microplates between the Carboniferous and the early Permian (e.g., Stampfli & Borel, 2002; Stampfli et al., 2013; Pastor Galán et al., 2015). The Panthalassa sea surrounded Pangaea while, to the east, the Tethys Sea occupied a triangular gulf that included the tropics during most of the Mesozoic. Immediately after the formation of Pangaea, during the early-middle Permian, the compressive geodynamic regime which led to the Variscan orogenic cycle progressively gave way to a large-scale transtensional-extensional regime which favoured the beginning of the break-up of the supercontinent, the subduction of the Palaeotethys oceanic ridge beneath Eurasia (Stampfli & Borel, 2002; Stampfli et al., 2013), and the opening and westward expansion of the Neotethyan Ocean (e.g., Angiòlini et al., 2013). The dismantling of the Variscan orogenic system and the widespread evolution of the late Palaeozoic rifting phases produced several small basins filled with terrestrial sediments, and the deposition of these sequences occurred in seasonal to semi-arid conditions: the continentalization of the climate after Pangaea led to pronounced warming and aridification throughout the late Permian (Wignall, 2007), which persisted into the Early Triassic. This latter period was characterized by severe hothouse conditions (e.g., Bourquin et al., 2011) and high temperatures (Payne et al., 2007; Sun et al., 2012), which underwent great fluctuations, also influenced by strong and enduring volcanic activity in the Siberian Traps Large Igneous Province (Svensen et al., 2009), thereby contributing to a perturbation of the carbon cycle through the massive injection of CO₂ into the atmosphere, causing ocean acidification and anoxia. The persistence of volatile environmental conditions and the significant instability of the ecosystem throughout the Early Triassic delayed the biotic recovery after the major P–T boundary extinction event (Wignall, 2007).

Our study focuses on Sardinia, Italy, a key location for understanding the Lower-Middle Triassic sedimentary record of the Western Tethys domain. The Triassic of Sardinia is characterized by the classic Germanic threefold lithologic sub-division: Buntsandstein, Muschelkalk and Keuper, which were sometimes incorrectly used as chronostратigraphic units. Sparse clastic terrestrial to transitional Early-Middle Triassic (Buntsandstein) deposits crop out in various parts of Sardinia (Costamagna & Barca, 2002).

The first post-Palaeozoic marine transgression took place during the Middle Triassic and flooded the folded, metamorphosed and smoothed Variscan basement (Sinisi et al., 2014) in the southwestern, northwestern and central-eastern part of the island. This first transgressive pulse was represented by the transitional deposits of the upper Buntsandstein facies, or Röt facies, developed on alluvial fine-to-coarse grained deposits, eroded from the Variscan basement (i.e., Cala Viola, NW Sardinia, Fig. 1A; Monte Maiore and Escalapiano in Central-SE Sardinia, Fig. 1B; Scivu Is Arenas (Arburese) and Campumari in SW Sardinia, Fig. 1C, D). After these transitional deposits, a succession of dolomites, limestones and marls, or Muschelkalk facies, represents the first complete incursion of the Tethys Sea into Sardinia (e.g., Bourquin et al., 2011).
More particularly, central Sardinia is considered a structural highpoint during the Anisian that was progressively submerged until the maximum eustatic flooding during the Ladinian (Costamagna & Barca, 2002, 2016). The palynological characterization of these Middle Triassic deposits in this area and other parts of Sardinia has permitted some authors to propose correlations with the Alpine standard stages and substages (Pittau Demelia & Del Rio, 1980; Frechengues et al., 1983; Pittau Demelia & Flaviani, 1982a, 1982b, 1983; Barca et al., 1985; Pittau & Del Rio, 2002). However, despite the good characterization and correlation with the adjacent domains, a more detailed study of these successions could enhance our understanding of processes that still remain unclear, such as the detailed configuration and distribution of the subsiding and emerging landmasses and the temporal development of the transgressions of the Western Tethys during the Middle Triassic. New stratigraphic analyses and palynological samplings were made in the Escalaplano area (Central Sardinia, Fig. 1B) and Campumari (SW Sardinia, Fig. 1D) to accurately define the age of such sediments and, thus, the beginning of Triassic deposition and the first marine incursion into this sector of the Western Peri-Tethys realm. Together with these new samplings in the cited areas, the known Anisian palynological associations of Escalaplano, Campumari, Scivu Is Arenas (Arburese) and Nurra were considered to obtain a regional correlation for the Middle Triassic continental-to-transitional deposits in the island. This work also provides up-to-date stratigraphical and sedimentological analyses, which particularly further our knowledge of the palynostratigraphical zonation of these successions and permit a more accurate determination of the age of such sediments and the beginning of both continental and marine Triassic deposition in this sector of the Western Peri-Tethys domain.

2 Geological setting

In Sardinia, the post-Variscan deposits are arranged in three main sedimentary sequences: the first (lower Permian) is related to the development of the aforementioned
intra-Pangaea lateral mega shear system; the second
(lower Permian to early middle Permian) is related to a
more mature post-orogenic rifting phase; and the third
(Early-Middle Triassic) is associated with fluvial sedi-
mentation in medium-sized basins and the first eastward
marine incursions through narrow corridors (Cassinis
et al., 2003). This third sedimentary sequence led to the
deposition of red continental terrigenous sequences in
Buntsandstein facies, represented by the Punta S’Arridelli
Formation and the Riu Is Corras Formation (SW Sardinia
Fig. 2: 1,2), the Escalaplano Formation in the Sarcidano
area (Central Sardinia Fig. 2: 3, 4) and the Conglomerato
del Porticciolo and Arenarie di Cala Viola Formation in
the Nurra region (NW Sardinia Fig. 2: 5, 6). According to
Costamagna and Barca (2002), these units were mainly
formed in a small ephemeral distal fan environment, as
the development of a significant fan-delta complex could
have been hindered by the low landforms resulting from
the several post-Variscan erosion cycles, which severely
reduced most of the reliefs through intense chemical and
mechanical weathering processes (Scotese & Schettino,
2017). The passage from the Buntsandstein to the shallow
marine, carbonate platform environment in Muschelkalk
facies is marked by the presence of transitional deposits in
Germanic-like “Röt” facies, which present different lith-
ologies from, for instance, those defined in Iberia. The first
accurate and illustrated documentation of the Sardinian
“Röt” facies can be found in Costamagna, (2011, 2012); it
is characterized by marls and evaporitic lithologies which
can be seen, for example, in the Punta S’Arridelli For-
nation and at the uppermost levels of the Riu Is Corras
Fm (Fig. 2). These fms. also show a prominent carbonate
influence, the genesis is still subject to debate; it is dif-
ficult to interpret due to the occurrence of pedogenetic
processes, as testified by the presence of caliches (Barca
et al., 1995b; Cocozza & Gandin, 1976). As regards the
NE and SE successions, the transition to the marine envi-
ronment is quite abrupt, with only a few meters of marls

![Fig. 2 Simplified sections, from SW to NW, with * indicating the
pollen samples dating the successions. (1) Su Passu Malu (Campu-
mari, Iglesiente) (2) Punta su Nuraxi (Scivu is Arenas, Arburese) (3)
Arcu is Fronestas (Escalaplano) (4) Escalaplano SW (Escalaplano)
(5) Cala Viola (Nurra) (6) Cugiareddu well (Nurra). (1) Marls (2)
Sandstones (3) Limestones (4) Crossbedded conglomerates, (5)
Sandy limestones (6) Gypsum (7) Breccias (8) Bedded sandstones (9)
Dolomitic limestones (10) Interbedded sandstones and siltstones (11)
Schist (12) Dolostones (13) Conglomerates (14) Crossbedded sand-
stones (15) Calcretes (16) Interbedded shales and silty limestones
(17) Clays (18) Silty limestones. See Fig. 1 for locations]
passing into the dolostones of the Muschelkalk, as in the Escalapiano Formation, where the influence of the marine environment is testified by the presence of the aforementioned “Röt” facies, consisting of calcareous-evaporitic intercalation containing wrinkled algal mats (Costamagna & Barca, 2002). The studied sections are included in four regions of the island: Escalapiano-Sarcidano/Gerrei region (Central-SE Sardinia), Campumari-Iglesiente region (SW Sardinia), Scivu Is Arenas-Arburese region (SW Sardinia) and Nurra region (NW Sardinia).

### 2.1 Central-SE Sardinia (Sarcidano–Gerrei region)

Close to the village of Escalapiano, to the SW (Sarcidano-Gerrei region, Fig. 1B), the post-Variscan deposition is mainly represented by a lower Permian volcano-sedimentary sequence that fills a small (about 15 km²) intramontane basin (Fig. 1B). On the whole, the extruded calc-alkaline magmatic products in this succession have an extrabasinal origin and largely exceed the strictly sedimentary units.

According to Pecorini (1974), Ronchi (1997) and Ronchi et al. (2008), the entire Permian succession can be subdivided into two main parts, namely “Lower” and “Upper” volcanic and sedimentary successions: both of these begin with a coarse sedimentary unit, continue with reworked volcanoclastites, tuffites, lacustrine-to-palustrine deposits and end with, respectively, an acidic ignimbrite deposit and an andesitic lava flow. Nine lithostratigraphic units have been distinguished within the two cited volcano-sedimentary portions by Ronchi et al. (2008), which seem to be separated by a paraconformity(?). The estimated average thickness is approximately 150 m, possibly reaching a maximum of almost 200 m in the basin's northwestern sector.

Conversely, Buntsandstein deposits all around the Escalapiano area (Fig. 1B, 3) directly overlay the Variscan base almost 200 m in the basin's northwestern sector. The estimated average thickness is approximately 150 m, possibly reaching a maximum of about 200 m in the basin's northwestern sector. More precisely, the post-Variscan “Röt” facies, consisting of calcareous-evaporitic intercalation containing wrinkled algal mats (Costamagna & Barca, 2002), the studied sections are included in four regions of the island: Escalapiano-Sarcidano/Gerrei region (Central-SE Sardinia), Campumari-Iglesiente region (SW Sardinia), Scivu Is Arenas-Arburese region (SW Sardinia) and Nurra region (NW Sardinia).

The Campumari-Coremò area is located along the southwestern coast of Sardinia, in the Iglesiente area, and it consists of a series of small tabular reliefs with slightly different heights, forming a plateau with a maximum altitude of 219 m (Fig. 1D).

The post-Variscan “Röt” facies, consisting of calcareous-evaporitic intercalation containing wrinkled algal mats (Costamagna & Barca, 2002), the studied sections are included in four regions of the island: Escalapiano-Sarcidano/Gerrei region (Central-SE Sardinia), Campumari-Iglesiente region (SW Sardinia), Scivu Is Arenas-Arburese region (SW Sardinia) and Nurra region (NW Sardinia).

#### 2.2 SW Sardinia: Campumari (Iglesiente region)

The Campumari-Coremò area is located along the southwestern coast of Sardinia, in the Iglesiente area, and it consists of a series of small tabular reliefs with slightly different heights, forming a plateau with a maximum altitude of 219 m (Fig. 1D).

The post-Variscan “Röt” facies, consisting of calcareous-evaporitic intercalation containing wrinkled algal mats (Costamagna & Barca, 2002), the studied sections are included in four regions of the island: Escalapiano-Sarcidano/Gerrei region (Central-SE Sardinia), Campumari-Iglesiente region (SW Sardinia), Scivu Is Arenas-Arburese region (SW Sardinia) and Nurra region (NW Sardinia).

The Campumari-Coremò area is located along the southwestern coast of Sardinia, in the Iglesiente area, and it consists of a series of small tabular reliefs with slightly different heights, forming a plateau with a maximum altitude of 219 m (Fig. 1D).

The post-Variscan “Röt” facies, consisting of calcareous-evaporitic intercalation containing wrinkled algal mats (Costamagna & Barca, 2002), the studied sections are included in four regions of the island: Escalapiano-Sarcidano/Gerrei region (Central-SE Sardinia), Campumari-Iglesiente region (SW Sardinia), Scivu Is Arenas-Arburese region (SW Sardinia) and Nurra region (NW Sardinia).
bearing sulphate pseudomorphs and chert nodules, and the Grifoneddu de S’acqua Member, which is composed of dolostones and starts with a breccia horizon marking the passage to a shallow marine, restricted lagoonal environment (Costamagna & Barca, 2002).

2.3 SW Sardinia: Scivu Is Arenas (Arburese region)

The Triassic of the Scivu-Is Arenas area overlies the Variscan metamorphic basement and is in turn covered by Quaternary deposits (calcarenites and aeolian sands), forming small reliefs (Figs. 1C, 4A). The area was first studied by Bornemann (1881), who attributed the outcrops to the Triassic sedimentary record on the basis of the fossil content (e.g., presence of *Myophoria goldfussi* Von Alberti, *Gervileia subglobosa* Credner, *Rhyzocorallium jeneense* Zenker, among others) and correlated the succession to the Grès Bigarré of Provence, due to similarities in facies. It was only after more recent studies (Barca et al., 1995b; Costamagna & Barca, 2002; Damiani & Gandin, 1973b) that these deposits received more detailed chrono- and litho-stratigraphic subdivisions, as reported below.
The older Triassic unit, namely Punta S’Arridelli Formation (Costamagna & Barca, 2002), lies unconformably on top of the Palaeozoic basement (Fig. 2: 2, 4A) and consists of two sub-units, the lower Su Ripostiggiu Member and the upper Brunco Pilloni Member, representing the evolution from a continental braided stream environment, to a more transitional, sabkha-to-shallow marine setting (Costamagna & Barca, 2002). The Su Ripostiggiu Member starts with thin reddish breccias continuing to coarse sandstones with angular-to-subrounded clasts coming from the eroded metamorphic basement and volcanic detritus, and it then evolves upwards to purple-reddish paleosols and calcified carbonate layers containing fragments of basement and reddish sandstone (Fig. 4C). From the base to the top of this member, there is a decrease in the clast size and a variation in clast composition, which changes from almost totally volcanic to exclusively metamorphic basement fragments, marking an increase in erosive sub-aerial conditions (Barca et al., 1995a, 1995b). The Su Ripostiggiu Member (about 20 m) passes upwards (or laterally to the south) to the Brunco Pilloni Member, formed by dedolomitized, locally cavernous limestone, bearing siliceous pseudomorphs, levels of dissolution-collapse breccias and traces of calcitization processes in its upper part.

The Punta Su Nuraxi Formation (Costamagna & Barca, 2002) overlies Punta S’Arridelli Formation with a slight angular unconformity (Fig. 4A) and is divided into two different sub-units: a lower Case Pisano Member and an upper Brunco Zippiri Member (Costamagna & Barca, 2002). The Case Pisano Member starts locally with a dark, marly mudstone layer, yielding a microflora assemblage suggesting an upper Anisian age, according to Barca et al. (1995b).

There follow metric alternations of massive, cavernous, calcareous mudstones bearing siliceous pseudomorphs and evaporitic minerals, and whitish layered and cross-laminated calcarenites-calcilutites. Salt tectonic structures (folds several metres in size) occur in this sub-unit, along with collapse-dissolution breccias and localized calcrete structures. The Case Pisano Member evolves upwards in the Brunco Zippiri Member through a thick layer of dissolution-collapse breccias. The Brunco Zippiri Member consists of two facies, the first being represented by blue-gray limestone with reddish intercalation of bioclastic grainstones-packstones, locally presenting cross, wavy and planar lamination, fossil content (bivalves, foraminifera and algae) and rare evidence of storm beds eroding the substratum (Costamagna & Barca, 2002). The second facies is represented by massive calcarenite-calcilutite (packstones to wackestones) evolving upwards into gray-reddish (Fig. 4E), marly limestones (wackestones to mudstones), showing bioturbation structures classified as Planolites and Paleophycus tubularis (Costamagna & Barca, 2002; Moore, 1962).

### 2.4 NW Sardinia (Nurra region)

The post-Variscan succession of the Nurra region (Northwestern Sardinia, Fig. 1A) was deposited on the Variscan crystalline basement during the early Permian to Middle Triassic time-span; it is represented by a thick pile of continental sediments (about 700 m thick), mainly Permian, evolving into continental-to-shallow marine Triassic deposits with the classic Germanic facies (Buntsandstein, Muschelkalk and Keuper Auct.) (Fig. 4B). The first and second sequence belong to the Permian and are represented by the stacking of different fluvial to lacustrine formations (e.g., Cassinis et al., 2003; Costamagna, 2019).

The third sequence (approx. 50 m thick) consists of two formations, namely the Conglomerato del Porticciolo and Arenarie di Cala Viola (Fig. 2: 5), separated by a minor erosional surface. The former (up to 12 m thick) was accumulated in a gravelly braided river setting under conditions of persistent aridity, as suggested by the common occurrence of wind-worn clasts (Cassinis et al., 2003; Durand, 2008). Its base consists of the alternation between massive to cross-bedded ortho- and para-conglomerates (mainly polycrystalline quartz), presenting imbrication features and cross-laminated siltstones to sandstones. The top of the formation consists of a 4–5 m alternation of trough cross-bedded, medium-fine sandstones of fluvial and aeolian origin and coarser pebbly sandstones.

The Arenarie di Cala Viola Formation is about 40 m thick and unconformably overlies the Conglomerato del Porticciolo Formation. Its base is mainly represented by dark continental red sandstones and siltstones arranged in thin beds that present small, pedogenic-origin, intraformational breccias, sets of climbing ripples evolving into horizontal to low-angle laminated or trough cross-bedding, with subordinate mudstones in the lower part. It is overlain by a few meters of gray-green, pink and reddish, medium- to coarse-grained sandstones, with the presence of lensoid geometries and trough cross-bedding (Fig. 4D). Further up, in the middle-upper part of the unit, there are thinly bedded to well-bedded, medium- to fine-grained, dark orange/red to purple sandstones and siltstones, while, finally, the top of the unit consists mainly of whitish-green to gray siltstones and claystones. The Arenarie di Cala Viola Formation marks a dramatic change in sedimentary and climatic conditions. In fact, while the Conglomerato di Porticciolo was probably deposited during the late Early Triassic (late Olenekian) sedimentary cycle, under arid to hyper-arid conditions (Durand, 2006, 2008; Bourquin et al., 2007, 2011; Borruel-Abadía et al., 2019), similarly to the Poudingue de Port-issol in Provence, the Arenarie di Cala Viola Formation with its finer grained facies, was deposited in a terminal fan setting under semi-arid conditions (Cassinis et al., 2003; Citton et al., 2020; Durand,
as testified by the presence of pedogenetic carbonate concretions, mud cracks, tree-related bio-sedimentary structures and the presence of inundation sequences from Arenarie di Cala Viola Formation (2006, 2008), (Fig. 4F) (sensu Seilacher, 1982). Some authors (i.e. Costamagna, 2012; Fontana et al., 2001) have postulated a tidal influence in the Arenarie di Cala Viola Formation based on the sedimentology and stratigraphic position of this unit, which narrowly predates the widespread Middle Triassic marine transgression documented by the ‘Muschelkalk’-type carbonates.

3 Material and methods

3.1 Stratigraphy

For this work, detailed bibliographical research was undertaken, in order to review and update the stratigraphical and sedimentological data related to the areas of interest. The sections mentioned below were re-examined and studied, with particular attention to sedimentary facies recognition and associations. They crop out in the Iglesiente (SW Sardinia) and the Sarcidano-Gerrei (Central-SE Sardinia) regions of the island (Fig. 1).

In the former area, more specifically on the Campumari plateau, the Su Passu Malu section was analyzed. In the latter area, two sections were described: the first cropping out at the southern entrance of the Escalaplano village, and the second a few km to the north, in the Arcu Is Fronestas locality (Fig. 1B). The stratigraphy and facies analyses provided by the fieldwork were integrated into the pre-existing information and complemented by new palynological data and revised older data. Based on the new interpretation of the microfloristic associations, correlations were drawn at a regional level. In a broader inter-regional context, the data have been used to better frame Sardinia in the palaeogeographic evolution of the Western Tethys during the Anisian.

3.2 Palynology

3.2.1 Methodology for palynological revision

A precise review of all the previous palynological publications on the Sardinian Anisian was undertaken for the present work, and it was necessary to establish the validity of these data for our purposes.

The minimum conditions for considering the data valid were:

1) correct figuration: lists of taxa without representation were not considered valid since there was no possibility of confirming or identifying the palynomorph.
2) correct location: each palynomorph association must be referred to an exact position in the stratigraphic section in which it was sampled.

Based on these premises, identifications from previous papers that meet these requirements could be incorporated into the discussion, together with unpublished data (Diez, 2000) and new data obtained in the last field trips undertaken by the authors of the present paper.

3.2.2 Palynological analyses

This paper presents unpublished and revised results from Diez’s PhD thesis (2000) collected in 1996 in the Escalaplano area: three samples (PC-2, PC-3 and PC-4) at the southern entrance to Escalaplano village (Escalaplano SW section, Fig. 5) and another sample (PC-7.2) taken from the Arcu Is Fronestas section, north of the same village (Fig. 6). Three new samples (AIF-2, AIF-5, and AIF-9) were later collected in 2015 and 2016 fieldwork in the Arcu Is Fronestas section and another one (GRIFO 3) was collected from the Su Passu Malu section on the Campumari site (Campumari section, Fig. 7).

Palynological samples were processed using HCl-HF-HCl classic attack techniques, as described by Wood et al. (1996), in the Palynology Laboratory in the Department of Geosciences at the University of Vigo (AIF-2, AIF-5, AIF-9, GRIFO 3) and the Paleobotany Laboratory in the University Pierre et Marie Curie, Paris-6 (PC-2, PC-3, PC-4 and PC-7.2). A dispersing agent was added to facilitate filtering and sieving at 10 µm. The palynological slides were studied under a Leica DM2000 LED, and the photomicrographs were taken with a Leica ICC50 W camera using ×1000 magnification.
Fig. 5 Stratigraphic section of the outcrop located at the Escalaplano SW entrance. (A) Basal reddish conglomerates lying over the Variscan basement; (B) Anisian satin spar-bearing marly argillites with pollen sample site (asterisk) (pen for scale); (C) contact between the Muschelkalk and the Eocene conglomerates (booklet for scale). See also Fig. 2 to complete the legend.
Fig. 6 Arcu Is Fronestas section. (A) basal reddish conglomerate lying over the Variscan basement's schists; (A1) halite casts; (B) dark gray claystones and marly sandstones (C) black claystones to yellowish marly claystones; see also Figs. 2 and 4 to complete the legend.
Su Passu Malu
(Campumari, SW Sardinia)

Fig. 7 Campumari section. (A) Panoramic view of the Campumari-Coremò plateau; (B) conglomerates of the Riu Is Corras Formation; (C) detail of the dark gray mudstones overlaid by the yellow, laminated dolostones; (D) detail of the yellow, laminated dolostones; (E) alternation of breccias and dolostones from the upper part of the Grifoneddu Member. See also Figs. 2 and 4 to complete the legend
The slides are stored in the Palynology Laboratory in the Department of Geosciences at the University of Vigo.

4 Results

4.1 Stratigraphic sections

4.1.1 Escalaplano

Reddish clastic sediments with chalky and marly-clayey intercalations, up to about 20 m in thickness, unconformably overlie the Variscan metamorphic basement at the northeastern margin of the Permian Escalaplano basin (Fig. 1). The marked unconformity between the crystalline basement and these Middle Triassic siliciclastics can be observed along the SS 128 Ballao-Escalaplano road, just before the first buildings at the southern entrance to the village of Escalaplano (Fig. 1B). A stratigraphic superimposition of the Triassic deposits on the Permian succession has been described so far (Ronchi, 1997) only in the Arcu ‘e Azzinuri locality (i.e., along the Escalaplano-Orroli road, just a few hundred metres west of the village).

Some representative stratigraphic sections have been described in the Triassic sedimentary deposits in the Escalaplano area (Fig. 1). Two of these are described herein, with indications of the palynomorph horizons. At Escalaplano’s southern entrance (SW Escalaplano section, Fig. 5), the depositional environment evolves from continental alluvial environment (Buntsandstein) to transitional salted lagoons, forecasting the marine (Muschelkalk) transgression (Costamagna et al., 2000). The following lithostratigraphic units can be recognized, from their base lying on violet schists from the basement to the Eocene siliciclastics:

- reddish basal polygenic conglomerates and breccias (Fig. 5A), with angular elements of the underlying metamorphic basement, quartz pebbles and Permian volcanic rocks, embedded into a sandy matrix alternating with reddish sandstones (0–2 m). This unit is very reduced northwestwards, in the area where the unconformable contact with the basement is underlined by fine-grained deposits;

- dark red to violet to gray-green, evenly bedded in cm-dm thick layers, mica-rich siltstones, sandstones, marly claystones and marls. Irregular white-to-pink satin spar veins occur frequently (0–10 m) (Fig. 5B). This lithofacies can reach up to 15 m in the area; in the upper part, there are alternating beds of dark claystones, thin dolomitic marls, siltstones and cm-irregular layers of pink and white satin spar;

- yellowish light brown to gray irregularly bedded limestones and dolomitic limestones (Muschelkalk Auctt.) (3 m) (Fig. 5C). These carbonates, which can reach about 20 m in the area, are unconformably overlain by alluvial coarse Eocene deposits in this locality. To the north of the village of Escalaplano (i.e., Is Forreddu and Arcu Is Fronestas sections), the same Middle Triassic siliciclastics are in turn directly overlain by Middle Jurassic quartz conglomerates (Genna Selole Formation, Costamagna, 2016; Costamagna et al., 2007; Dieni et al., 1983) (Fig. 3).

In the Arcu Is Fronestas locality (Arcu Is Fronestas section, Fig. 6), located about 3 km to the NE of Escalaplano, on the road to Perdasdefogu (Fig. 1B), the Middle Triassic succession is less than 20 m thick. It lies unconformably over the Variscan basement and is unconformably overlain by the Middle Jurassic quartz conglomerates of the Genna Selole Formation. The section can be described as follows:

- the base of the succession consists of pinkish-reddish polygenic conglomerates and breccias and it unconformably overlies the schists of the Variscan basement (Fig. 6A). Quartz pebbles, angular clasts of metamorphic basement and Permian volcanites are supported by a sandy matrix alternating with reddish sandstones (80 cm);

- it follows an approximately 4 m-thick alternation of dark gray to reddish claystones and greenish-yellow marly claystones, with centimetric intercalations of medium-coarse sandstones bearing halite casts, mudcracks and bioturbation (AIF2, AIF5 pollen samples, Fig. 6A1);

- moving upwards, there is an increase in the carbonate content, resulting in the presence of reddish marls and clayey marls over claystones (10–15 m; Fig. 6B);

- dark gray-black claystones to yellowish marly claystones (5 m) (AIF 9 pollen samples, Fig. 6C) make up the upper part of the Escalaplano Formation in this area, and they are overlain by the Jurassic quartz conglomerates of the Genna Selole Formation.

4.1.2 Campumari

Sparse and thin “Permian–Triassic” auctt. successions unconformably cover the early Palaeozoic slightly metamorphic rocks in the Iglesiente and Arburese regions (SW Sardinia, Cocozza & Gandin, 1976; Barca & Costamagna, 2003a). The studied section is about 50 m thick and is located in the Su Passu Malu locality, along the SP83, between the villages of Nebida and Gonnese (Fig. 7 A and Fig. 1). From the base to the top, the section shows:

- the Riu Is Corras Formation lies unconformably over the folded Variscan basement and shows marked lateral heterogeneity. The first 14 m of the studied section consist of yellowish calcrite, organized in thick banks, often brecciated and with evidence of calcitization processes;

- this is followed by about 8 m of well-cemented, heterogeneous conglomerates organized in metric strata (Fig. 7B). Subordinated, dolomitic crusts, nodular and brecciated dolomitic mudstones, rare sandstones with caliches and reddish argillaceous siltites occur;
- the passage to the Campumari Formation lower member, i.e., the Su Passu Malu Member, is marked by 1.5 m-thick, thinly bedded light gray mudstones. This level is followed by a conglomerate bank about 1 m thick, which is again followed by 2.5 m of gray mudstones and dolomitic mudstones, locally rich in plant debris, sulphate pseudomorphs and carbonate-rich silt intercalations (pollen sample GRIFO 3) (Fig. 7C);
- there follow 4 m of laminated dolostones (Fig. 7D), organized in centimetric to decimetric strata and showing bioturbation and tepee structures;
- the passage to the Campumari Formation upper member, i.e., the Grifoneddu de S’acqua Member, is marked by a collapse breccia horizon (1–2 m thick) (Fig. 7E) followed by massive to well-stratified dolostones, showing laminations, evidence of bioturbation (*Rhyzocorallium jenense* Zenker; Cocozza & Gandin, 1976), and pseudomorphs after evaporitic minerals.

### 4.2 Palynological data

#### 4.2.1 Revision of previous works

Various palynological studies have previously analyzed Anisian assemblages in Sardinia. Displaying the information in chronological order, a detailed review was attempted of the following publications: Damiani and Gandin (1973c), Pittau Demelia & Del Rio (1980), Flaviani (1980), Pittau Demelia and Flaviani (1982a, 1982b a,b), Frechengues et al. (1993), Barca et al. (1995b), Ronchi (1997), Costamagna et al. (2000) and Pittau and Del Rio (2002).

The first reference to the presence of a Middle Triassic pollen association is found in Damiani and Gandin (1973c). These authors mentioned a productive sample collected in reddish marly layers just southwest of the village of Escalapiano (level 2 of the section that corresponds to km 47.4 of the s.s. Nurri-Escalapiano, now SP10) (Fig. 2). At the time of the publication of Damiani & Gandin’s work, the palynological sample was being studied by Del Rio and, for this reason, the authors limited themselves to preliminarily pointing out the presence of a continental floristic association from the Middle Triassic, represented mainly by gymnosperms.

The first formal palynostratigraphic study on the Anisian of Sardinia was undertaken by Pittau Demelia & Del Rio (1980) via a sparse and poorly preserved palynological assemblage (see the complete list of taxa in Supplementary Material) in the clay levels of the upper part of member B (sensu Cocozza & Gandin, 1976) of the stratigraphic section of the Campumari outcrop, at km 1.7 between Funtanamare and Nebida (Fig. 2). These authors assigned to this sample a “Lower Muschelkalk” age due to the presence of *Stellapollenites muelleri* (= *Hexasaccites muelleri*), *Minutosaccus crenulatus* and the genus *Triadispora*. Although the figures do not confirm all the taxonomic attributions, we could suggest an Anisian sensu lato age through the correct identification of *Hexasaccites muelleri* (Visscher & Brugman, 1981; Brugman, 1983, 1986; Diez, 2000; Kürschner & Herngreen, 2010).

In Flaviani (1980), the palynostratigraphy from the subsurface of Nurra (Cugiareddu well, Figs. 1A, 2: 6) was presented. This is an unpublished study whose results were used at the time to make lithostratigraphic correlations between Triassic outcrops in Sardinia. In this work, new palynomorphs were described; the authorship of these new species was attributed to P. Pittau in later papers (Pittau & Del Rio, 2002; Pittau Demelia & Flaviani, 1982a, 1982b), and they were used only for Sardinian Triassic studies. Normally this type of publication should not be treated in the context of a review as it is unpublished research, but it has been necessary to include it due to its importance in the development of our review.

The samples used for palynostratigraphic studies in Flaviani’s thesis were provided from a previous work by Pomesano Cherchi (1968) on the Cugiareddu well (Fig. 1). These samples correspond to level 545 (sample 970 in Flaviani, 1980), ascribed to the Permian; levels 477 and 443 (samples 756 and 755 respectively, in Flaviani, 1980), which Pomesano Cherchi (1968) described as “Buntsandstein” but Flaviani attributed to the Lower and Middle Muschelkalk respectively; finally, a level 429 (sample 754 in Flaviani, 1980) was described as Lower Muschelkalk by Pomesano Cherchi (1968), and later attributed to the Upper Muschelkalk by Flaviani (1980).

As for sample 970, Flaviani (1980) showed a poor assemblage (see the complete list of taxa in Supplementary Material) and ascribed it to an inconclusive Permian–Triassic age through comparison with the Germanic Zechstein associations. However, the joint appearance of the guide taxa *Lueckisporites virkkiace*, typical of the middle and upper Permian, and *Hexasaccites muelleri* that appears during the Anisian (Middle Triassic) and other Triassic taxa, such as *Triadispora crassa*, *Enzonalsporites leschikii* and *Illinites* sp., suggests an Anisian sensu lato age. The presence of a single specimen of *Lueckisporites virkkiace* would not be sufficient for any Permian affinity.

The next two associations, of samples 756 and 755 (see the complete list of taxa in Supplementary Material), were included in “Zone A”: this Zone would correspond to the Lower and Middle Muschelkalk interval (Anisian). It would be characterized by the significant presence of *Hexasaccites muelleri* and *Triadispora crassa*, and the *Alisporites-Cuneatisporites-Sulcatisporites* bisaccate pollen morphogroup. Flaviani also differentiated two subzones: A1 (sample 756) and A2 (sample 755). Subzone A1 (Lower Muschelkalk, Anisian) would be characterized by the presence of...
Aratrisporites bulloides (n. sp. in Flaviani, 1980), Lunatisporites rhaticus and Lunatisporites acutus. Subzone A2 (Middle Muschelkalk, Anisian) would be characterized by Myriampsporites triassicus (n. sp. in Flaviani, 1980) and Aratrisporites distalirrugulatus (n. sp. in Flaviani, 1980), as well as Krauselisporites cuspidus, Aratrisporites paraspinosus, Ellipsoidovelsporites plicatus, Striatabioteites ayuguii and Angustisulcites klausii. As we explain in the next section, the presence of Hexasaccites muelleri would indicate an Anisian age for samples 756 and 755. Unfortunately, we believe that the sub-divisions A1 and A2 could not be justified when using new species from levels that have not been geochronologically dated or correlated with other sources previously.

Flaviani (1980) assigned the fourth association (see the complete list of taxa in Supplementary Material), referred to as sample 754 (429 m.), to the Upper Muschelkalk (“Zone B”, Anisian-Ladinian transition), based on the absence of Hexasaccites muelleri and the presence of Ovalopollis pseudoaalatus. However, following our methodology, we cannot endorse this datum, since we do not accept the criterion of absence.

Pittau Demelia and Flaviani (1982b) included a partial publication of the study by Flaviani (1980) of the Cugiareddu well. The featured palynomorphs are not correctly referenced, however, and neither do these authors show photos of all the listed taxa, nor any references to the studied samples. It can be deduced, solely from the wording of the text, that the specimens are the same, and the new species described in Flaviani (1980) already appear as Pittau’s in Flaviani, 1980. Therefore, the same considerations applied to Flaviani (1980) can be used for Pittau Demelia and Flaviani (1982b). Some photos of taxa are included, without mentioning what level they correspond to. In this case, we can confirm the existence of Hexasaccites muelleri and the possible classification of Triadispora crassa and Prodiploxypinus gracilis, which reaffirms the notion that nothing can be said about those levels containing H. muelleri that does not correspond to the Anisian sensu lato.

Subsequently, new palynological data (see the complete list of taxa in Supplementary Material) were described from the Punta del Lavatoio section (Fig. 1A) by Pittau Demelia and Flaviani (1982a). The authors sampled different dark clay layers located in the “Lithofacies C” (Costamagna, 2002). Due to the presence of the morphological group Alisporites-Sulcatisporites-Cuneatisporites, Triadispora crassa, Aratrisporites sp., Aratrisporites paraspinosus, Camarazonosporites cf. rudis, Polyopiaceoisporites sp. and Verrucosisporites sp, in sample 1275, coming from one of these levels, it was possible to correlate it with subzone A2 of the Cugiareddu well (Flaviani, 1980; Pittau Demelia & Flaviani, 1982a, 1982b). With this correlation, the authors pointed out that, as in the A2 subzone defined in the Cugiareddu well (not in Punta del Lavatoio), Stellapollenites muelleri (= Hexasaccites muelleri) occurs, and so this level can be ascribed to the late Anisian, and the upper part to the early Ladinian due to the presence of Diplonopora. This reasoning is not viable under our methodology because photos of only seven taxa are presented (Aratrisporites sp., Chordasporites singulicorda, Convacisporites sp., Polyopiaceoisporites sp., Striatabioteites sp., Triadispora plicata and T. suspecta). Furthermore, the determination is based on a taxon that would not even have been present in the sample.

Subsequently, Frechengué et al. (1993) described palynological results for a sample (see the complete list of taxa in Supplementary Material) in a dark clay layer, included in the “Escalaplano section”, which they also compare to those mentioned above by Damiani and Gandin (1973a) (Fig. 2: 4). The authors suggested a Ladinian age to this sample due to the presence of a large amount of Triadispora spp., numerous Alisporites, Pityosporites neomundanus and Cycadopites, the absence of Ovalipollis and Circumpollales and the low quantity of spores, except for Aratrisporites saturni and A. fisheri. In the same work, the authors compared this assemblage with similar ones in the Pyrenean ranges and with the association described in Pittau Demelia and Flaviani (1982a) for the section of Punta del Lavatoio. Of all the taxa referenced, only the photo of Heliosaccus dimorphus is published. This does not allow us to conclude that the classification is correct and, because of the lack of characterization of the forms presented in that work, we prefer not to attribute these levels to the Ladinian.

In Barca et al. (1995b), a well-preserved association (see the complete list of taxa in Supplementary Material) is yielded by the basal marly levels of the carbonate Case Pisan no Mb (Punta Su Nuraxi Formation, Costamagna & Barca, 2002) in the Scivu-Is Arenas section (Figs. 1C, 2: 2). The authors reported a very diverse palynomorph content with fifty-three different taxa, but photos of only twenty-six of these are shown. Due to the presence of Triadispora crassa, together with Illinites chitonoides, Angustisulcites klausii, Microcachrydites fastidioides, Stellapollenites thiergartii (= Hexasaccites muelleri), Pterotriletes minor and Christianisporites triangulatus, they consider that the association would be Pelsonian-Illyrian in age and would be correlated with the “phase Mu-1” of Dockter et al. (1980). Barca et al. (1995b) illustrate some taxa, but not all, to evaluate the identifications presented. According to our interpretation of the original diagnoses, we would change some of the published identifications, including Aratrisporites sp. for Cerebropollenites mesozoicus Nilsson 1958, Chordasporites singulichorda Klaus 1964 for Microcachrydites doubingeri Klaus 1964, Cuneatisporites radialis Leschik 1955 for Angustisulcites sp., Giggiospora escapolaynoi Pittau Demelia 1980 for Enzonalsporites sp., Myriamsporites triassicus Pittau Demelia in Flaviani, 1980 for Paleospongisporis europaeus
Schulz 1965, *Perotriletes minor* (Mädler) Antonescu & Taugourdeau Lantz 1973 for *Perotriletes* sp., *Stellapollenites muelleri* (Reinhardt & Schmitz) Pittau Demelia 1983 (= *Hexasaccites muelleri*), *Striatoabieites aytagii* Visscher 1966 for *Strotersporites richteri* (Klaus) Wilson 1962, *Triadispora maxivestita* Pittau Demelia in Flaviani, 1980 for *Triadispora* sp., *Varirugosisporites roeticus* (Schulz) Pittau Demelia in Flaviani, 1980 for *Verrucosisporites* sp., *Verrucatosporites cugiareddu* Pittau Demelia in Flaviani, 1980 for *Verrucosisporites thuringiacus* Mädler 1964. This
Fig. 8  Synthesis of the palynomorphs found in the Sardinian sections. Scale bar: 20 μm. The acronym indicates section-sample number slide_England Finder slide coordinates. 1. Bascanisporites sp. GRIFO3_02_E154. 2. Brachisaccus neomundanus (Leschik) Mädler, 1964. 3. Cf. Cordaitina sp. GRIFO3_02_F123. 4. Cerebropollenites mesozonicus Nilsson, 1958. PC-3_B_02_H310. 5. Chasmatosporites sp. AIF-5_03_H401. 6. Cycadopites sp. AIF-5_01_M443. 7. Striatosaccites aytugii (Visscher) Scheuring, 1978. GRIFO3_01_L411. 8. Strotersporites jansonii Klaus, 1963. PC-3_B_02_T340. 9. Striatopodosporites cancellatus (Balme & Hennelly) Hart, 1963. PC-3_B_01_U232. 10. Enzonalasporites vigens Leschik, 1955. PC-3_B_03_N404. 11. Paracirculina sp. AIF-9_04_C173. 12. Microcachryidites doubugeri Klaus, 1964. GRIFO3_03_N163. 13. Microcachryidites fastidioides (Jansonius) Klaus, 1964. AIF-5_01_S192. 14. Microcachryidites sittleri Klaus, 1964. PC7.2_01_K352. 15. Microcachryidites sp.1. GRIFO3_01_R180. 16. Ovalipollis ovalis (Krutzsch) Scheuring, 1970. GRIFO3_01_E052. 17. Duplicispores granulatus (Leschik) Scheuring, 1970. GRIFO3_04_K353. 18. Kraeuselisporites sp. PC-3_B_03_K294. 19. Araritispores cf. granulatus (Klaus) Playford and Dettmann, 1965. AIF-5_02_O301. 20. Araritispores sp. AIF-5_01_O094. 21. Uvaesporites sp. PC-3_B_03_L291. 22. Rewanispora vermiculata Anonescu and Taugourdeau-Lantz, 1973. PC-2_B_04_W343. 23. Rewanispora sp. PC-3_B_01_T342. 24. Cyclotrites granulatus Mädler, 1964. PC-3_B_03_R452. 25. Cyclotrites oligogranijer Mädler, 1964. PC-3_B_02_H270. 26. Limbosporites sp. PC-2_B_03_Q274. 27. Calamospora tener (Leschik) Mädler, 1964. PC-4_B_02_E133. 28. Calamospora sp. PC-2_B_01_M520. 29. Densoisporites nejburgii (Schulz) Balme, 1970. AIF-5_03_C430. 30. Densoisporites sp.PC7.2_01_W391. 31. Micronoreticulatisporites galili Adloff and Doubingen, 1969. PC-4_B_02_K250. 32. Reticulatisporites sp. PC7.2_01_R410. 33. Punctatisporites fungosus Balme, 1963. PC-3_B_01_P144. 34. Punctatisporites triassicus Schulz, 1964. PC-3_B_03_N281. 35. Camarozonospores sp. AIF-5_04_J353. 36. Anunnulispora sp. GRIFO3_02_J401. 37. Dictyophyllidites mortonii (de Jersey) Playford and Dettmann, 1965. GRIFO3_01_M420. 38. Deltoisporites sp. GRIFO3_01_K262. 39. Unidentified spore PC-4_B_01_Q292. 40. Verrucosisporites thur-ingiacus Mädler, 1964. PC7.2_02_U432. 41. Paleospongisporis europaeus Schulz, 1965. PC-2_B_01_E472

new interpretation of the data has allowed us to specify the previous dating in the Discussion section.

In Ronchi (1997), two palynological associations (see the complete list of taxa in Supplementary Material) from samples collected in levels known as the Buntsandstein of the Triassic basin of Escalaplano were studied by Pittau. The ARPE-02 sample was obtained at the northeast of the basin (Arcu Is Frontestas) along the Escalaplano-Perdasdefogu road and the ARPE-04 sample at the southern entrance to Escalaplano (Fig. 1B). Both levels were attributed to the Anisian by Pittau (A. Ronchi Pers. Com.), as the presence of Stellapollenites tiergartii is referable to Anisian. Unfortunately, we cannot make any assessment as the work does not present any photos of the taxa mentioned.

In order to formalize the Escalaplano Formation, Costamagna et al. (2000) described three levels with palynomorphs (see the complete list of taxa in Supplementary Material) of two different sections of the “lithofacies B”: two levels in a section (nowadays covered by a road wall) not far from the southern entrance to the village of Escalaplano—along the Escalaplano-Orroli road, 2 and 4 m from the underlying contact on the Palaeozoic basement—and the third level along a cut on the Escalaplano-Perdasdefogu road in the locality of Arcu Is Frontestas. Based on the presence of Stellapollenites muelleri, Cristianispores triangulatus and Dyupetalium vicentinense, these levels were considered upper Anisian (Pelsonian), correlating with the “vicentinense-muelleri” phase, according to Brugman (1986), Visscher and Brugman (1981) and Van Der Eem (1983), and the Escalaplano Fm is thus upper Anisian-basal Ladinian.

Observation of the photographs allows us to verify the referenced taxa and propose a new attribution for some of them, as appropriate. We consider that the form attributed to Dyupetalium vicentinense could also be Cristianispores triangulatus, among others (see supplementary material).

According to the authors, the coexistence of these taxa would justify a late Anisian (Pelsonian-Illrian) interval to early Ladinian attribution. Unfortunately, it is impossible to know the stratigraphic relationship between the studied samples and their relative position since these authors do not provide separate lists and do not attribute their published photos to specific sampled levels.

The last published reference would be Pittau and Del Rio (2002), in which the authors publish a compilation of all the previous palynostratigraphic works on the Permo-Triassic sequences of Sardinia. For the Scythian to early Anisian interval, the authors refer to a listed association (with only three photos, however) consisting of Enzonalasporites leschikii Mädler 1964, Microcachryidites fastidiosus Jansonius 1962, Sulcatisporites splendens Leschik 1955, Triadispora crassa Klaus 1964, cf. Stellapollenites muelleri (Reinardt & Schmitz) Pittau Demelia 1993 and Voltziacesporites heteromorpha Klaus 1964. This is the same association first described by Flaviani (1980) and related to the Permian in Pittau Demelia and Flaviani (1982b) for level 545 (sample 970). In this work, the authors reevaluate this pollen association and consider a possible Olenekian (late Scythian) or, more probably, early Anisian due to the impossibility of affirming the identification of Stellapollenites muelleri (= Hexasaccites muelleri). However, Voltziacesporites heteromorpha made its first appearance in the late Olenekian, according to Brugman (1986). This deduction based on the criterion of absence is not acceptable, and therefore the attribution of level to the “Scythian” is similarly unacceptable. The following section of this compilation is dedicated to the Anisian and it repeats the arguments presented in Pittau Demelia & Flaviani, (1982b), Barca et al. (1995b), Pittau & Del Rio, (2002) and Costamagna et al. (2000).
4.2.2 Reexamined and new palynological data

The original palynological slices analyzed in Diez (2000) have been revised and re-photographed with better image capture systems, offering a slightly more comprehensive taxa list. These slices correspond to samples PC-2, PC-3, PC-4 ("Escalapano SW", Fig. 5) and PC-7.2 ("Arcu is Fronestas" section, Fig. 6).
Palynological analyses from different Sardinian outcrops, including the Escalaplano section, have recently been performed. New productive samples (AIF-2, AIF-5 and AIF-9) were obtained in the "Arcu Is Fronestas" section (Fig. 2: 3 and Fig. 6) to complete the information of Diez (2000). Moreover, a new sample was obtained in Su Passu Malu (Campumari) (Grifo 3, Figs. 2: 1 and 7).

Synthetic plates of all the samples studied are presented (Figs. 8 and 9). The complete palynological assemblages are shown in the supplementary material (Table 1 and Figs. S1–S8). Based on the taxonomic similarity of the palynomorph assemblages found and their stratigraphic location, these assemblages have been grouped into several synthetic associations indicating the same age.

The synthetic association of the Escalaplano southern entrance is the "Escalaplano SW Section" (Figs. 1B, 5), corresponding to the C-2, PC-3 and PC-4 samples and composed of: Alisporites grauvelogi Klaus, 1964, Alisporites magnus Jain 1968, Alisporites opii Daugherty, 1941, Alisporites sp., Angustisulcites grandis (Freudenthal) Visscher, 1966, Angustisulcites klausii (Freudenthal) Visscher, 1966, Aratrisporites sp., Calamospora tener (Leschik) Mädler, 1964, Calamospora mesozoicus Nilsson, 1958, Chordasporites singulichorda Klaus 1964, Cylotrilites oligogrammer Mädler, 1964, Cylotrilites granulatus Mädler, 1964, Enzonalasporites vigenes Leschik, 1955, Heliosaccus cf. dimorphus. Mädler, 1964, Hexasaccites muelleri (Reinhardt & Schmitz) Adloff & Dubinger, 1969, Illinites krasaknei Klaus, 1964, Illinites chitonoides Klaus, 1964, Klauspollenites schaubergeri (Potonié and Klaus) Jansonius, 1962, Kraeusselisporites sp., Limbsporites sp., Lunatisporites acutus Leschik, 1955, Lunatisporites noviaulensis (Leschik) de Jersey, 1979, Lunatisporites cf. puntii Visscher, 1966, Microcachryidites doubingeri Klaus, 1964, Microcachryidites fastidioides (Jansonius) Klaus, 1964, Microreticulatisporites gallii Adloff & Dubinger, 1969, Paleospondisporites europaeus Schulz, 1965, Platsaccus papilionis Potonié and Klaus, 1954, Platsaccus sp., Punctatisporites fungosus Balme, 1963, Punctatisporites triassicus Schulz, 1964, Rewanispora vermiculata Antonescu and Taugourdeau-Lantz, 1973, Rewanispora sp., Striatolepites aytugii (Visscher) Scheuring, 1978, Strenatopodicarpides cancellatus (Balme & Hennelly) Hart, 1963, Strotersporites jansonii Klaus, 1963, Triadispora crassa Klaus, 1964, Triadispora falcata Klaus, 1964, Triadispora plicata Klaus, 1964, Triadispora staplinii (Jansonius) Klaus, 1964, Triadispora strophata Scheuring, 1970, Triadispora sp.1., Uvaesporites sp., Vernicosisperites sp.1. and two unidentified spores.

The samples from the "Arcu Is Fronestas" section can be grouped into two synthetic associations. The first corresponds to the AIF-2 and AIF-5 samples collected in the lower part of the section (Fig. 6) and is composed of: Alisporites grauvelogi Klaus, 1964, Alisporites magnus Jain 1968, Alisporites opii Daugherty, 1941, Alisporites sp., Angustisulcites gorpji Visscher, 1966, Angustisulcites klausii (Freudenthal) Visscher, 1966, Angustisulcites sp.1. and two unidentified spores.
The second synthetic association of the section "Arcu Is Fonestas" corresponds to the samples AIF-9 and PC-7.2 extracted from the upper part of the Buntsandstein facies, just under the Jurassic quartz-conglomerates (Fig. 6). They are represented by: Alisporites grauvogeli Klaus, 1964, Alisporites opii Daugherty, 1941, Alisporites sp., Angustisulcites klasii (Freudenthal) Visscher, 1966, Angustisulcites sp., Calamospora tener (Leschik) Mäddler, 1964, Calamospora sp., Cerebropollinites mesozoicus Nilsson, 1958, Chordasporites singulichorda Klaus, 1960, Cristianisporites triangulatus Antonescu, 1969, Cycadopites sp., Cyclotriletes ologranifer Mäddler, 1964, Cyclogranisporites sp., Densosporites sp., Enzonalasporites vigens Leschik, 1955, Hexasaccites muelleri (Reinhardt & Schmitz) Adloff & Hexasaccites muelleri sp.1., Fastidioides (Jansonius) Klaus, 1964, Microcachryidites doubingeri Klaus, 1964, Microcachryidites sp., (Leschik) De Jersey, 1979, Microcachryidites granulatus Duplicisporites (De Jersey) Playford & Dettmann, 1965, Deltoidospora Mädler, 1964, Dictyophyllidites mortoni (De Jersey) Playford & Dettmann, 1965, Duplicisporites granulatus Leschik Scheuring, 1970, Enzonalasporites vigens Leschik, 1955, Hexasaccites muelleri (Reinhardt & Schmitz) Adloff & Doubinger, 1969, Illinites chitonoides Klaus, 1964, Illinites kukkankei Klaus, 1964., Kraeuselisporites sp., Microcachryidites doubingeri Klaus, 1964, Microcachryidites fastidioiides (Jansonius) Klaus, 1964, Microcachryidites sp.1., Ovalipollis ovalis (Krutzsch) Scheuring, 1970, Paleospangisporis europaeus Schulz, 1965, Paracirculina sp., Rewanispora vermiculata Antonescu & Taugourdeau-Lantz, 1973, Rewanispora sp., Striatoabietes aytugii (Visscher) Scheuring, 1978, Triadispora crassa Klaus, 1964, Triadispora falcata Klaus, 1964, Triadispora plicata Klaus, 1964, Triadispora staplinii (Jansonius) Klaus, 1964, Triadispora suspeta Scheuring, 1970, Triadispora sp., Uvaesporites sp., Verrucosisporites thuringiacus Mäddler, 1964, and Verrucosisporites sp.

5 Palynostratigraphical discussion

From the set of results obtained from the review of previous works, as well as from unpublished data and new pollen samples, we can infer that there has been no palynological dating corresponding to the Early Triassic in Sardinia, in contrast with neighbouring paleogeographical regions such as the Iberian Peninsula (Diez et al., 2005) and the South of France (Diez, 2000).

Furthermore, sample 1275 collected in the section of Punta del Lavatoio (Pittau Demelia & Flaviani, 1982a) shows photos of only seven taxa and, although the authors initially ascribed it to the Anisian, this age is not consistent. The three species identified have a wide biozone distribution: Chordasporites singulichorda, which corresponds with the base of the Anisian to the Longobardian (Eshet, 1990); Triadispora plicata, from the Anisian to the Carnian; and Triadispora suspeta, from the Pelsonian to the Carnian (Doubinger & Adloff, 1983). Therefore, our dating would be broader, and a Pelsonian-Longobardian interval is proposed for this sample (Fig. 10). A later publication by Posenato et al. (2002) studied the same outcrop and, through biostratigraphic analyses of various groups of marine invertebrates, attributed the entire section to the Ladinian. Likewise, palynological data from the same Muschelkalk facies from the Monte di Santa Giusta section to the north of Alghero (Carrillat et al., 1999) are consistent with this proposed age. Therefore, since our study is focused on the Anisian, the work of Pittau Demelia & Flaviani (1982a) has not been considered.

As regards the rest of the works referred to in our study, it has been possible to verify the presence of Hexasaccites muelleri, which indicates that all levels can be dated as being of the Anisian age (Visscher & Brugman, 1981; Brugman, 1983; Diez, 2000; Diez et al., 2005; Kürschner & Herrgreen, 2010).

Regarding the Cugiareddu well (Fig. 10), although most of the Flaviani (1980) work remains unpublished, the few photos published in Pittau Demelia and Flaviani (1982b) and Pittau and Del Rio (2002) allow us to address the following arguments. In their final work of compilation (Pittau & Del Rio, 2002), the authors reevaluated the palynological association, first described by Flaviani.
(1980) and referred to in Pittau Demelia and Flaviani (1982b), for level 545 (sample 970), and considered it a possible late Scythian or early Anisian, due to the impossibility of confirming the identification of *Stellapollentes muelleri (= Hexasaccites muelleri)*. However, *Voltziaceaisporites heteromorpha* made its first appearance in the upper Olenekian, according to Brugman (1986). As we said before, the criterion of absence is not acceptable, but since this publication presents photos of three taxa we can infer from the text that they come from level 545. For this reason, we can confirm the identification of *Triadispora crassa* and *Voltziaceaisporites heteromorpha*. Therefore,
we agree that V. heteromorpha begins in the upper Scythian, but its biozone extends to the Pelsonian (Brugman, 1983, 1986; Diez, 2000; Visscher & Brugman, 1981) (Fig. 10). Furthermore, the Triadispora crassa biozone extends from the Anisian to the base of the Carnian. If we add the fact that the association is very poor based on the above, we can only say that it is Anisian without much precision and possibly does not extend to Illyrian.

In Pittau and Del Rio (2002), levels 477 (sample 756) and 443 (sample 755) of the Cugiareddu well are related to photos of Hexasaccites muelleri, corresponding with the Anisian, as mentioned above, while Cristianisporites triangularis corresponds with a biozone between the Pelsonian (Anisian) and Fassanian (Ladinian) (Antonescu, 1969; Diez, 2000; Dobbinger & Adloff, 1983), which would place these two levels within the Pelsonian-Illyrian interval (late Anisian).

Regarding level 429 (sample 754), we reject the use of the criterion of absence. Moreover, the presence of Ovalopollis pseudoalatus, with a photo in Pittau and Del Rio (2002), does not allow us to say that the level is later than the base of the Pelsonian (Brugman, 1983; Diez, 2000; Dobbinger & Buhmann; Visscher & Brugman, 1981) or be more specific.

Most of the published works (e.g., Pittau Demelia & Del Rio, 1980; Ronchi, 1997; Costamagna et al., 2000 and Diez, 2000), as well as the new data presented in this work, refer to the outcrops of the Sarcidano-Gerrei region. Nevertheless, as we have already explained in the previous section, the data presented in Pittau Demelia & Del Rio (1980), Ronchi (1997), Costamagna et al. (2000) cannot be used, due to their incomplete or non-existent sheets of photographs or the unknown stratigraphic locations (level and section) of each of the taxa photographed and classified. We could only attribute all the levels of these sections to the Anisian for the reasons mentioned above (Fig. 10).

The revised and new levels are collected in the sections of Escalaplano (Figs. 1B, 5) and Arcu Is Fronestas (Fig. 6). In the Escalaplano section, the three samples do not present a very different composition and they have been treated as a single synthetic association (for more details, see the supplementary material). If we consider the main Triassic palynostratigraphic works on the Western pery-Tethys domain (Dobbinger & Buhmann, 1981; Visscher & Brugman, 1981; Brugman, 1983; Eshet, 1990; Diez et al. 2010), Enzonalasporites vigens, Microcachryidites dourbingeri, Microcachryidites fastidioides, Triadispora crassa and Triadispora staplinii are consistent with the Anisian dating provided by Hexasaccites muelleri. Cyclotriletes oligogranifer, Illinites chitonoides, Triadispora plicata, and Triadispora suspecta made their first appearance in the Pelsonian (Dobbinger & Adloff, 1983; Eshet, 1990). Punctatissporites triassicus was usually present until the Pelsonian (Dobbinger & Buhmann, 1981) and, finally, Illinites kosankei was last recorded in the middle Pelsonian (Doubinger & Adloff, 1983) levels of facies, so we can infer that the Buntsandstein facies levels of the Escalaplano Section were deposited during the lower Pelsonian. We report the appearance of a single specimen of Heliosaccus cf. dimorphus Mädler 1964 in sample 3, in poor conditions. This species is considered to have its first record in the Anisian-Ladinian transition (Doubinger & Adloff, 1983; Visscher & Brugman, 1981; Brugman, 1983; Kurscher & Herngreen, 2010), and if it is confirmed, we should reconsider its biozone (Fig. 10).

The second section studied in the Escalaplano basin is called Arcu Is Fronestas (Figs. 1D, 6). Four samples were studied but, as mentioned in the previous section, they have been unified in two synthetic associations (see the complete lists of the samples in the supplementary material) due to their composition and stratigraphic position. The first corresponds to the lower part of the sedimentary unit in Buntsandstein facies composed of samples AIF-2 and AIF-5, and the second to the upper part composed of samples PC-7.2 AIF-9. The two synthetic associations present few differences between them; both can be attributed to the lower Pelsonian, following the same reasoning used for those of Escalaplano, and based on the same taxa sets. The only appreciable difference is the appearance of Cristianisporites triangularis in the upper-part association, which has its first record in Central Europe in the Pelsonian (Doubinger & Adloff, 1983). Its presence does not allow us to say that the age is more modern than the base samples, but its relative stratigraphic position could be used as a correlation criterion with the Grifo-3 sample in Campumari Section, which also presents this taxon (Fig. 10).

In the Iglesiante region (Fig. 1), the first reference is that of Pittau Demelia & Del Rio (1980), in which a poor association is described for the Campumari outcrop. Due to the presence of Hexasaccites muelleri, the sampled unit can be attributed to Anisian sensu lato, as suggested by the authors (Fig. 10). We can confirm this attribution thanks to the photo of the taxon, as discussed in the previous section.

Furthermore, in the same region, we carried out a new sampling with a productive result in the section of Su Passu Malu (Figs. 1D, 7), where, as we reported in the previous section, a rich well-preserved Anisian palynological association with Cristianisporites triangularis, Enzonalasporites vigens, Illinites chitonoides, Triadispora falcatula, T. plicata and T. falcatula together with Hexasaccites muelleri would indicate a Pelsonian-Illyrian age (Brugman, 1983; Diez, 2000; Dobbinger & Adloff, 1983; Visscher & Brugman, 1981), which would be restricted by the presence of Duplicisporites granulatus, whose genus has its first record in Illyrian.

The presence of Enzonalasporites vigens and Duplicisporites granulatus according to Cirilli (2010) and Mietto et al.


**6 Paleogeographic inferences**

The precise configuration of the Western Tethys during the Middle Triassic, and in particular the position of Sardinia in this domain, has always been subject to debate (e.g., Costamagna & Barca, 2002). The data presented in this work shed more light on this topic, as the microfloristic associations studied, along with the regional facies correlations, enhance our understanding of the timings of the Western Tethys transgression in the western Mediterranean Triassic domain. This allows us to propose a new hypothesis regarding the paleogeographical evolution of this domain during the Anisian. It has been possible to identify three important steps/stages of evolution:

1) First step (late Pelsonian, Fig. 11a). The northwestern and southeastern part of Sardinia (data from Cugiareddu well, Nurra region and ourcrops in the Sarcidano region) were the first sectors of the island to be affected by the first transgressive pulse, which occurred through the development of small seaways that previously crossed the southern Catalan basin and parts of the eastern Iberian basin (Fig. 12), determining the deposition of the lower Muschelkalk facies or Landete Fm, represented by a shallow marine carbonate platform environment (Escudero-Mozo et al., 2015). During this period, most of the islands of Sardinia and Minorca still constituted...
high terrestrial areas (Costamagna & Barca, 2002; Escudero-Mozo et al., 2014) where erosion or continental sedimentation persisted. At this stage, these elevated areas acted as a barrier between the different Tethys realms and still experienced continental sedimentation in the Buntsandstein facies.

2) Second step (early Illyrian, Fig. 11b). As the transgression progressed, during the Pelsonian/Illyrian, there was a gradual evolution to a more transitional marine environment. Following this new sea level rise, related to the northward shift of Cimmeria (Escudero-Mozo et al., 2014, 2015), more areas were progressively covered by epicontinental seas, including the southernmost sector of Sardinia (Sulcis-Iglesiente region), while Minorca and the northern Catalanian basin (Escudero-Mozo et al., 2014, 2015) and the eastern Castellón area (López-Gómez et al., 1998; Escudero-Mozo et al., 2015; Ortí et al., 2020) in eastern Iberia were still represented by continental elevated areas during the middle Illyrian (Fig. 12). This configuration represented an important paleogeographic barrier in the Tethys Sea and it determined the distribution of fauna in northern and southern Cimmeria (Escudero-Mozo et al., 2015).

3) Third step (Fassanian, Fig. 11c). The new transitional pulse that took place during the middle-late Illyrian represented the complete incursion of the Tethys sea in its western domain, including central-eastern Iberia and the Balearic Islands, as well as most of Central and Southern Europe (Gianolla & Jaquin, 1998; Ziegler, 1999;

Fig. 12 Paleogeographic reconstruction of the western Tethys realm for the Middle Triassic (middle Anisian). AM Armorica; AB Alborán; AG Authoctonous Greece; AP Apulia; BA Balearic; BD Bey-Daglari; BM Bohemian Massif; CA Carnic; CB Calabria; CM Central Massif; IB Iberian Massif; IM Irish Massif; LBM London-Brabant Massif; MA Mani; MEL Meliata; PEL Pelagonia; SC Sardinia-Corsica; TA Taurus; TN Tunisia; TU Tuscan; RH Rhenish Massif; VH Vindelician High; Mi Minorca; Ma Majorca; CCB Catalan Coastal Basin; Ca Castellón. Image modified from Escudero-Mozo et al. (2015) Ziegler and Stampflı (2001), Stampflı and Borel (2002) and Muttoni et al. (2009)
Sanz De Galdeano et al., 2001; Martín-Algarra & Vera, 2004; Pérez-López & Pérez-Valera, 2007; Martín-Rojas et al., 2009; Mercedes-Martín et al., 2013; Escudero-Mozo et al., 2015; Ortí et al., 2020). Over the course of this step, the evaporitic conditions (sabkha environment) which characterized most of the upper Anisian in Sardinia eventually gave way to a shallow marine environment in the whole island.

7 Conclusions

The new stratigraphic analyses and palynological samplings presented in this work, as well as the close review of all the previous palynological publications on the Sardinian Anisian, enhance our framing of the stratigraphical, sedimentological and palynological aspects of the three key Middle Triassic successions of Sardinia: the Su Passu Malu section (Campumari, SW Sardinia), the Arcu is Fronestas section and the Escalaplano SW section (Escalaplano, Central Sardinia). Moreover, the integration of these data with those obtained from other sectors of Sardinia and Western Europe make it possible to evaluate the paleogeographical evolution of the Western Tethys realm during the late Anisian-early Ladinian with greater precision.

The main conclusions can be summarized as follows:

1) The palynostratigraphical associations analyzed provided precise data on the age of the studied sections. It was possible to attribute the Escalaplano Formation to the Pelsonian, thanks to the data obtained from the Escalaplano SW and Arcu is Fronestas sections. As regards the Campumari succession, the sample from Su Pasu Malu Member (Campumari Formation) gave an Illyrian age-constraint. No indications of Early Triassic or lower Anisian associations were identified.

2) These data allow us to define with greater accuracy the Tethys Sea incursion towards its westernmost domains during the Middle Triassic, as well as the different stages of the transgression in Sardinia during the late Anisian-early Ladinian.

3) Sardinia, together with Minorca and the eastern area of Castellón (easternmost Iberia), constituted a topographical high area until the middle-late Illyrian (late Anisian), when an important change in the configuration of the Western Tethys realm occurred. Up until that point, the Sardinia-Minorca block had played a key role by acting as a barrier between the realms of the Paleotethys and Neotethys seas.

4) From the late Illyrian to the early Fassanian, the new transgression of the Tethys Sea progressively covered Sardinia with shallow marine deposits that also reached the neighbouring easternmost Iberia and Minorca areas. During this transgression, almost all the elevated areas of the Western Tethys domain were finally covered by the shallow seas.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41513-021-00184-x.

Acknowledgements The authors thank Annalisa Flaviani and Anna Gandin for their kindness and support in providing part of the data. Funds were provided by a University of Pavia PhD research grant (Lorenzo Stori) and project PGC2018-098272-B-100 (Spanish Ministry of Science, Innovation and Universities). This research is also a contribution to the University Complutense Research Projects: Basin Analysis (910429) and Palaeoclimatology and Global Change (910198). We thank Matthew Clarke for the English revision of the manuscript. The authors thank Alberto Pérez-López, an anonymous reviewer and the associate editor Laura Domingo for their helpful comments on the manuscript.

Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Angiolini L., Crippa G., Muttoni G & Pignatti J., (2013). Guadalupian (Middle Permian) paleobiogeography of the Neotethys Ocean. Gondwana Research 24: 173–184
Antonescu, E., (1969). Deux nouveaux types de spores dans les depots du Trias Moyen des Environs De Cristian (Roumanie). Rev. Micropaleontol. ; Fra ; 1969(6), Vol, 12(0001), 9–15.
Barca, S., & Costamagna, L.G., (2003a). Analisi di facies e stratigrafia della successione permo-triasica di Campumari-Coremò (Iglesiente, Sardegna SW). Boll. Soc. Geol. It. 122, 25–45
Barca S., Costamagna L.G. & Del Rio M. (1995a). La successione triassica di Scivu-Is Arenas (Sardegna sud-occidentale). Nuovi dati stratigrafici e sedimentologici. Atti Soc. Tosc. Sci. Nat., Mem Serie A, 102, 5–15
Barca S., Costamagna L.G. & Del Rio M. (1995b). Affioramenti permo-carboniferi e mesosiluriani fra Porto Piscinas e Punta Acqua Durci (Arburese, Sardegna SW) Boll. Soc. Sarda Sci. Nat Sassari , 30, 1–11.
Barca S. & Costamagna L.G. (1997b). The Triassic succession of Campumari and Scivu-Iso Arenas (SW Sardinia, Italy): analogues, correlations and some remarks. 18° IAS Meeting, Heidelberg, September 1997, Abstracts Book, 60, Heidelberg.

Barca S., Del Rio M. & Pittau P. (2004). The Middle Triassic deposits of Escalaplano. In BARCA S. & Cherchi A. (eds), Sardinian Paleozoic Basement and its Meso-Cainozoic covers, Field Trip Guide Book, XXXII IGC Firenze 2004, APAT.

Borruel-Abadía V., Barrenechea J.F., Galán-Abellán A.B., De La Horra R., López-Gómez J., Ronchi A., Luque F.J., Alonso-Azárate J & Marzo M. (2019). Could acidity be the reason behind the Early Triassic biotic crisis on land?. *Chemical Geology*, 515, 77–86, ISSN 0009-2541.

Bourquin S., Durand M., Diez J.B., Broutin J. & Fluteau, F. (2007). The Permian-Triassic transition and the onset of Mesozoic sedimentation at the northwestern peri-Tethyan domain scale: Paleogeographic maps and geodynamic implications, *Paleogeo. Paleocl. Paleoecol.*, 299(1–2), 265–280.

Bourquin S., Durand M., Diez J.B., Bourquin S. & Fluteau, F. (2007). The Permian-Triassic boundary and early Triassic sedimentation in Western European basins: an overview. *Journal of Iberian Geology*, 33, 221–236.

Broutin J., Cassinis G., Cortesogno L., Gaggero, L., Ronchi, A. & Sarria, E. (1996). Research in progress on the Permian deposits of Sardinia (Italy). *Permophiles, a Newsletter of SPS*, 28, 45–48.

Brugman, W.A. (1983). Permian-Triassic palynology state university of Utrecht, The Netherlands 121.

Brugman, W.A. (1986). A palynological characterization of the Upper Scythian and Anisan of the Transdanubian Central Range (Hungary) and the vincentian Alps (Italy). PhD Thesis. Univ. de Utrecht, p. 95.

Carrillat A., Martini R., Zaninetti L., Cirilli S., Gandin, A. & Vrielynck, B. (1999). The Muschelkalk (Middle to Upper Triassic) of the Monte di Santa Giusta (NW Sardinia): sedimentology and biostратigraphy, *Eclogae Geologicae Helvetiae*, 92, 81–97.

Cassinis, G., Durand, M. & Ronchi, A. (2003). Permian-Triassic continental sequences of northwest Sardinia and south Provence: stratigraphic correlations and palaeogeographic implications. In: Decandia F.A., Cassinis G. & Spina A., Eds., Spec. Proc. Int. Meeting «Late Palaeozoic to Early Mesozoic events of Mediterranean Europe, and additional regional reports», Siena, 2001, *Boll. Soc. Geol. It.*, Vol. Spec., 2, 119–129.

Cirilli S. (2010). Upper Triassic-lowestmost Jurassic palynology and palynostratigraphy: a review. *Geological Society, London, Special Publications*, 334, 285–314.

Citon P., Ronchi A., Nicosia U., Sacchi E., Maganuco S., Circiani A., Innamorati G., Zuccari C., Manucci F. & Romano M., (2020). Tetrapod tracks from the Middle Triassic of NW Sardinia (Nurra region, Italy), *Ital. J. Geosci.*, 139(2), 309–320. 6 figs. (https://doi.org/10.3301/JIG2020.07) © Società Geologica Italiana, Roma 2020.

Cocozza, T. & Gandin, A. (1976). Età e significato ambientale delle facies detritico-carbonatiche dell’altopiano di Campumari (Sardegna sud-occidentale). *Boll. Soc. Geol. It.*, 95, 1521–1540.

Costamagna, L.G., Barca, S., Del Rio M. & Pittau, P. (2000). Stratigraphy, paleogeography ed analisi di facies deposizionale del Trias del Sarcidano-Gerrei (Sardegna SE). *Boll. Soc. Geol. It.*, 119, 473–496.

Costamagna, L.G. & Barca, S. (2002). The «Germanic» Triassic of Sardinia (Italy): a stratigraphic, depositional and paleogeographic review. *Riv. Ital. Paleont. Strat.*, 108(1), 67–100.

Costamagna, L.G., Barca S & Lecca L. (2007). The Bajocian-Kimmeridgian Jurassic sedimentary cycle of eastern Sardinia: stratigraphic, depositional and sequence interpretation of the new «Baunei Group». *C.R. Geoscience*, 339(9), 601–612.

Costamagna, L. G. (2011). Alluvial, aeolian and tidal deposits in the Lower to Middle Triassic “Buntsandstein” of NW Sardinia (Italy): a new interpretation of the Neo-Tethys transgression. *Z. dt. Ges. Geowiss.*, 163(2), 165–183, 18 figs., 2 tables Article Stuttgart, June 2012.

Costamagna, L.G. (2012). 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.

Costamagna, L.G. (2016). Middle Jurassic continental to marine transition in an extensional tectonics context: the Genna Selole Fm depositional system in the Tacchi area (central Sardinia, Italy). *Geological Journal*, 51, 722–736.

Costamagna, L. G., Barca, S. (2016). The Triassic and Jurassic sedimentary cycles in Central Sardinia: stratigraphy, depositional environment and relationship between tectonics and sedimentation. *Geological Field Trips*, 8(1), 78. https://doi.org/10.3301/GFT.2016.01.

Costamagna, L. (2019). The carbonates of the post-Variscan basins of Sardinia: The evolution from Carboniferous-Permian humid-persistent to Permian arid-ephemeral lakes in a morphophetocenose framework. *Geological Magazine*, 156(11), 1892–2014. https://doi.org/10.1017/S0016756819000232.

Damiani, A.V. & Gandin, A. (1973a). L’affioramento triassico del Monte Maiero di Nurra (Sardegna centrale) Nota i. *Boll. Soc. Geol. It.*, 92, 355–362.

Damiani, A.V. & Gandin, A. (1973b). Geologia ed ambiente di sedimentazione della successione triassica di M. Maiero (Sardegna centrale). *Nota II Boll. Soc. Geol. It.*, 92 (Suppl.), 41–83.

Damiani, A.V. & Gandin, A. (1973c). Il Muschelkalk della Sardegna centrale meridionale. *Boll. Serv. Geol. It.*, 94, 81–116.

Dieni, I., Fischer, J.C., Massari, F., Salard-Cheboldaef, M. & Vozenin, S.C. (1983). La successione di Genna Selole (Baunei) dans le cadre de la paléogéographie mésourjassique de la Sardaigne orientale. *Mem. Sci. Geol Padova*, 36, 117–148.

Diew, J.B., (2000). Geología y Palaeobotánica de la Facies Buntsandstein en la Rama Aragonesa de la Cordillera Ibérica. Implicaciones bioestratigráficas en el Periétibys occidental. Ph.D. thesis, Universidad de Zaragoza/Université Paris VI.

Diew, J.B., Bourtin J. & Ferrer, J. (2005). Difficulties encountered in defining the Permian-Triassic in Buntsandstein facies of the western Periétibys based on palynological data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 229, 40–53.

Diew, J.B., Bourtin, J., Grauvogel-Stamm, L., Bourquin, S., Bercovici, A., & Ferrer, J. (2010). Anisian floras from the NE Iberian Peninsula to the post-Variscan Nurra basin evolution. *Geological Field Trips*, 162, 522–542.

Dockter J., Puff P., Seidel G. & Kozur, H. (1980). Zur trias gliederung der Genna Selole-Gruppe in der Gonna Selole (Sardinien Sud-occidentale). *Eclogae Geologicae Helvetiae*, 81, 1521–1540.

Dockter J., Puff P., Seidel G. & Kozur, H. (1980). Zur trias gliederung der Genna Selole-Gruppe in der Gonna Selole (Sardinien Sud-occidentale). *Eclogae Geologicae Helvetiae*, 81, 1521–1540.

Doubinger, J. & Bühmann, D. (1981). Röt bei Borken und bei Schluchtern (Hesse, Deuschland) Palynologie und Tonmineralo- et Géochimie de la Surface, Strasbourg, France, p. 26.

Doubinger, J. & Bühmann, D. (1981). Röt bei Borken und bei Schluchtern (Hesse, Deuschland) Palynologie und Tonmineralo- et Géochimie de la Surface, Strasbourg, France, p. 26.

Doubinger, J. & Adloff, M.C., (1983). Triassic palynomorphs of the NE Iberian Peninsula and the vincentian Alps (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 229, 40–53.

Doubinger, J. & Adloff, M.C., (1983). Triassic palynomorphs of the NE Iberian Peninsula and the vincentian Alps (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 229, 40–53.
Escudero-Mozo, M.J., Martín-Chivelet, J., Goy A., López-Gómez, J. (2014). Sedimentary. *Geology*, 310, 41–58.

Escudero-Mozo M.J., Márquez-Aliaga A., Goy A., Martín-Chivelet J., López-Gómez J., Márquez L., Arche A., Plasencia P., Pla C., Marzoe M. & Sánchez-Fernández, D. (2015). Middle Triassic carbonate platforms in eastern Iberia: evolution of their fauna and palaeogeographic significance in the western Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 417, 236–260.

Eshet, Y. (1990). Paleozoic-Mesozoic palynology of Israel. 1. Palynological aspects of the Permo-Triassic succession in the Subsurface of Israel. *Geological Survey of Israel*, 81, 1–57.

Fazzini P., Gasperi G. & Gelmini, R. (1974). Ricerche sul Verrucano. 2. *Boll. R. Com. Geol. d'It.*, 93, 221–243.

Flaviani, A. (1980). Palinologia e stratigrafia del Trias del sondaggio Cugiareddu: Sardegna nord occidentale. Thesis, unpublished. Cagliari University.

Fontana, D., Gelmini, R. and Lombardi, G. (1982). Le successioni sedimentarie e vulcaniche carbonifere e permo-Triasiche della Sardegna. In Guida alla Geologia del Paleozoico sardo. *Guida Geologiche Regionali, Boll. Soc. Geol. It.*, 183–192.

Fontana D., Neri, C., Ronchi, A. & Stefani, C. (2001). Stratigraphic architecture and composition of the Permian and Triassic siliciclastic succession of Nurra (north-western Sardinia). In Cassinis G. (Ed.): The Continental Permian of the Southern Alps and Sardegna (Italy). *Regional reports and general correlations*, 25, 149–161.

Frechengués, M., Peybernes, B., Fournier-Vinas, C. & Lucas, C. (1993). Palynologic assemblages within the deposition sequences from the middle to Late Triassic series of the spanish and french Pyrenees. *Rev. Esp. Paleo.*, 25(3), 91–105.

Gianolla, P. & Jaquin, T. (1998). Triassic sequences stratigraphic framework of western European basins. In: DE Graciansky P.C., Hardenbol J., Jaquin T. & Vail P. (Eds.), *Mesozoic and Cenozoic Sequences Stratigraphy of European Basins*. Society for Sedimentary Geology, Special Publication 60, 643–650.

Kürschner W. & Waldemaar Hernandez, G.G., F. (2010). Triassic palynological setting of central and northwestern Europe: a review of palynofloral diversity patterns and biostratigraphic sub-divisions, in: LUCAS et al. *Triassic Timescale*, 1–25. https://doi.org/10.1344/GeologiaActa2020.18.4.

Le successioni basali dei Tacchi tra Escalaplano e Jerzu (Sardegna sud-orientale). Thesis, unpublished. Cagliari University.

Martín-Algarra, A, & Vera, J.A., (2004) La Cordillera Bética y las Baleares en el contexto del Mediterráneo POCioccidental. In: Vera, J.A. (Ed.), Geología de España. Sociedad Geológica de España. Instituto Geológico y Minero de España, Madrid, 352–354.

Martín-Rojas, I., Somma, R., Delgado, F., Estévez, A., Iannace, A. & Perrone, V. (2009). Triassic continental rifting of Pangea: direct evidence from the Alpjarjardie carbonates, Betic Cordillera, SE Spain. *Journal of Geological Society*, London, 166, 447–458.

Müttöni, G., Gaetani, M., Kent, D.V., Sciunchn, D., Angiolini, L., Berra, F., Garzanti, E., Mattei, M. and Zanchi, A. (2009). Opening of the Neo-Tethys Ocean and the Pangea B to Pangea A transformation during the Permian. *GeoArabia*, v. 14, no. 4, 2009, p. 17–48 Neo-Tethys opening and Pangea transformation. Gulf PetroLink, Bahrain.

Novarese, V. (1914) Il rilevamento geologico delle tavolette Iglesias e Nebida. *Boll. R. Com. Geol. Italiano*, 44, 29–59, Roma.

Ortí, F., Guimerà, J., & Götz, A. E. (2020). Middle–Upper Triassic stratigraphy and structure of the Alt Palancia (eastern Iberian Chain): A multidisciplinary approach. *Geologica Acta*, 18(4), 1–25. https://doi.org/10.1344/GeologiAActa2020.18.4.

Pastor-Galán, D., Groenewegen, T., Brouwer, D., Krijgsman, W. & Dekkers, M.J. (2015). One or two oroclines in the Variscan orogen of Iberia? *Implications for Pangea amalgamation Geology*, 43: 527–530.

Payne, J.L. & Kump, L.R. (2007). Evidence for recurrent Early Triassic massive volcanism from quantitative interpretation of carbon isotope fluctuations. *Earth and Planetary Science Letters*, 256, 264–277.

Pecorini, G. (1974). Nuove osservazioni sul Permo-Trias di Escalaplano (Sardegna sud-orientale). *Boll. Soc. Geol. It.*, 93, 991–999.

Payez-López, A. & Pérez-Valera, F. (2007) Palaeoecography, facies and nomenclature of the Triassic units in the different domains of the Betic Cordillera (SE Spain). *Palaeoecography, Palaeoclimatology, Palaeoecology*, 254, 606–626.

Pertusati, P.C., Sarria, E., Cherchi, G.P., Carmignani, L., Barca, S., Benedetti, M., Chighine, G., Cinotti, F., Oggiorno, G., Ulzega, A., Orru, P. & Pintus, C. (2002a). Note illustrative della Carta Geologica d’Italia alla scala 1:50.000—Foglio 541 Jerzu. *Servizio Geologico Nazionale—Regione Autonoma Sardegna*, p. 168.

Pertusati, P.C., Sarria, E., Cherchi, G.P., Carmignani, L., Barca, S., Benedetti, M., Chighine, G., Cinotti, F., Oggiorno, G., Ulzega, A., Orru, P. & Pintus, C. (2002b). Foglio 541 Jerzu—Carta Geologica d’Italia alla scala 1:50.000. *Servizio Geologico Nazionale Guide Autonoma Sardegna.*

Pittau Demelia, P. & Del Rio, M. (1980). Pollini e spore del Trias medio e del Trias superiore negli affioramenti di Campumari e di Ghissicera Mala (Sardegna). *Boll. Soc. Paleont. It.*, 19, 241–249, Modena.

Pittau Demelia, P. and Flaviani, A. (1982a). Palinofloristica della serie Triassica di Punta del Lavatore (Sardegna nord–occidentale). *Riv. It. Paleont. Strat.*, 88, 401–416, Milano.

Pittau Demelia, P. and Flaviani, A. (1982b). Aspect of the palynostratigraphy of the Triassic Sardinia sequences (Preliminary report). *Rev. Palaeobot. et Palyn.* 37, 377–380, Amsterdam.

Pittau, P. & Rio Del, M. (2002). Palynofloral biostratigraphy of the Permian and Triassic sequences of Sardinia. *Rend. Soc. Paleont. It.*, 1, 93–109.

Pittau, P., Del Rio M. & Funedda, A. (2008). Plant communities characterization and basin formation in the Carboniferous-Permian of Sardinia. *Boll. Soc. Geol. It. (Ital. Geosci.)*, 127(3), 637–653.

Pomesano, C.A. (1968). Studio biostratigrafico del sondaggio Cugia reddu nel Trias e Permico della Nurra nord—oce Univ 61.

Ponenato, R., Simone, L., Urtichs, M. & Ibba, A. (2002) The Ladinian Muschelkalk of Punta del Lavatario (Alghero, NW Sardinia). *Rend. Soc. Paleont. It.*, 1, 283–291.

Ronchi, A. (1997). I prodotti sedimentari e vulcanici dei bacini permi-animali di Escalaplano e Perdasdefogu nella Sardegna sud-orientale: stratigrafia e loro inquadramento nell’evoluzione tardo-paleozoica del settore sudeuropeo. PhD Thesis, Univ. Parma, p. 231.
Ronchi, A., Sarria, E. & Broutin, J. (2008) The «Autuniano Sardo»: basic features for a correlation through the Western Mediterranean and Paleoeurope. *Boll. Soc. Geol. It.*, 127(3), 655–681

Sanz De Galdeano, C., Andreo, B., García-Tortosa, F.J. & López-Garrido, A.C. (2001). The Triassic palaeogeographic transition between the Alpujárride and Malaguide complexes, Betic Rift Internal Zone (S Spain, N Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 167, 157–173.

Scotese, C.R., Schettino, A., (2017). Late Permian-Early jurassic paleogeography of western Tethys and the world, Permo-Triassic salt provinces of Europe, North Africa and the Atlantic margins, 57–95.

Seilacher, A. (1982). Distinctive features of sandy tempestites G Einsele A Seilacher Eds Cyclic and event stratification, Springer, 333–349.

Sinisi, R., Mongelli, G., Mameli, P., Oggiano, G., (2014). Did the Variscan relief influence the Permian climate of mesoeurope? Insights from geochemical and mineralogical proxies from Sardinia (Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 396.

Stampfli, G.M., & Borel. G.D (2002) A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. *Earth and Planetary Science Letters*, 196, 17–33.

Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C. & Raumer Von, J. (2013). The formation of Pangea. *Tectonophysics*, 593, 1–19.

Sun Y.D., Joachimski M.M., Wignall Ch Chunbo P.B., Haishui J., Lina W. & Xulo, L. (2012). Lethally hot temperatures during the Early Triassic greenhouse, *Science*, 338, 366–370

Svensen, H., Planke, S., Polozov, A.G., Schmidbauer, N., Corfu, F., Podladchikov, Y.Y. & Jamtveit, B. (2009). Siberian gas venting and the end-Permian environmental crisis. *Earth and Planetary Science Letters*, 277, 490–500.

Toricco, M. (1928). Il Cambriano del Sulcis (Sardegna). *Res. Ass. Min. Sarda*, 33, 10–29, Iglesias.

Tornquist, A. (1902). Die Gliederung und Fossiliferung der ausserlpinen Trias auf Sardinien. *Sitz. K. Preuss. Akad. Wiss.*, 38, 1098–1117, Berlin.

Van Der Eem, J.G.L.A., (1983). Aspects of middle and late triassic palynology. 6. Palynological investigations in the Ladinian and lower Karnian of the Western Dolomites, Italy. *Review of Palaeoecology and Palynology*, 39(3–4), 189–300.

Visscher, H. & Brugman, W.A (1981). Ranges of selected palynomorphs in the Alpine Triassic of Europe. *Review of Palaeobotany and Palynology*, 34, (1), 115–128.

Wignall, P.B (2007). The End-Permian mass extinction—How bad did it get? *Geobiology*, 5, 303–309.

Wood, G.D., Gabriel, A.M., & Lawson, J.C. (1996). Palynological techniques—processing and microscopy. In: Jansonius J. & Mcgregor D.C. (eds.) *Palynology: principles and applications*, American Association of Stratigraphic Palynologists Foundation, I, 29–50.

Ziegler, P.A. (1999). Evolution of the Artic-North Atlantic and the Western Tethys AAPG. *Bulletin*, 43, 164–196.

Ziegler, P.A. & Stampfli, G.M. (2001). Late Paleozoic-EarlyMesozoic plate boundary reorganization: collapse of the Variscan orogen and opening of NeoTethys Natura Bresciana. *Ann. Mus. Civ. Sc. Nat. Bresci*, 25, 17–34.