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Facies analysis and sedimentary environments

Interpreting siliciclastic sedimentation in the upper Paleozoic Mulargia-Escalaplano Basin (Sardinia, Italy): influence of tectonics on provenance

Luca G. Costamagna [a,*], *Sara Criniti* [b]

[a] *Dipartimento di Scienze Chimiche e Geologiche, Cittadella Universitaria, Blocco A, 09042 Monserrato CA, Italy*

[b] *Dipartimento di Ingegneria dell'Ambiente, Università della Calabria, 87036 Arcavacata di Rende CS, Italy*

Abstract Late to post-Variscan molassic basins of Late Pennsylvanian-Permian age are exposed in Sardinia (Italy). Here, the compositional and stratigraphic evolution of the Mulargia-Escalaplano sedimentary basin (central Sardinia) has been investigated to highlight how the tectono-magmatic processes have influenced the sedimentation. Ruditic and arenitic samples were collected along well-characterized stratigraphic sections to provide a new insight into the impact of the tectono-magmatic processes on siliciclastic sedimentation. As a result, the conglomerates are mainly clast-supported, petromictic, and thus immature, with no defined maturity trend upwards. Nevertheless, pebble composition changes in times from Variscan basement pebble-rich to volcanic rock-rich, as a consequence of the basin widening and the dismantling and reworking of the coeval volcanic activity. The sandstone composition clearly changes from quartzolithic to feldspatholithic upwards, as a response to the same change of feeding and reworking of the volcanic rocks. Occasionally, interbedded quartzolithic arenites suggest exceptional floods carrying debris from the far borders of the basin. Also, the immature sandstone composition has been interpreted as being controlled by a continuous supply of fresh debris and to a rapid burial rate. In addition, the disappearance of metaradiolarite (lydite AA) Paleozoic grains in the sandstone mineral suite could represent a distinctive marker of a progressive unroofing of the Variscan chain and a clastic supply from deeper tectonic units.

Keywords Petrography, Stratigraphy, Provenance, Molassic basins, Sardinia

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* Corresponding author. Department of Chemical and Geological Sciences of the Cagliari University, Italy.
E-mail addresses: lucakost@unica.it (L.G. Costamagna), sara.criniti@unical.it (S. Criniti).

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1. Introduction and geological framework

Recent papers (Costamagna, 2021, 2022) have examined the stratigraphic and sedimentological aspects of the molassic Mulargia-Escalaplano Basin in Central Sardinia (Fig. 1). This represents the molassic basin of the Southern Variscan realm where the stratigraphic record persists more continuously from the Late Pennsylvanian to the Triassic, showing the geometrical relationships between the different depositional cycles. Thus, it offers an excellent chance to investigate compositional evolution in times of a Variscan molassic basin.

The petrographic features of both conglomerates and arenites of the Mulargia-Escalaplano late to post-Variscan molassic basin have been investigated here. Several stratigraphic sections have been sampled (Costamagna, 2022) to define the 2D basin model (Fig. 2) while the general stratigraphic succession, deriving from the interpolation of several stratigraphic columns of the Mulargia (Figs. 3 and 4) and Escalaplano (Figs. 5 and 6) sub-basins (Costamagna, 2022), is provided. This paper aimed to investigate the gradual evolution of the feeding in times and consequently to infer both the basin evolution and the progressive exhumation of lower basement portions.

Fig. 1 Synthetic map of the principal Upper Paleozoic molassic cover above the Variscan basement and localization (red stars) of the several post-Variscan molassic basins in Sardinia: the studied Mulargia-Escalaplano Basin is yellow highlighted (from Costamagna, 2022, modified).

After the Variscan orogenesis (Carmignani *et al.*, 1994), from the Late Pennsylvanian to the Permian, Sardinia experienced continental sedimentation that took place in scattered basins and developed along major tectonic discontinuities (Carmignani *et al.*, 2001; Elter *et al.*, 2020): those were hypothesized to be Variscan thrusts reactivated as transcurrent lines (Ziegler and Stampfli, 2001). These basins are related to the fragmentation of the Variscan chain (Barca *et al.*, 1995; Carmignani *et al.*, 2001) and have been studied for stratigraphic, sedimentological, and palaeontological aspects (Cassinis *et al.*, 2000; Ronchi et al., 2008, 2014; Costamagna, 2019, 2021, 2022).

In Sardinia, late to post-Variscan successions are discontinuous and do not allow the petrographical investigations to cover all the molassic basin lifespan in space and time (Cassinis *et al.*, 2000; Costamagna, 2019). Some attempts in the Nurra area (NW Sardinia, Fig. 1) were carried out by Cassinis *et al.* (1996) and by Costamagna (2011). However, Upper Pennsylvanian-Permian-Middle Triassic successions in the Nurra area are fragmentary and problematic to be entirely reconstructed, owing to the difficulty in correlating stratigraphic segments with scarce fossil content and also with tectonic controversy (Barca and Costamagna, 1997).

The Mulargia-Escalaplano Variscan molassic basin crops out in central Sardinia (Barca *et al.*, 1995; Cassinis *et al.*, 2000; Barca and Costamagna, 2005; Costamagna, 2022). It is referred to the Late Pennsylvanian-Permian age (Pittau *et al.*, 2008). At its base, lies the blackish limnic Rio Su Luda Formation (Ronchi and Falorni, 2004) of the Lower Rotliegend Group, followed (unconformably?) by the upper red-bed volcano-sedimentary succession made of the Mulargia Formation, the Sa Fossada Rhyolites Unit, the Pegulari Formation, and the Mataracui Andesites Unit, forming the Upper Rotliegend Group (Costamagna, 2021, 2022) (Fig. 2).

The whole sedimentary basin consists of two adjacent sectors separated by a Variscan basement

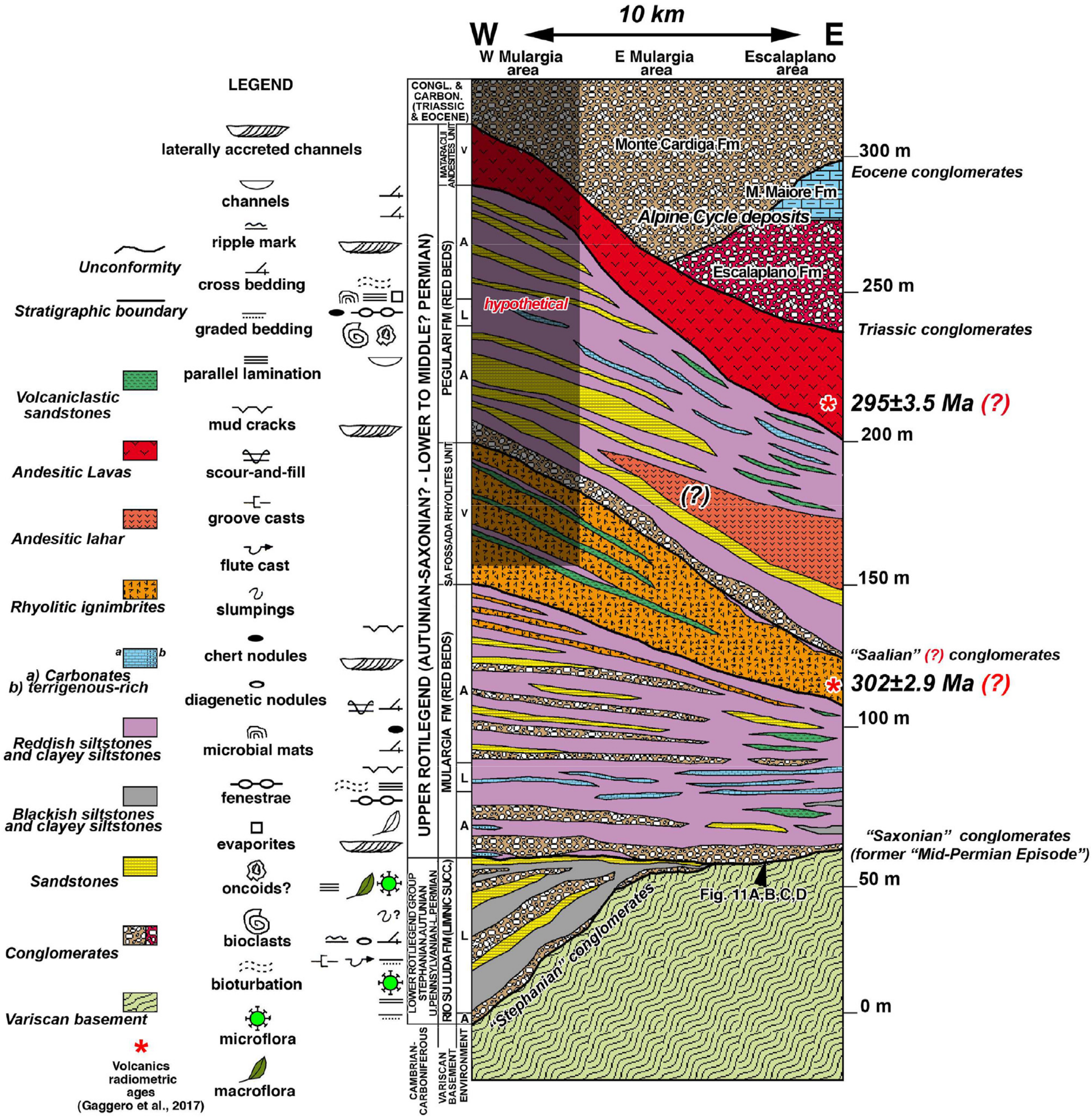

Fig. 2 A 2D - model of the Mulargia-Escalaplano Basin (modified from Costamagna, 2022) showing the NW—SE stratigraphic evolution. **A:** Alluvial environment; **L:** Lacustrine-palustrine(?) environment; **V:** Volcanic rocks. Radiometric data after Gaggero *et al.* (2017).

rocks-made structural high risen during the Cenozoic tectonic extension (Funedda *et al.*, 2008): the discontinuous Mulargia sector to the NW (Figs. 3 and 4) and the Escalaplano sector to the SE (Figs. 5 and 6).

The Mulargia and Escalaplano sectors of the studied basin were initially considered distinctive subsiding areas, although the close stratigraphic and sedimentological relationship of the Mulargia and Escalaplano Upper Paleozoic successions was known for a long time (Pecorini, 1974; Cassinis *et al.*, 2000). This relationship had suggested to consider them as a single depositional alluvial to lacustrine basin with significant differences in the depositional facies related to SE-ward decreasing energy environments. Costamagna (2021, 2022) have defined the evolution of the depositional environment in

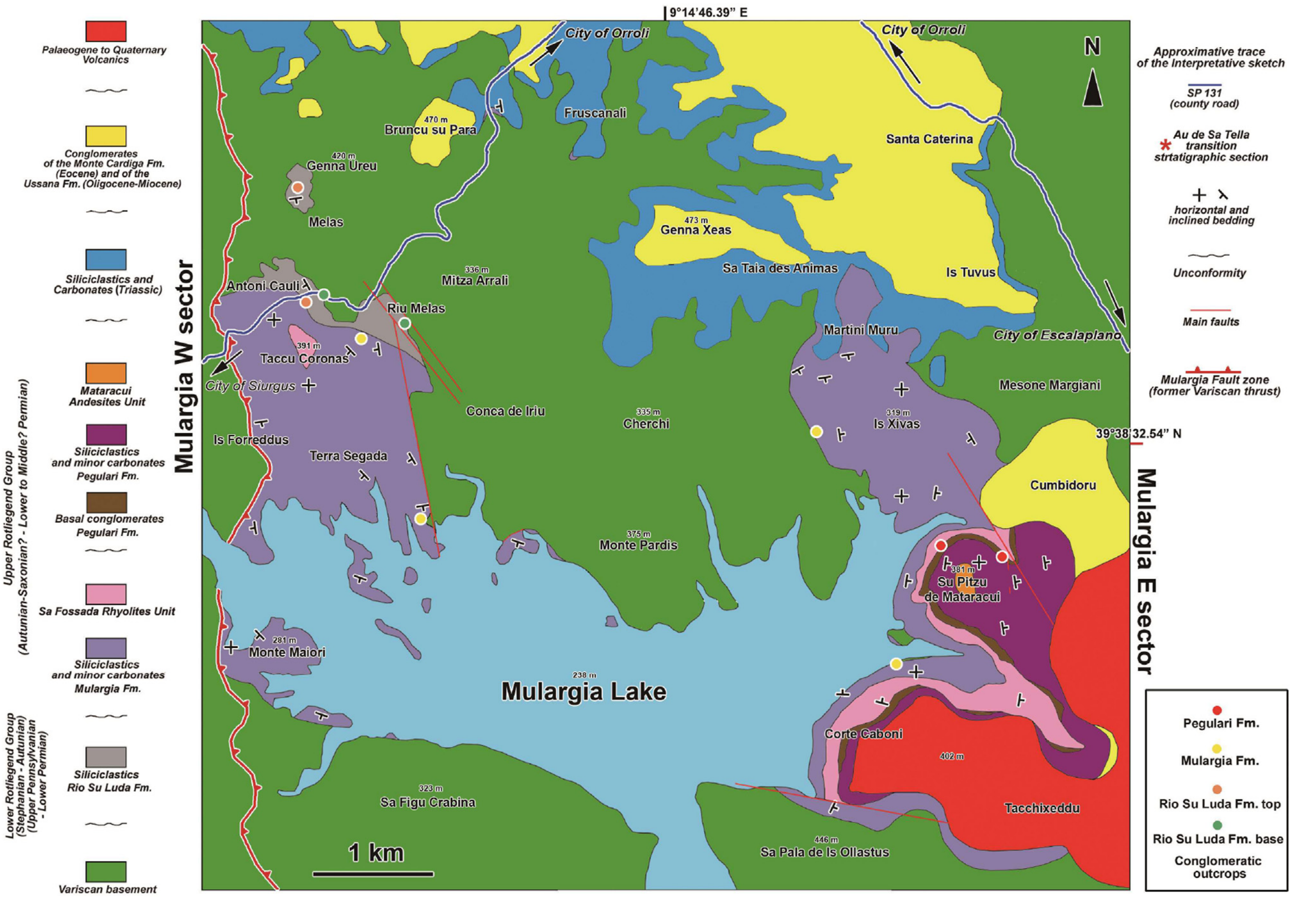

Fig. 3 Geological map of the Mulargia area with location of the analyzed conglomerate outcrops (modified from Costamagna, 2022).

time and space and the strong tectonic control on it, suggesting a pull-apart model evolving to extension. Barca *et al.* (1995) have evidenced a progressive unroofing during the collapse of the Variscan Chain based on the compositional variation of pebbles along the stratigraphic units. Moreover, this increasing tectonic extension during the basin opening is also testified by the high diagenetic grade of the clayey siltstones and the organic matter of the Rio Su Luda Formation (Barca *et al.*, 1995). In particular, these authors related the increased thermal gradient connected to the crustal thinning during the main Permian extensional event. The Lower Rotliegend Group sedimentary cycle and Upper Rotliegend Group subcycles show a SE-oriented compositional, textural, and grain-size fining directional trend. This SE flow direction is supported also by sedimentary structures, such as flute-, groove, and tool casts, cross-bedding, imbrications, and channel directions (Costamagna, 2021, 2022). The fluvial style evolves southeastward from braided towards sinuous channel patterns.

The Upper Paleozoic succession is unconformably sealed by Triassic (Escalaplano Formation, Costamagna *et al.*, 2000) or Eocene (Monte Cardiga Formation, Pertusati *et al.*, 2002) deposits.

2. Methods

Sedimentologic and petrographic investigations have been undertaken in field outcrops of the Mulargia-Escalaplano Basin. Attention has been devoted to reconstructing the vertical and lateral evolution of the lithofacies in different sectors. Given the volumetric importance of the conglomerate deposits in the basin succession and their meaning in the paleoenvironmental reconstructions (Pettijohn, 1975; Lindholm, 1987; Boggs, 2009), several conglomerate outcrops have been analyzed (Figs. 3–7). The conglomerate texture and composition of each stratigraphic unit have been qualitatively evaluated directly in the field through the analysis of the three best-exposed bed surfaces by using visual comparators (Folk, 1980; Folk *et al.*,

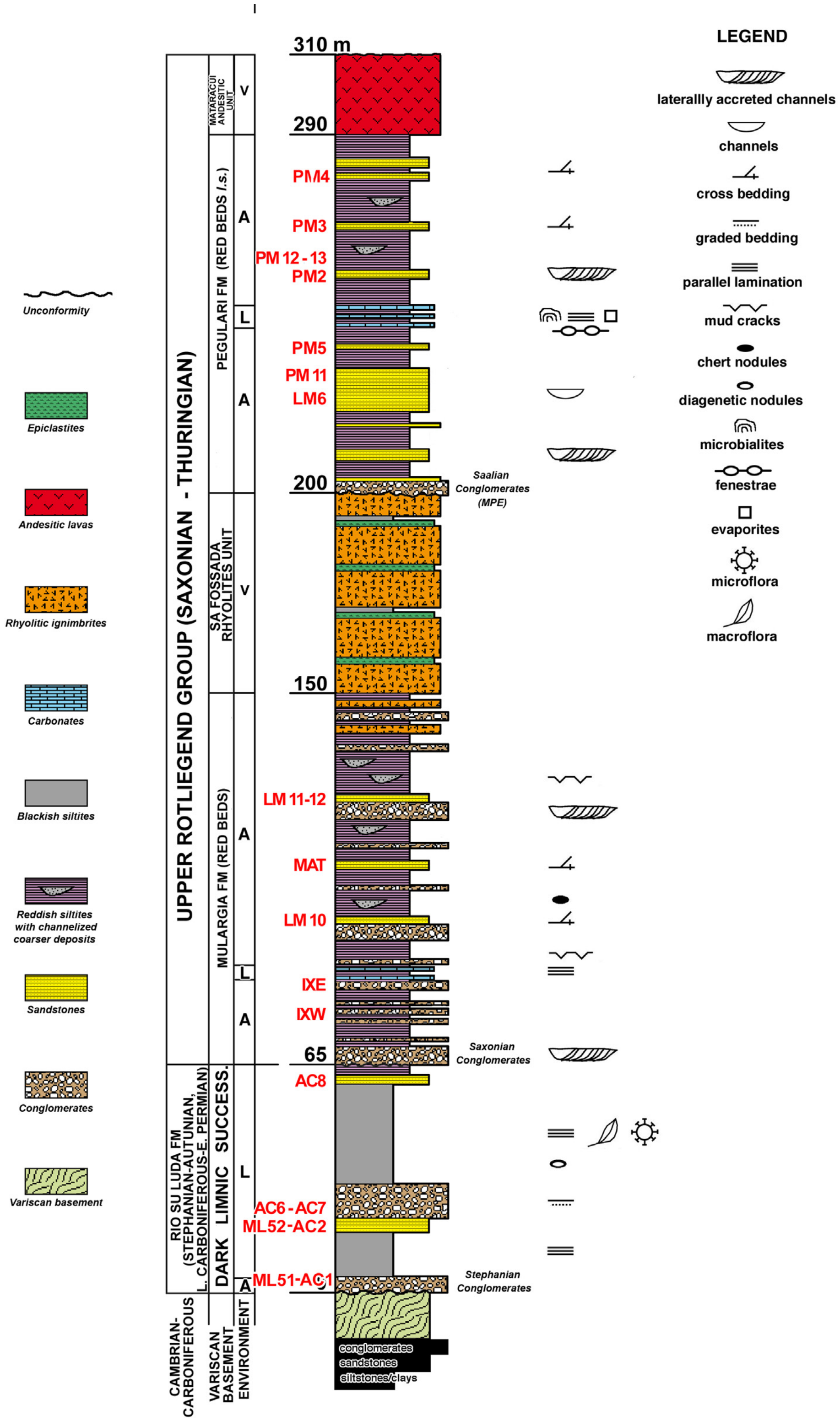

Fig. 4 General stratigraphic column of the Mulargia sector with location of the studied sandstone samples (red label). **A:** Alluvial environment; **L:** Lacustrine-palustrine environment?; **V:** Volcanic rocks. (modified from Costamagna, 2019).

1970; Swanson, 1981; Jerram, 2001) and the half-meter-size square method (Tucker, 2014) with a square side enlarged to 60 × 50 cm.

Only pebbles with more than 3 cm in diameter (for ease of recognition) were divided into two main categories, ultrastable and meta/unstable (e.g., Boggs,

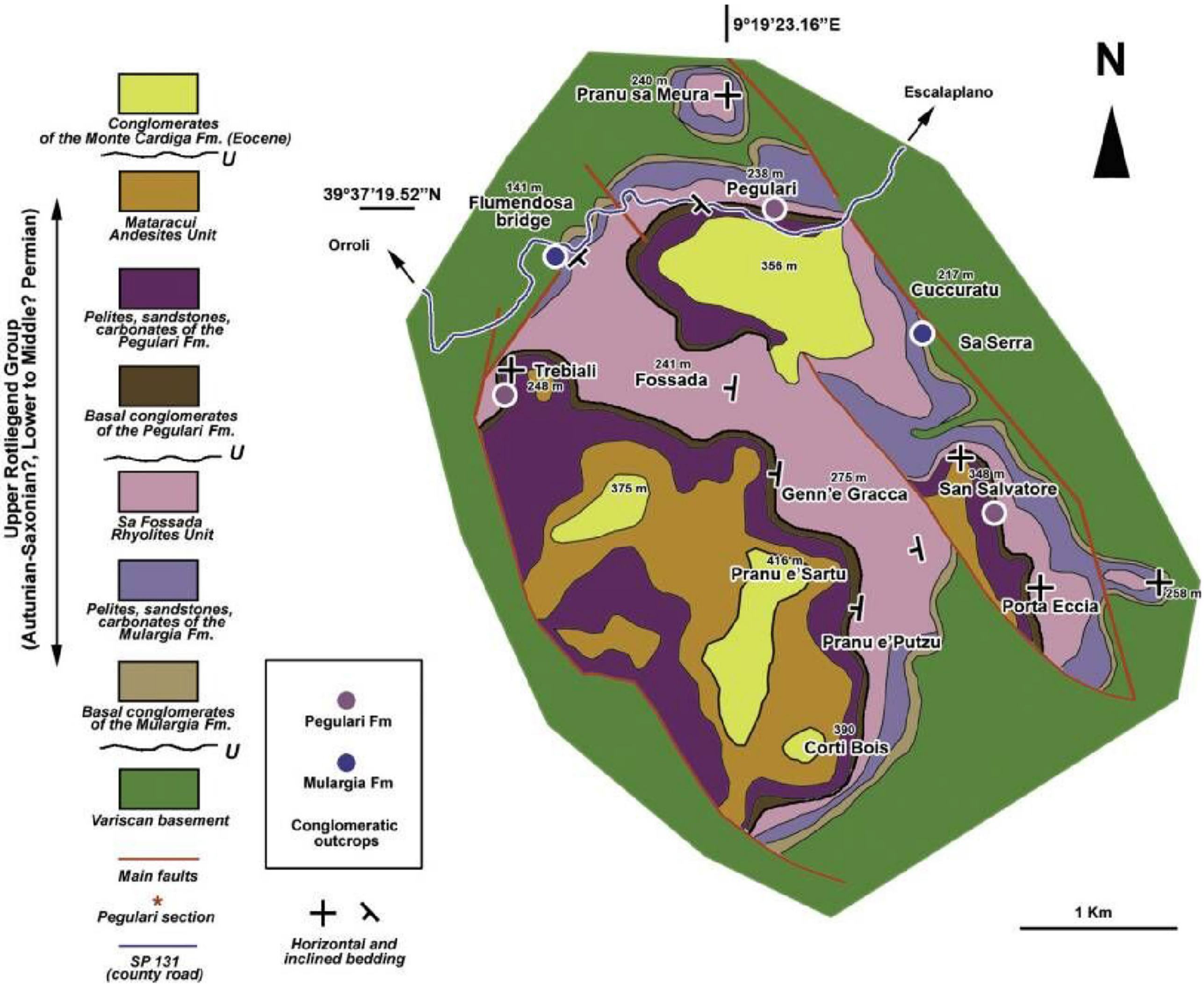

Fig. 5 Geological map of the Escalaplano area with location of the analyzed conglomerate outcrops (modified from Costamagna, 2022).

2009). Thus, quartz (ultrastable pebbles) has been separated from low-grade metamorphic rock pebbles, sedimentary, and volcanic (andesitic and rhyolitic) rock pebbles (meta/unstable pebbles). The main lithologies were identified, and their percentage was plotted in tables and schemes (Table 1).

Petrographic modal analysis was carried out using a Zeiss polarizing microscope on 22 medium-sized sandstone samples (6 thin-sectioned samples for Rio Su Luda Fm., 7 for Mulargia Fm. and 9 for Pegulari Fm.). A mean of 500 points was point-counted, according to the Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970; Ingersoll *et al.*, 1984; Zuffa, 1985). Sandstone detrital modes were defined according to Ingersoll and Suczek (1979), Critelli and Ingersoll (1995), Critelli and Criniti (2021), and Critelli *et al.* (2023), and modal percentages of each formation were expressed as a mean value (Table 2).

3. Results

3.1. *Sedimentation and composition of conglomeratic successions*

The Rio Su Luda Formation of the Lower Rotliegend Group, is at least 60 m thick and crops out only in the northern area of the NW Mulargia sector (Figs. 3 and 4). The unit thins out rapidly southeastwards until it disappears entirely in the Escalaplano area (Figs. 2, 5 and 6).

It is formed by dark-grey to greenish siliciclastic, conglomeratic to silty-clayey deposits, initially showing a gradually fining-upward trend, turning rapidly to a gradually coarsening-upward one. The finest silty-clayey intermediate deposits are thinly laminated and contain scattered sandstone cm-thick

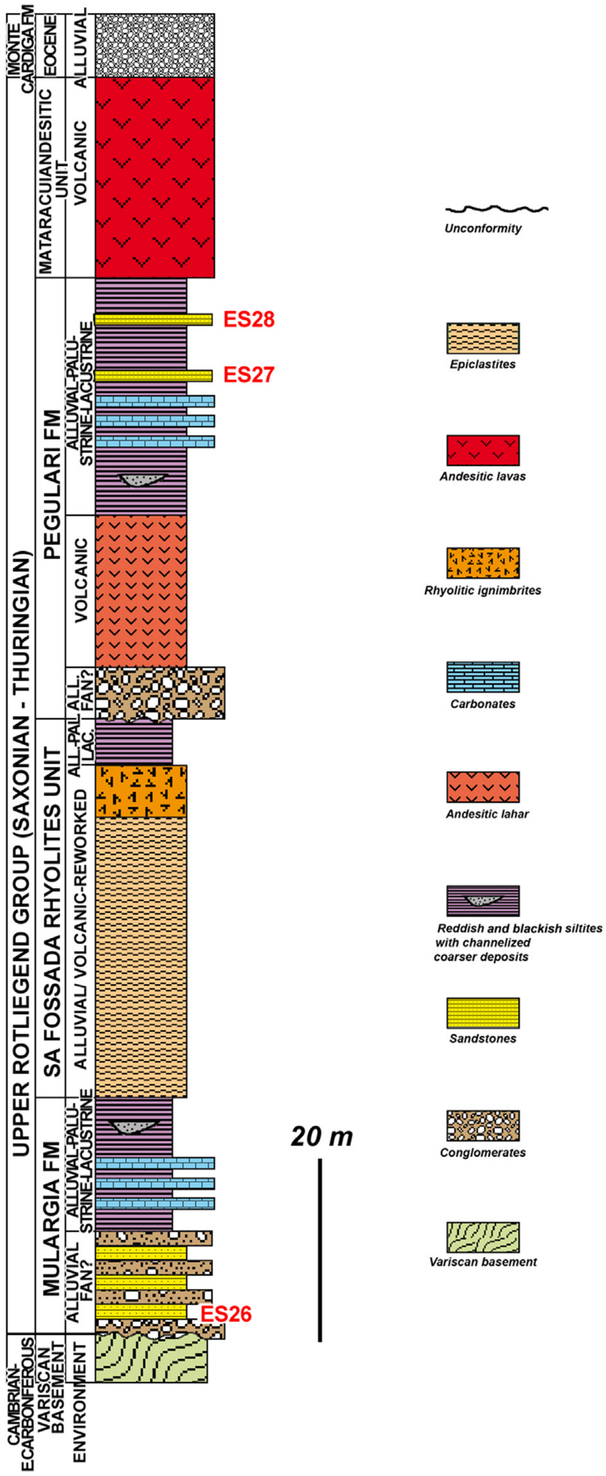

Fig. 6 General stratigraphic column of the Escalaplano sector with location of the studied sandstone samples (red label).

graded beds. They are rich in plant remains supporting a Stephanian age (Pittau *et al.*, 2008) (the "Autuniano sardo" of Ronchi *et al.*, 2008). The top of the unit is featured by meter-thick coarser depositional events with waning-waxing structures and is referable to subaqueous debris flows (Costamagna, 2021, 2022; cf. Nemec and Steel, 1984). The depositional environment of the Rio Su Luda Formation can be referred to as a tectonically active narrow alluvial to palustrine(?)-lacustrine pull-apart basin subject to variable energy in times (Costamagna, 2019, 2021, 2022) under a wet climate (Pittau *et al.*, 2008).

Conglomerates (Table 1) are diffuse at the bottom and the top of the Rio Su Luda Formation, but their textural and compositional features differ according to the stratigraphic position. In the lower part, the conglomerate pebbles are up to 15 cm in diameter but 1—2 cm on average (Fig. 7A). They are subangular to angular in shape and poorly-to well-sorted in texture. The composition is almost totally referred to Variscan basement metamorphic pebbles and cobbles (VB) from different rocks outcropping in the vicinity: Ordovician metasandstones, Silurian black schists, Devonian quartzites, and carbonates (surveys in Funedda *et al.*, 2008). In some beds, the Silurian schist fragments (the only black schists outcropping) become almost exclusive. The quartz pebbles (Qz) are rare and usually angular in shape. Their estimated percentage rate through the half-meter-size square method (Tucker, 2014) is 4 (Qz)/96(VB). In the upper part of the unit, the conglomerate pebbles are up to 20 cm thick, but 3—4 cm on average (Fig. 7B). They are subangular to rounded in shape but the subrounded shape prevails, while the sorting is from moderate to poor degree. Ordovician metasandstones and felsitic metavolcanic rocks dominate (VB), while the quartz (Qz), usually angular in shape, is rare with an estimated percentage of 5(Qz)/95(VB).

The upper and coarsest deposits of the Rio Su Luda Formation (Lower Rotliegend Group) are followed by the Upper Rotliegend Group with an erosive but gradual contact (Fig. 2). The transition occurs with a slow colour change from blackish to greenish until it alternates with reddish matrix. In the end, the green colour disappears completely: the Upper Rotliegend Group basal conglomerates exclusively display red matrix, clearly marking the passage to the upper Mulargia Formation of the Upper Rotliegend Group. The changing colour of the whole rock is due to a reddish matrix and a superficial reddening of the pebbles, instead of pebble composition variation. Everywhere, except in the northern area of the NW Mulargia sector, the Upper Rotliegend Group rests unconformably over the Variscan metamorphic basement. The Upper Rotliegend Group can be subdivided into two fining-upward subcycles, each topped by high-K sub-alkaline affinity volcanic deposits (Cassinis *et al.*, 2000). They are separated by a weak

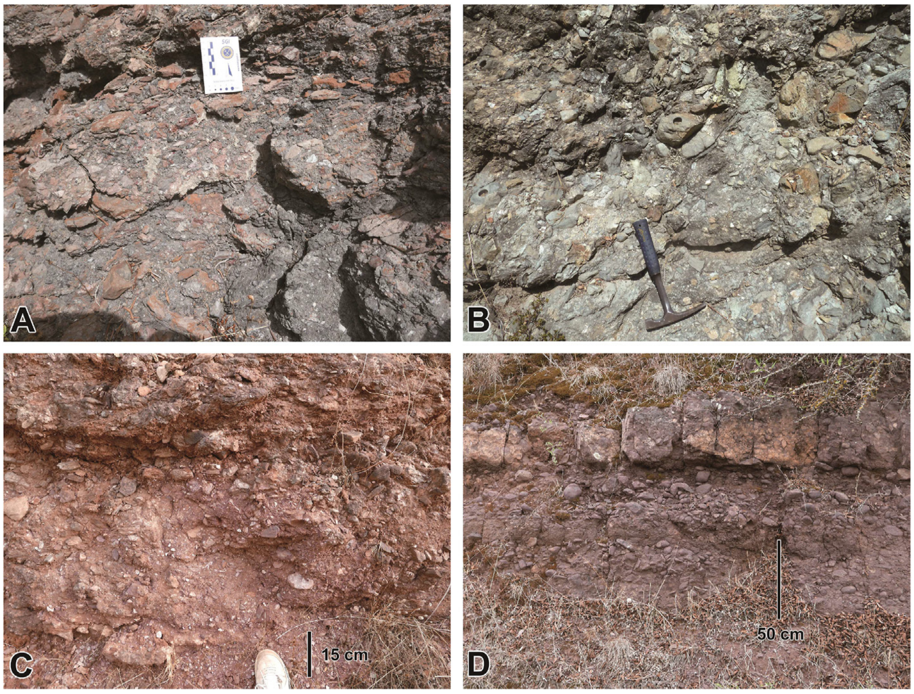

Fig. 7 Conglomerate outcrops: **A)** Rio Su Luda Fm. base, Antoni Cauli locality, Mulargia sector (scalemeter side 8 cm); **B)** Rio Su Luda Fm. top, Antoni Cauli locality, Mulargia sector (hammer length 30 cm); **C)** Mulargia Fm. base, Antoni Cauli locality, Mulargia sector (shoe part 15 cm); **D)** Pegulari Fm. base, San Salvatore locality, Escalaplano sector (scale 50 cm).

unconformity marked by a rhyolitic volcanic-rock-rich conglomerate level of variable thickness.

This group starts with the Mulargia Formation (Table 1), a red-bed siliciclastic deposit with scattered carbonate beds. Its thickness thins southeastward, reaching a maximum of 150 m in the western Mulargia sector. The grain size varies from conglomeratic to silty-clayey but shows a fining-upward trend. Moreover, imbrication in conglomerates is frequent while cross-lamination is well visible in sandy beds. The Mulargia Formation thins out eastward with compositional and textural features variable from the west (Mulargia sector) to the east (Escalaplano sector). In fact, the conglomerates are particularly abundant in the Mulargia sector, as the maximum pebble size is from 25 (W) to 12 (E) cm, and the average diameter is 2—3 to 3—4 cm (Fig. 7C). The pebbles are usually subangular to angular in shape, while the sorting is usually from poor to moderate degree. At its base, the Mulargia Formation conglomerates show Variscan basement metamorphic pebbles (VB), but also rare cobbles, pebbles, and grains from the lower Rio Su Luda Formation (CS) and very rare undeformed quartzrudites cobbles (QP), unknown in outcrop, both rapidly vanish eastwards. Angular pebbles from the quartz vein (Qz) are quite represented as their percentage is 2(Qz)/1(CS)/1(QP)/96(VB) in the Mulargia sector, and 4(Qz)/2(CS)/94(VB) in the Escalaplano sector.

The volcano-sedimentary Sa Fossada Rhyolites Unit gradually follows the Mulargia Formation. Radiometric dating was reported for this unit giving an age of 302 ± 2.9 Ma (Gaggero *et al.*, 2017). This volcano-sedimentary unit is covered unconformably by about 80 m-thick red bed of Pegulari Formation (Table 1) with a conglomerate level of extremely variable thickness at the base (12—1.5 m) (Fig. 7D). Siltstones and clayey siltstones follow it with rare carbonate beds with very scarce laminations. Besides the basal conglomerate, coarse beds (conglomerates and sandstones) are rare in this unit. The pebbles vary from up to 12 (west) to 15 (east) cm in size, with mean value of 4—5 cm. Their shape spans from subangular (west) to rounded (east), but subrounded pebbles are frequent, while sorting varies from moderately well-sorted to well-sorted. In the Pegulari Formation, volcanic pebbles appear since the conglomerate basal level is a volcanic rock-rich level (PV). Here, the Variscan basement metamorphic pebbles (VB) are subordinate while sandstone and siltstone pebbles from the lower Mulargia Formation (PS) are well-represented. The percentage of volcanic pebbles in the Escalaplano sector is higher than the Mulargia sector, respectively 6(Qz)/54(PV)/11(PS)/29(VB) and 4(Qz)/46(PV)/15(PS)/35(VB).

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Table 1 Conglomerates sedimentological features in the late Pennsylvanian-Permian Mulargia-Escalaplano Basin (Sardinia).

	Conglomerates: Formation and measurement localities	Grain size	Composition (%)	Sorting	Grain shape	W/T channel ratio	Coarse beds average thickness
Upper Rotliegend Group	Pegulari base (Escalaplano area) Pegulari, Trebiali, San Salvatore	Max: 15 cm Mean: 5 cm	*Meta/unstable:* Volcanic rocks (54), Metamorphic rocks (29), Red bed sdst & sltst (11) *Ultrastable:* Quartz (6)	Moderately well-sorted to well- sorted	Rounded to subrounded	>5?	<0.5 m
	Pegulari base (Mulargia area) Pitzu De Mataracui	Max: 12 cm Mean: 4 cm	*Meta/unstable:* Volcanic rocks (46), Metamorphic rocks (35), Red bed sdst & sltst (15) *Ultrastable* Quartz (4)	Moderately well-sorted to well- sorted	Subrounded to subangular	5<x < 10	<0.5 m
	Mulargia base (Escalaplano area) Flumendosa bridge, Cuccuratu	Max: 12 cm Mean: 2–3 cm	*Meta/unstable:* Metamorphic rocks (94), Pennsylv-Perm sandstones (2) *Ultrastable:* Quartz (4)	Moderately to poorly sorted (rarely well-sorted)	Subangular to angular	>5	0.5 m
	Mulargia base (Mulargia area) Taccu Coronas, Terra Segada, Is Xivas, Corte Caboni	Max: 25 cm Mean: 3–4 cm	*Meta/unstable:* Metamorphic rocks (96), Pennsylv-Perm sandstones (1) and quartzrudites (1) *Ultrastable:* Quartz (2)	Poorly to moderately sorted	Subangular to angular	>10	2 m
Lower Rotliegend Group	Rio Su Luda top Antoni Cauli, Genna Ureu	Max: 20 cm Mean: 3–4 cm	*Meta/unstable:* Metamorphic rocks (95) *Ultrastable:* Quartz (5)	Moderately to poorly sorted	Subangular to rounded	>10	1.5–2 m
	Rio Su Luda base Antoni Cauli, Riu Melas	Max: 15 cm Mean: 1–2 cm	*Meta/unstable*: Metamorphic rocks (96) *Ultrastable*: Quartz (4)	Moderately sorted to well-sorted	Subangular to angular	?	<0.2 m

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Table 2 Recalculated modal point count data for the studied sandstone.

	Formation	Sample	%			%			%		
			Qm	F	Lt	Qp	Lvm	Lsm	Lm	Lv	Ls
Upper Rotliegend Group	Pelugari Formtion	PM4	10.0	3.6	86.4	0.0	5.2	94.8	94.6	5.2	0.3
		PM3	6.5	33.3	60.1	0.0	96.7	3.3	3.4	96.6	0.0
		ES28	1.3	41.6	57.1	0.4	96.3	3.4	2.3	96.6	1.1
		ES27	2.8	3.7	93.5	0.0	85.0	15.0	12.0	85.0	3.0
		PM12-13	22.2	4.7	73.1	1.9	0.5	97.6	98.3	0.5	1.2
		PM2	1.3	32.8	65.9	0.0	98.5	1.5	1.5	98.5	0.0
		PM5	14.6	19.1	66.3	0.3	47.1	52.6	57.3	39.0	3.7
		PM11	8.8	41.2	50.0	2.7	60.7	36.6	39.7	60.3	0.0
		LM6	10.8	32.5	56.6	0.0	75.0	25.0	27.9	71.5	0.6
		$\bar{x}$	**8.7**	**23.6**	**67.7**	**0.6**	**62.8**	**36.6**	**37.4**	**61.5**	**1.1**
		σ	***6.8***	***16.1***	***14.4***	***1.0***	***38.2***	***37.8***	***38.4***	***38.6***	***1.4***
	Mulargia Formation	LM12	20.1	2.0	77.9	0.0	35.6	64.4	67.3	29.5	3.2
		LM11	10.8	0.5	88.7	0.0	40.1	59.9	52.1	38.5	9.3
		MAT	26.1	17.8	56.1	0.0	24.4	75.6	75.3	24.4	0.4
		ES26	9.1	2.6	88.4	4.5	33.9	61.6	54.6	35.1	10.2
		LM10	15.1	4.2	80.7	1.6	0.0	98.4	90.3	0.0	9.7
		IXE	12.9	0.2	86.9	0.9	0.7	98.4	88.7	0.7	10.6
		IXW	14.2	0.0	85.8	0.9	0.0	99.1	90.7	0.0	9.3
		$\bar{x}$	**15.5**	**3.9**	**80.6**	**1.1**	**19.2**	**79.6**	**74.1**	**18.3**	**7.5**
		σ	***5.9***	***6.3***	***11.5***	***1.6***	***18.4***	***18.5***	***16.6***	***17.5***	***4.0***
Lower Rotliegend Group	Rio Su Luda Formation	AC8	15.7	1.5	82.8	5.2	7.7	87.1	90.6	8.1	1.3
		AC6-7	9.5	1.0	89.5	0.3	11.9	87.8	73.8	12.0	14.2
		AC2	28.5	2.6	68.9	2.0	0.3	97.7	97.3	0.3	2.4
		ML52	6.2	1.1	92.7	1.4	5.2	93.4	86.9	4.9	8.1
		AC1	26.5	0.0	73.5	14.3	0.0	85.7	100.0	0.0	0.0
		ML51	29.7	0.2	70.1	3.2	1.1	95.7	86.1	1.1	12.7
		$\bar{x}$	**19.3**	**1.1**	**79.6**	**4.4**	**4.4**	**91.2**	**89.1**	**4.4**	**6.5**
		σ	***10.2***	***0.9***	***10.2***	***5.1***	***4.8***	***5.0***	***9.3***	***4.9***	***6.1***

Bold represents the average of the above-listed samples.
Italic represents the standard deviation from the above average.

This unit is topped by the volcanic Mataracui Andesites Unit, aged 295 ± 2.9 Ma (Gaggero *et al.*, 2017), which seals the Variscan molassic basin succession.

3.2. Sandstone petrology

Upper Pennsylvanian — Lower Permian Sardinian sandstones were studied in Mulargia-Escalaplano Basin, within the Rio Su Luda Formation (Stephanian-Autunian), the Mulargia Formation and the Pegulari Formation (Saxonian-Thuringian). The principal recalculated parameters are displayed in Table 2.

Both basins have similar compositional trends along the whole considered succession and have quartzolithic and feldspatholithic sandstone petrofacies (Fig. 8).

The meaningful variation is appreciated by considering the vertical variation of lithic content (Fig. 9). Indeed, the most evident inflection is highlighted by an up-decrease in metamorphic lithic fragments, starting with the Mulargia Formation. At the same time, volcanic lithic grains, of rhyolitic to andesitic source, abruptly increase upward. In particular, within the Mulargia-Escalaplano Basin, the sandstone of the Rio Su Luda Formation occurs exclusively in the Mulargia sector and always keeps quartzolithic composition with consistent low-grade metamorphic lithic fragments input. Similarly, in both sectors, the sandstone of the Mulargia Formation still has a quartzolithic composition, but lithic fragment content varies. Volcanic input increases abruptly in the upper portions of the Pegulari Formation, moving sandstone composition to feldspatholithic interbedded with minor quartzolithic sandstone strata within the middle part of Pegulari Formation.

3.2.1. Quartzolithic petrofacies

Quartzolithic compositions are typical petrofacies in sandstone of the Rio Su Luda Fm. (mean recalculation values $Qm_{19}F_1Lt_{80}$ — $Qp_4Lvm_4Lsm_{92}$ — $Lm_{89}Lv_4Ls_7$) and sporadically in the middle Pegulari

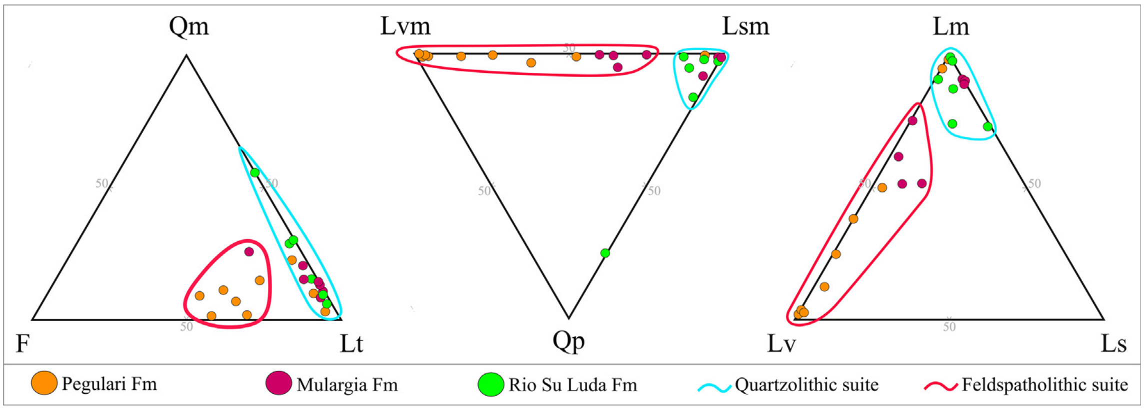

Fig. 8 Composition of studied sandstone within Mulargia-Escalaplano Basin. Each triangular plot highlights two different petrofacies as the composition shifts from quartzolithic to feldspatholithic (Qm-F-Lt plot) upward the succession. Lithic content and type (Qp-Lvm-Lvs and Lm-Lv-Ls plot) varies from low-grade metamorphic (black metasediments, slates, and phyllites) to volcanic (rhyolitic and andesitic composition) upward.

Formation. The composition of Rio Su Luda Fm. sandstone (Fig. 9A) includes dominant low-grade metamorphic lithic fragments such as meta-radiolarites (lydites AA, Cf. Randon and Caridroit, 2008), phyllite, quartzite, and slate. Sedimentary lithic fragments are minor and decrease upward along the succession with extrabasinal carbonates, rare fossils, intraclasts, and oxide-Fe concretions. Volcanic lithic fragments gradually appear upward with microlitic texture. In addition, plagioclases are rare and heavy minerals are mostly zircon, tourmaline, and rutile. The interstitial component is made up of phyllosilicate cement, followed by Fe-oxide, carbonate, and siliceous cement; quartz, and albite overgrowths are also present, and the matrix is always siliciclastic.

Sandstones of the Mulargia Formation are quartzolithic (mean recalculation values $Qm_{15}F_4Lt_{81}$ — $Qp_1Lvm_{19}Lsm_{80}$ — $Lm_{74}Lv_{18}Ls_8$) with abundant low-grade metamorphic lithic fragments such as phyllite and minor slate (Fig. 9B). Plagioclase and quartz are minor while volcanic lithic fragments occur with

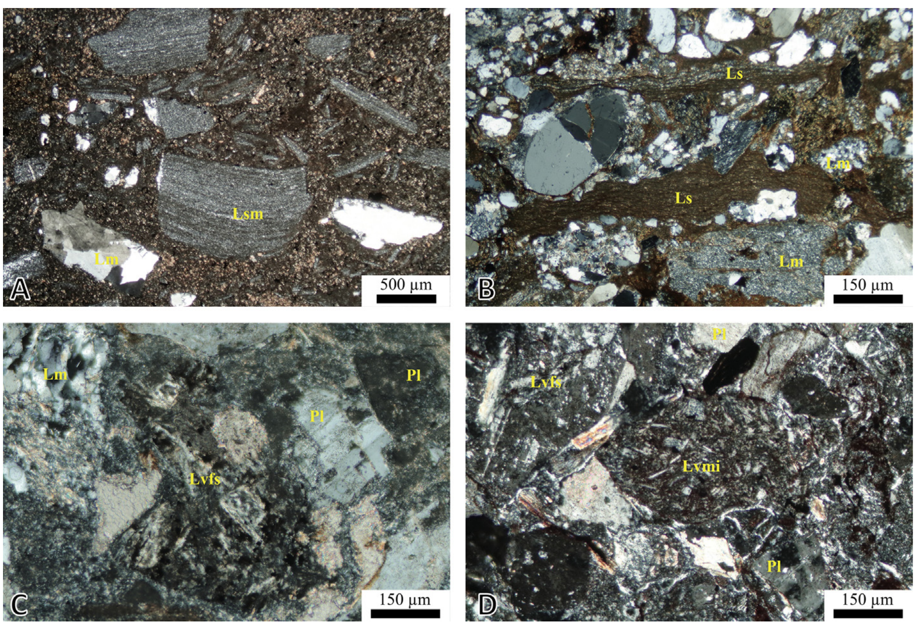

Fig. 9 Petrography of studied sandstone within Mulargia-Escalaplano Basin. **A)** Rio Su Luda Fm. sandstone (quartzolithic) with black metasediments (Lsm), slates and phyllites (Lm); **B), C)** Mulargia Fm. sandstone (quartzolithic) with volcanoclastic grains (Lvfs), slates, and phyllites (Lm); **D)** Pegulari Fm. sandstone (feldspatholithic) with rhyolitic and andesitic lithic grains. Lm: Metamorphic lithic grain; Lsm: Black schist; Ls: Sedimentary lithic grain; Lvfs: Volcanic lithic grain with seriate felsitic texture; Lvmi: Volcanic lithic grain with microlitic texture; Pl: Plagioclase.

microlitic and felsitic seriate textures (Fig. 9C). Sedimentary grains are minor and consist of shale and less impure chert. Intergranular space is filled by phyllosilicate and Fe-oxide cement. Other types of cement, such as carbonate and siliceous, are scarce; besides, rare albite and quartz overgrowth are also found. Minor content of siliciclastic matrix persists along the entire succession.

3.2.2. *Feldspatholithic petrofacies*

Sandstones of the Pegulari Formation have a feldspatholithic composition (mean recalculation values $Qm_8F_{24}Lt_{68}$—$Qp_0Lvm_{63}Lsm_{37}$—$Lm_{37}Lv_{62}Ls_1$) that dominates both sectors of the basin. Volcanic lithic fragments represent the primary input of detritus with microlitic and felsitic granular textures (Fig. 9D). Subordinate low-grade metamorphic lithic fragments of phyllite and slate persist and start to become more abundant at the top of the succession, being characterized by quartzolithic composition (samples PM12—13, PM4). Sedimentary lithic fragments are fewer, with evidence of siliciclastic and carbonate grains. The feldspar input is dominated by plagioclase in volcanic lithic fragments. Phyllosilicate cement is the most represented, followed by siliceous and ferruginous cement. Rarely, carbonate cement, siliciclastic matrix, and clay coatings appear. In the Mulargia sector, two samples show a quartzolithic composition interbedded within feldspatholithic sandstones. In both samples, lithic content is mostly related to an input from low-grade metamorphic rocks (phyllite, slate), while sedimentary lithics are subordinate. Quartz occurs as crystals in metamorphic grains and plagioclase is present in volcanic lithic grains with microlitic texture. Phyllosilicate cements decrease upward instead of carbonatic and Fe-oxide cements, and siliciclastic matrix is rare.

4. Discussion

The distinction of ultrastable and meta/unstable pebbles (Fig. 10) within conglomerates allowed us to emphasize the role of the climatic and mechanic wearing in time and space and has some essential genetic significance in the basin and environmental interpretations. The conglomerates of the Rio Su Luda Formation and the Mulargia Formation are pebble-rich basement with scarce angular quartz. They differ in colour, from grey-green to red. Conversely, the conglomerates of the upper Pegulari Formation are volcanic rock-rich, while the basement pebbles are scarce, and the quartz is almost absent. Compositional and sedimentological differences within the Mulargia Formation and Pegulari Formation (Upper Rotliegend

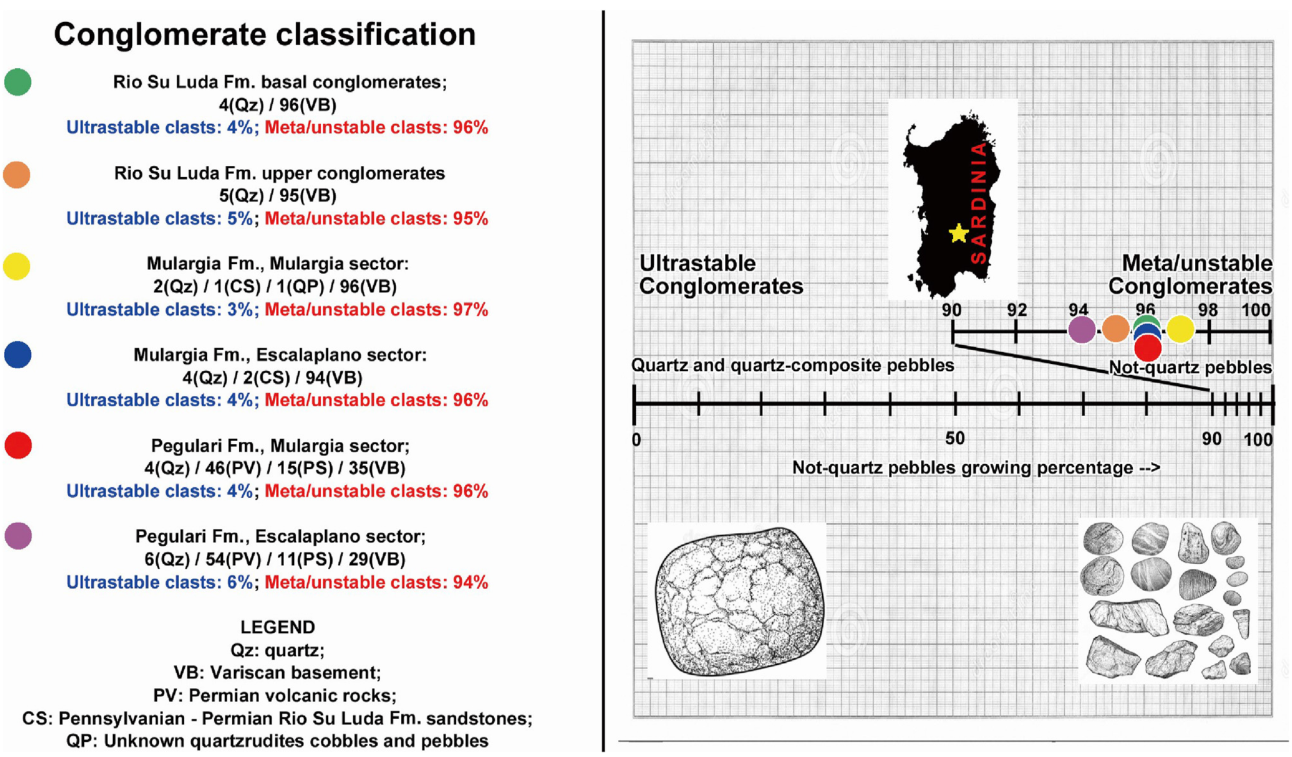

Fig. 10 Plot of the conglomerate compositional data based on relative clast stability and durability.

Group), are also visible in both Mulargia and Escalaplano sectors (Table 1). This further supports a growing distance in times from the Variscan basement-made borders of the basin, and then a progressive eastward widening.

The Rio Su Luda Formation of the Lower Rotliegend Group was deposited in a narrow alluvial to lacustrine basin characterized by a limited circulation under a warm-humid climate. The limited thickness of the basal conglomerates and their small grain size suggests limited topographic differences, at least initially. Hints of increased tectonic activity in times are from the renewed and amplified conglomerates abundance and grain-size growth in the upper part of the unit. The clast composition shows an immature deposit fed from a young, articulated morphology of the source terrains.

The depositional environment of the Upper Rotliegend Group can be referred to a broader alluvial to playa-lake basin showing evolving lower-energy fluvial styles in space and time, and thus subject to variable energy under a dry climate (Costamagna, 2022). The conglomerate abundance marks significant height differences, especially in the Mulargia sector. The evolution of the red bed basin was marked by a tectonomagmatic climax rejuvenating the surrounding landscape, triggering a cyclical abundance of conglomerate events: this is also suggested by their compositional evolution and the presence of volcanic pebbles related to the neo-volcanic input.

The coarsest and finest deposits of the Rio Su Luda Formation and Mulargia Formation are concentrated close to the NW-most outcrops, as the maximum thickness of the investigated stratigraphic units. A gradual decrease of the present dip of the beds, from the bottom to the top of the entire succession, until a near-horizontal attitude has also been detected. Overall, the basin presents an apparent NW/SE asymmetry of the filling (Costamagna, 2021, 2022). All those features suggest closeness to synsedimentary ruling tectonic lines (cf. McCann and Santot, 2003) and a pull-apart basin model development (Costamagna, 2022; cf. Christie-Blick and Biddle, 1985).

The compositional maturity of the several conglomerate beds sampled is steady (Fig. 10), showing no clear trend upwards.

The constant numerical value of the metastable and unstable pebbles is likely due to the replacement of the soft pebbles from the surrounding Variscan basement by the erosion of newly formed Permian volcanic and sedimentary rocks. Local variability of the conglomerates pebble composition can also be due to variations of the hydrographic feeding basin (change or mixing of sources). The sedimentary rock contribution of contemporary sandstones is always meager. It tends to disappear, possibly due to the cannibalistic processes decrease (Vai and Ricci-Lucchi, 1977) related to the smoothing of the landscape. The rare presence of quartzrudites cobbles, now unknown in outcrop, suggests a complete dismantling of a mature cover older than the Rio Su Luda Formation and at least to the Gzhelian.

On the contrary, the conglomerate textural maturity grows significantly, being characterized by the decrease in matrix content, the disappearance of angular pebbles, and the increase of the sorting: this is possibly due to more stable waterways with the regularizing of the hydrographic profile and the smoothing of the landscape.

The petrographic analysis discriminated two different sandstone petrofacies within the Mulargia-Escalaplano Basin, marked by the variation of lithic content and type along the succession (Fig. 11).

From the bottom to the top, the Rio Su Luda Formation has a crystalline source area, probably from the nearby oldest Silurian metamorphic basement (Carmignani *et al.*, 2001) made up of low-grade metamorphic rock such as black metasediments and slates. This testifies to the progressive erosion of the Silurian-Mississippian cover of the Variscan outer thrusts zone. Metamorphiclastic detritus typically produces quartzolithic detrital modes around the Circum-Mediterranean region, as a progressive dismantling of the Variscan orogen (Criniti, 2023). An almost contemporary example is well documented within the underlying Permian succession of the Apulia Unit (Criniti, 2023) that describes the progressive dismantling of low-to medium-grade metamorphic thrust units. Other similar tectonic-driven sedimentation styles are available in the literature due to the evolution of thrust belt and foreland basin (Critelli, 1993; Barbera *et al.*, 2011; Critelli, 2018; Matano *et al.*, 2020; Criniti *et al.*, 2023; Kairouani *et al.*, 2023; Fornelli *et al.*, 2022; Critelli and Martin—Martin, 2022). The Mulargia Formation shows the same composition as the Rio Su Luda Formation. However, the lithic composition starts to move upward due to the enrichment of coeval volcaniclastic input (due to the neovolcanic activity; e.g. Critelli and Ingersoll, 1995; Marsaglia *et al.*, 2016; Critelli *et al.*, 2023) that masks and progressively covers the metamorphic lithic input. This progressive change of lithic composition suggests an active volcanism impact on basinal sedimentation (e.g. Smith, 1991) that

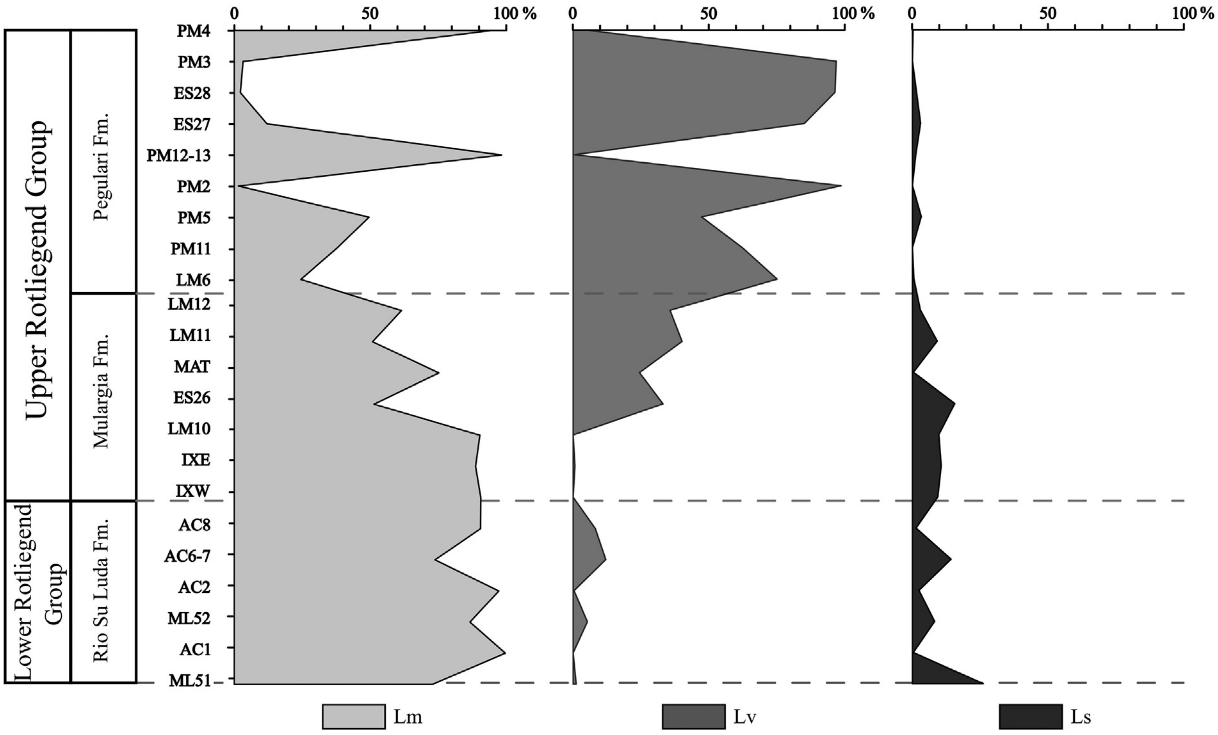

Fig. 11 Vertical variation sketch (not in scale) of lithic content and type. Beside a decrease of metamorphic lithic content upward the succession, volcanic lithic grains deeply increase as a sign of coeval volcanic activity.

overtakes the regular erosion of the Variscan basement. This is typical in the orogenic context, since volcaniclastic sand(stone)s are minor with respect to quartzolithic and quartzofeldspathic suites, as evidence of recycled orogenic provenance (e.g. Dickinson, 1970). Several proofs of this are available within the Circum-Mediterranean Region (e.g. Critelli, 1993; Amendola *et al.*, 2016; Critelli, 2018; Critelli and Criniti, 2021; Critelli and Martin—Martin, 2022) and the southern continental margin Eurasia that display volcaniclastic sand(stone) interbedded with quartzolithic suites, in both remnant ocean basins and foreland basins (e.g. Critelli, 1993; Barbera *et al.*, 2011; Caracciolo *et al.*, 2011; Cavazza *et al.*, 2013; Critelli, 2018; Corrado *et al.*, 2019; Malekzadeh *et al.*, 2020; Jafarzadeh *et al.*, 2022; Civitelli *et al.*, 2023).

The Pegulari Formation points out a different petrofacies that outlines a main synsedimentary volcanic activity of rhyolitic and andesitic composition, and a mild basement erosion or an increased distance from the expanding basin border made of the Variscan metamorphic basement.

To sum up, the quartzolithic composition prevails at the beginning of the basin development, as a consequence of the basin borders closeness, made up of the Variscan metamorphic rocks. Meanwhile, the widening of the basin made the intrabasinal (volcanic and sedimentary) clastic input prevalent: the temporary trend inversion with quartzolithic events could be related to exceptional floods carrying debris from the basin borders to its depocentral area.

Significantly, the presence of metaradiolarites (Lydites AA: Spalletta, 1982; cf. Randon and Caridroit, 2008) at the base of the Rio Su Luda Formation, and its abruptly replacement upwards by the metamorphiclastic Upper Pennsylvanian-Permian succession, demonstrates the progressive unroofing of the Variscan chain and the tectonic-driven outcropping of the lower Gerrei Variscan unit. Metaradiolarite beds (Lydites AA: cf. Randon and Caridroit, 2008) are presently contained in the Silurian graptolitic schists formation of the upper Gerrei Unit (Carmignani *et al.*, 2001), on which the Rio Su Luida Formation rests. Conversely, they are missing in the close outcrops of the lower Castello Medusa Unit (Carmignani *et al.*, 2001). This suggests that at Gzhelian times (Late Pennsylvanian) the Variscan chain just suffered important erosive phenomena. The quick disappearance of the lydites in the upper part of the Rio Su Luda Formation could mean a different feeding area in times for the Mulargia-Escalaplano Basin.

5. Conclusions

The sedimentology and petrology of a ruditic-arenitic succession within the latest Pennsylvanian to Lower Permian late-to post-Variscan Mulargia – Escalaplano Basin in SE Sardinia has been carried out. The results show that the siliciclastic sedimentation changes both as depositional style, texture and composition, suggesting flows that become more regular and less energetic in times, probably due to the smoothing of the reliefs behind, and thus a progressively well-established, perennial-type fluvial network. Although the compositional maturity of the products remains low along with the quartz content, there is a marked shift of the lithic composition from metamorphic to dominantly igneous, due to the growing content in volcanic grains and pebbles during the coeval volcanic activity. The sedimentary rock contribution of contemporary sandstones is low, minimizing the cannibalistic contributions. As the metamorphic lithic supply decreases with the widening of the basin, due to the upcoming erosion of the tectonic-widened basin borders, the progressive contemporaneous development of the coeval magmatic activity provides a significant quantity of intermediate to felsic volcanic rocks to the erosion process. The localized occurrence of not-stressed quartzrudite cobbles, absent in the post-Variscan succession, suggests that the Rio Su Luda Formation was not the first late-Variscan erosive sedimentary product. Also, the disappearance of the metaradiolarites (lydites AA) upwardly is significant concerning the tectonic framework of the Variscan chain over which the basin remains. Finally, this could suggest a progressive deepening of the debris metamorphic source and thus the gradual unroofing of the lowest units of the collapsing Variscan chain made of higher-grade metamorphic rocks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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