

Submarine canyon morphology and evolution along the Western and Southern margins of Sardinia

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ABSTRACT

Recent high-resolution and older medium-resolution seismic profiles, together with bathymetric data, have been integrated for a detailed investigation of the western and southern Sardinian margins. This study analyzes the trigger mechanism, morphologies, spatial distribution and temporal evolution of submarine canyon systems. The origin of these canyons is primarily influenced by the interplay between slope gradient, crustal vertical movements and sea-level changes, which destabilize the slopes and trigger retrogressive erosion. The canyon evolution, instead, is determined by the interaction between erosive processes, gravitational mass movements and bottom currents. Their path and sinuosity are influenced by the large amount of magmatic structures present on the western margin and by the structural highs on the southern margin. We classify the submarine canyons of Western and Southern Sardinia as type 2, i.e. they cut the shelf edge without connecting to large fluvial systems. Indeed, Sardinian canyons are primarily shaped not by major river systems, but by mass flow events and bottom currents, which act as primary mechanisms of sediment transport and incision. Ultimately, we conclude that the origin of the canyons is post-Messinian, resulting from more recent glacio-eustatic variations that occurred during the Quaternary, thus challenging earlier hypotheses that associated their formation with the Messinian Salinity Crisis.

1. Introduction

Submarine canyons, first highlighted by Shepard (1936), are defined as steep-walled, deep incisions cutting through the continental slope, sometimes starting from the continental shelf (Normark and Carlson, 2003; Covault et al., 2011; Harris and Whiteway, 2011; Fildani, 2017). These canyons act as major conduits for the transfer of sediment, pollutants and organic matter from continents to the deep sea (Puig et al., 2000; Normark and Carlson, 2003; Canals et al., 2006; Turchetto et al., 2007; Paull et al., 2010). At the same time, they represent biodiversity hotspots, playing a crucial role in nutrient distribution and supporting rich and diverse ecosystems. Their function as transport pathways also makes them reservoirs of high pollutant concentrations, posing potential risks to marine life (Fernandez-Arcaya et al., 2017 and references therein). Canyon development is due to upslope retrogressive erosion (Twichell and Roberts, 1982; Farre et al., 1983) or downslope incision caused by gravity-driven flows (Daly, 1936; Pratson et al., 1994). The interaction between sediment mass flows and seafloor topography plays

a key role in canyon evolution (Mitchell, 2005; Paull et al., 2013). On the western Sardinian margin, large canyon heads are found at the Oristano Gulf, where landslides occur along channel beds and walls (De Falco et al., 2024). Pockmark fields on the outer shelf are sometimes aligned with the thalweg of smaller canyons according to the structural framework of the margin (De Falco et al., 2024; Frisicchio et al., 2025). In Southern Sardinia, canyon heads at the shelf break and upper continental slope, formed by retrogressive erosion, also exhibit intra-channel landslides (Deiana et al., 2021). Furthermore, creeping areas and landslides on the upper slope are often associated with fluid emissions from pockmark fields (Deiana and Maleddu, 2017; Caradonna et al., 2025). On the southern Sardinian continental margin, Meleddu et al. (2016) investigated the Foxi and Sarroch canyons in the Gulf of Cagliari, identifying significant gravity flow activity and sediment spillover within the Foxi canyon system. Further evidence of gravitational mass movements in Sardinian canyons was presented by Orrù et al. (2024), who analyzed geohazard features in Southern Sardinia, particularly focusing on mass wasting processes at canyon heads. The morphology of

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submarine canyons is shaped by both structural and stratigraphic factors. Four geomorphological zones are generally distinguished: heads, axes, walls and distal reaches (Cronin et al., 2005). Canyon heads, characterized by intense along-canyon current activity and downward sediment transfer, represent dynamic environments (Green et al., 2007). Moving downstream, the axes of the canyon, which can vary in shape from straight to sinuous, are controlled by the interplay between slope angles and sediment supply, while faults and tectonic deformation often constrain their paths (Laursen and Normark, 2002). The walls, frequently subject to erosion and collapse, show both depositional and erosional features like levees and terraces, respectively (Babonneau et al., 2004). At the distal reaches, the topographic relief of the canyon diminishes, signaling the transition to more subdued terrain (Cronin et al., 2005). Several studies have examined sediment transport in coastal environments, highlighting different controlling factors. For instance, Palanques et al. (2006) investigated the role of bottom currents in sediment transport, Smith et al. (2007) focused on the influence of storms, and Paull et al. (2013) analyzed processes related to density currents. However, the connection between sediment transport and coastal processes remains unclear. In Southern and Western Sardinia, the integration of seismic profiles and bathymetric data enables the investigation of the architecture and morphology of submarine canyons, as well as the identification of the main tectonic and structural controls on canyon development. This work focuses on the processes and key factors shaping the evolution of these canyons over time.

2. Geological setting

The study area is located on the continental shelf and upper slope of the western and southern Sardinian margin in the Western Mediterranean Sea (Fig. 1). This region has experienced significant geological evolution, particularly during the Oligo-Miocene (OM), when the counterclockwise rotation of the Corso-Sardinia Microplate contributed to the development of the West Sardinian margin and of the onshore Sardinian Rift through a complex fault system. The rifting process was driven by the movement of the African and Eurasian Plates and subsequent west-ward subduction of the Tethys, which resulted in the opening of the Sardo-Provençal Basin (Cherchi and Montadert, 1982). In Southern Sardinia, the OM Rift comprises a network of grabens (Bosworth, 1985) separated by a transfer zone characterized by a prominent central uplift (Colletta et al., 1988; Maillard and Mauffret, 1993). This configuration highlights the tectonic complexity of the region and significantly influences the geological evolution of the western and southern Sardinian margin. Initially characterized by strike-slip tectonics, the southern margin transitioned to transtensional and extensional tectonics (Cherchi and Montadert, 1982). The OM rifting in this region led to the formation of a series of extensional basins, which played a key role in shaping the tectonic and sedimentary processes in the area (Casula et al., 2001). During the Plio-Quaternary (PQ), some OM faults were reactivated by the NW-SE trending Campidano Graben, associated with the opening of the southern Tyrrhenian back-arc basin (Cherchi and Montadert, 1982; Casula et al., 2001; De Falco et al.,

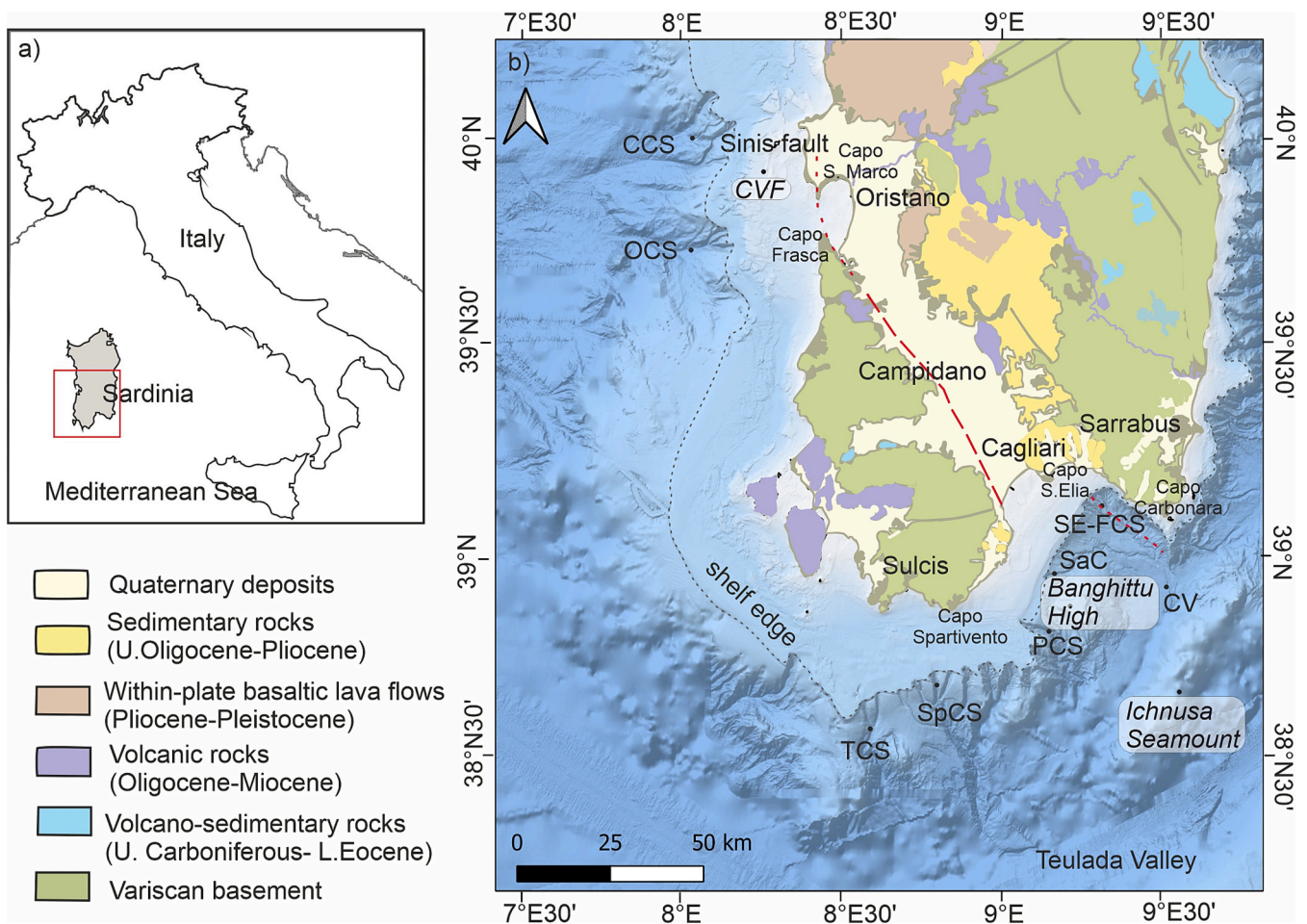


Fig. 1. a) Location map; b) Zoom of the study area with the location of the canyons investigated in this study. The red lines indicate the faults from Casula et al., 2001. Land geology from Carmignani et al. (2016). Bathymetry from EMODnet. CCS: Catalan Canyon System; OCS: Oristano Canyon System; TCS: Teulada Canyon System; SpCS: Spartivento Canyon System; PCS: Pula Canyon System; CV: Carbonara Valley; SaC: Sarroch Canyon; SE-FCS: S.Elia-Foxi Canyon System. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2022). Vertical movements occurred, primarily driven by thermal subsidence related to the opening of the Sardo-Provençal basin (Rehault, 1981; Savoye and Piper, 1991; Frisicchio et al., 2025). The cumulative effects of water and sediment loading since the Messinian Salinity Crisis (MSC) (Heida et al., 2022) further influenced the margins. The MSC occurred between 5.97 and 5.33 Ma and caused a dramatic sea-level drop, leading to lithospheric unloading, uplift in certain marginal areas, and subsidence in inland basins (Norman and Chase, 1986; Haq et al., 1987; Gargani, 2004; Roveri et al., 2014), impacting the Mediterranean sedimentation patterns (Heida et al., 2022). Pleistocene uplift in the Sinis Peninsula (Barca et al., 2016; Cocco et al., 2019) contributed to the margin's tilting, as evidenced by late Miocene marine deposits found at an elevation of 650 m above sea level at Capo San Marco (Funedda and Carmignani, 2012; Coltorti et al., 2015). Late Miocene (Messinian) uplift and erosion, coupled with NW-SE compression, caused a localized reversal of the OM rift filling in the emerged southern region of the Sardinian rift and offshore areas (Casula et al., 2001). Seismic data from the Gulf of Cagliari indicate that maximum uplift, as reported by Casula et al. (2001), occurs in the Cagliari hills, where total vertical displacement reaches approximately 1000 m. This uplifted zone is also observable to the southward offshore.

The continental outer shelf and upper slope of the west Sardinian margin are characterized by depositional processes, while erosional processes dominate the inner shelf (MaGIC project). East of the Oristano Gulf, syn-rift continental deposits and Pliocene basaltic flows fill the horst and graben OM structures, whereas Miocene and Lower Pliocene volcanic and marine deposits influence the inner shelf to the west (Conforti et al., 2016). The primary sediment sources in the Oristano Gulf include Holocene terrigenous deposits from the Campidano Graben, Upper Miocene marine deposits interfingering with Plio-Pleistocene basalts, and Mesozoic marine deposits south of Capo Frasca (Carmignani et al., 2016). The Gulf of Cagliari forms the innermost section of the sedimentary system along the southern Sardinian margin, influenced by tectonic features such as the Ichnusa Seamount and Banghittu High (Fanucci et al., 1976). The continental shelf receives terrigenous input from the hinterland, Miocene and Quaternary sequences dominate the eastern sector, and Hercynian granitic basement rocks and volcanic systems are characteristic of the western sector (Meleddu et al., 2016).

Key geological events that have influenced the region include the MSC regression and subsequent Pliocene phases (Marini and Murru, 1983). The sea-level lowering associated with the MSC (Cherchi and Montadert, 1982) and glacio-eustatic oscillations of the latest Quaternary (Haq et al., 1987) have significantly shaped the formation of submarine canyons (Deiana et al., 2021). During the last Würmian glaciation, sea levels fell by approximately 130 m, exposing extensive areas of the continental shelf to erosion (Finetti and Morelli, 1974; Deiana et al., 2021). These eustatic fluctuations led to repeated lowstand conditions during the Pleistocene, driving prograding events observed at the canyon margins (Ulzega and Hearty, 1986).

2.1. Regional geomorphological submarine setting

The western and southern Sardinian shelf and slope are dissected by a wide network of submarine canyons and tributary channels (Fig. 1b). In addition to canyons, local seafloor topography depends on other geomorphological features such as seamounts and the isolated Carbonara Valley (CV). Notably, the western Sardinian margin is characterized by the extensive Catalano Volcanic Field (CVF) (Fig. 1b), dated to the early Pliocene (Geletti et al., 2014; Conforti et al., 2016), consisting of >40 volcanic cones. Some of the shallower edifices show evidence of erosion at their top, due to exposure during sea-level lowstands (Conforti et al., 2016; Frisicchio et al., 2025). In the southern margin, the two important structures of Ichnusa Seamount (Bouma, 1985) and Banghittu High (Lecca et al., 1998) represent the main topographic elements.

Several canyons incise the western Sardinia platform, such as the Catalano Canyon System (CCS), in the northern part of the study area, and the Oristano Canyons System (OCS), in front of the Gulf of Oristano (Fig. 1b) (Ulzega, 1988; Frisicchio et al., 2025). The branches of the CCS were previously identified by Ulzega (1988), who distinguished the northern branches as “Mannu Canyon”, while designating the southern branch as “Putzu Idu Canyon”. In the south-western sector of the Sulcis slope, the Teulada (TCS) and Spartivento Canyons (SpCS) are two of the most significant features (Fig. 1b). Proceeding eastwards, the Pula Canyon (PCS) (Fig. 1b) descends towards the Sardinia Channel, while the Sarroch (SaC) and the S.Elia-Foxi (SE-FCS) Canyon Systems merge in the Carbonara Valley (CV). Todde (2012) classified these canyon systems on the basis of geodynamic structures into three distinct sectors: the SE-FCS Canyon sector presents a tectonic control; the SaC sector, with a large part of the upper slope affected by widespread erosion, shows typical characteristics of passive margins where no tectonic activity is recorded; the southernmost sector, where both tectonic and erosional process were active. Several studies have provided evidences of gravitational landslides, unchannelized turbidite flows and active submarine landslides across the upper continental slope and within the heads of submarine canyons along the southern Sardinian margin (Paliaga et al., 2014; Meleddu et al., 2016; Deiana et al., 2021; Caradonna et al., 2025; MaGIC data project). On the western Sardinian margin, De Falco et al. (2024) mapped landslides affecting the upper slope of the northern and central sectors of the margin and identified landslide niches along the OCS bed and walls.

3. Data and Methods

3.1. Data

For this study, 2D multichannel seismic reflection profiles collected during several campaigns were used (Fig. 3, Table 1): CG, WS, MS, CROP and ES. In 2010, the National Institute of Oceanography and Applied Geophysics (OGS) acquired the CG and WS medium-resolution seismic datasets as part of the WS10 project, aimed at exploring the western and southern margins of Sardinia (Zgur et al., 2011; Geletti et al., 2014; Caradonna et al., 2025; Frisicchio et al., 2025). The acquisition parameters (Table 1) for the WS10 campaign (Zgur et al., 2010) were optimised to investigate the PQ sequences and the Messinian layers (Geletti et al., 2014; Frisicchio et al., 2025). The CG and WS profiles

Table 1
Acquisition parameters for the multichannel seismic profiles used in this work.

MCS Profiles	CG & WS	MS	CROP-M32	ES
Vessel/ Operator	R/V OGS- Explora/OGS	R/V Marsili/ OGS	R/V OGS- Explora/OGS	Western Geophysical
Time Period	2010	1969–71	1994	1968
Source Type	GI-guns (11I)	Flexotir	Air-guns (80 l)	Acquapulse
Recording Filters	3 Hz LC Antialias HC	10–72 Hz	HC 77 Hz 70 dB/Oct	10–80 Hz
Recording Length	8 s	10 s	17 s	4 s
Sampling Rate	1 ms	4 ms	4 ms	2 ms
Group Interval	12.5 m	100 m	25 m	
Shot Interval	12.5 m	200 m	50 m	
Number of Groups	120	24	180	
Near Offset	25 m	270 m	150 m	
Coverage	3000 %	600 %	4500 %	1200 %
Streamer Length	1500 m	2400 m	4500 m	1600 m
Streamer Depth	5 m ± 0.5 m	10 m	10 m	
Source Depth	4 m ± 0.5 m	14 m	5 m	

form the main seismic dataset for this study, as their resolution allows detailed analysis of the architecture and evolution of the canyons. Advanced multi-channel seismic processing (Fig. 2), performed using the Echos industrial software, was applied to maintain maximum seismic resolution, allowing for more detailed seismic imaging. The processing sequence (Fig. 2) aims to extract the maximum acoustic information from the data. To improve the 2D seismic coverage, parts of the MS, CROP and ES profiles were integrated. The MS dataset (Finetti and Morelli, 1973), acquired by OGS between 1969 and 1973, provides regional coverage of the entire Mediterranean, including the study area. This was supplemented by the CROP-M32 line from the CROP project (Scrocca et al., 2003; Finetti, 2005), which runs orthogonally to the coast in the Gulf of Cagliari. The low-resolution ES profiles (ViDEPI project, 2009) derive from the SNAP data web portal of OGS.

3.2. Methods

3.2.1. Geomorphological analysis

The geomorphological analysis was conducted with the Global Mapper and QGIS Softwares, using bathymetric data from EMODnet (2020). This dataset provided a detailed representation of the seafloor topography, enabling the identification and analysis of key geomorphological features within the study area. Geomorphological parameters were obtained through longitudinal profiles along the canyon thalweg and transverse profiles across the three defined canyons sectors: upper, middle and lower (Table 2). The transverse profiles allowed us to measure the canyon relief, the width between its banks, and the wall angles, providing insights into the morphological variations across different sections (Table 2). Meanwhile, the longitudinal profiles were used to assess canyon length, depth, slope, and knickpoints, helping to identify slope variations and knicking points that could indicate recent geomorphological changes. Additionally, we calculated the mean slope and the overall sinuosity of the canyons (Table 2). To analyze canyon morphology, we used QGIS to generate location maps, calculate the bathymetric slope angle (Fig. 4) to highlight slope variations along the canyon path, and derive sinuosity-related parameters. Sinuosity is defined as the ratio between the total canyon length along the thalweg and the length of the valley in a straight line. The sinuosity index (SI), which quantifies local-scale sinuosity variations along the entire canyon, was calculated using 1 km moving windows.

3.2.2. Seismic interpretation

The interpretation of the seismic lines from the western and southern offshore regions of Sardinia was conducted using Schlumberger Petrel® software. We selected seismic profiles where canyon features were better imaged; it is important to note that some of these profiles are not perfectly perpendicular to the canyon axis.

Key geological horizons and features were identified and mapped

across the study area to develop a detailed understanding of the sub-surface structures. Following the previous local and regional criteria for defining stratigraphic boundaries, we utilised specific time-stratigraphic markers to aid in the interpretation of the canyons. These markers include:

i) the Ms. boundary, corresponding to the base of the Pliocene (Frisicchio et al., 2025). This is frequently observed as an erosional surface characterized by high amplitude and a rugged morphology, usually associated with the Messinian Erosional Surface at the margins (Lofi, 2018) which truncates the pre-Messinian fractured sequence on the continental shelf and slope, while appearing more concordant in the deep basin.

ii) the A₀ reflector, generally a concordant surface, represents the boundary between the lower, more seismically transparent Pliocene unit, and the upper, more reflective Quaternary unit, and is defined as the base of Quaternary (Frisicchio et al., 2025).

Among the interpreted seismic features, we recognized structures associated with tectonic highs in the southern region and volcanic edifices in the western region. In particular, the volcanic structures were identified by high seismic amplitude at their flanks and tops, accompanied by chaotic medium-amplitude internal reflections. Additionally, thin magmatic layers around these volcanic edifices are often characterized by continuous high-amplitude reflections, as previously described by Geletti et al. (2014) and Frisicchio et al. (2025).

4. Results

4.1. Physiography of the Sardinian margins

The western Sardinian continental shelf is approximately 40 km wide, with the shelf break at an average depth of ~250 m. The continental slope extends to the abyssal plain at a depth of about ~2850 m (Fig. 3). The shelf morphology shows tectonic highs and trenches parallel to the coastline (Fig. 4). The wide continental shelf and the steep slope are often cut by canyons (Figs. 1b, 3, 4a,b, 5). The southern Sardinia continental shelf break is located at an average depth of ~125 m. To the east, the Sarrabus sector (Fig. 4a,c) shows a long and narrow shelf and a steep continental slope that ends at around ~1000 m (Figs. 3, 4). Conversely, the Sulcis zone (Fig. 4a,c) features a considerably broader platform, spanning approximately 40 km, with a slope that descends towards the abyssal plain at about ~2000 m to the south and deepens further to ~2800 m on the south-western side (Fig. 3). This marked geological contrast between the Sarrabus and Sulcis sectors is attributable to the structural influence of the Sardinia Rift and Campidano graben and its associated with NNW to SSE tectonic lineaments (Fig. 1). Slope analysis indicates that the Gulf of Cagliari has a gentler gradient compared to the steeper slopes of Western Sardinia, particularly evident on the canyons' upper branches, and southern Sulcis, where the Pula (PCS), Spartivento (SpCS) and Teulada (TCS) canyons are located (Fig. 4). Additionally, the analysis reveals the high steepness (>10°) of canyon heads and walls (Fig. 4b,c), as well as the Sarrabus and Banghittu slopes and the flanks of magmatic buildings (Fig. 4b,c).

4.2. Western Sardinia Canyons

The western Sardinian continental margin is dominated by two major systems: the Catalano Canyon System (CCS) and the Oristano Canyon System (OCS). The OCS has been subdivided into its northern (N-OCS) and southern (S-OCS) branches (Fig. 5).

4.2.1. Catalano Canyon System (CCS)

The CCS (Fig. 5), ENE-WSW oriented, includes the Mannu Canyon, with its northern (NM) and southern (SM) branches, and the Putzu Idu Canyon (P), which join at a depth of ~1670 m. NM extends 26 km in a NE-SW direction, reaching the shelf edge, with two rectilinear tributaries at its head domain (Fig. 5). SM is 18 km long and follows the same

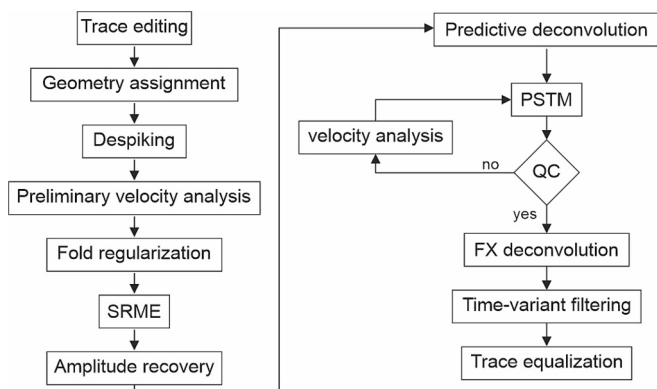


Fig. 2. Processing schematic flow-chart of the CG and WS lines (Caradonna et al., 2025; Frisicchio et al., 2025).

Table 2

Morphometric analysis of the studied Sardinian canyons, including parameters measured for the entire canyon and its upper, middle, and lower sections.

	Canyon Name	Length (km)	Width (m)	Relief (m)	Thalweg slope gradient (°)	Sinuosity
Western Sardinian	Catalano	56	600–2000	40–300	2.42	1.024
	upper	12.335	667	150	5.71	1.009
	middle	17.794	780	44	1.55	1.038
	lower	15.808	1434	60	1	1.01
	Oristano N	48.2	2000–5000	150–340	2.78	1.055
	upper	8.429	2400	330	6.17	1.045
	middle	15.403	4870	331	2.27	1.06
	lower	14.615	4280	270	1.21	1.015
	Oristano S	46.6	1500–2800	10–340	2.09	1.108
	upper	10.716	1854	131	2.8	1.233
	middle	21.256	2590	40	2.3	1.027
	lower	14.628	2245	160	1.05	1.016
Southern Sardinian	S.Elia-Foxi	28.9	500–1500	30–160	1.61	1.164
	upper	7.085	1500	159	3.9	1.039
	middle	10.936	620	57	1.1	1.082
	lower	10.879	667	35	0.78	1.247
	Sarroch	35.7	500–1300	30–150	1.28	1.175
	upper	11.1	1208	130	2.02	1.117
	middle	12.18	890	79	1	1.221
	lower	12.42	650	50	0.8	1.07
	Carbonara Valley	64	1000–3000	10–100	0.61	1.123
	upper	15.4	1000	12	0.8	1.093
	middle	19.4	2700	80	0.4	1.029
	lower	29.2	1900	30	0.66	1.071
	Pula	40.5	700–2500	50–350	1.67	1.247
	upper	14.157	1000	95	1.71	1.082
	middle	14.718	2090	343	2.63	1.476
	lower	11.625	2500	190	0.96	1.204
	Spartivento	49.6	1000–5000	100–400	2.27	1.056
	upper	17.207	1550	338	3.57	1.051
	middle	16.41	2000	380	2.26	1.006
	lower	15.983	4300	330	0.82	1.039
	Teulada	42.5	1200–2500	150–350	2.5	1.134
	upper	12.682	1296	170	3.6	1.016
	middle	13.271	2335	340	2.9	1.283
	lower	16.547	2507	193	1.3	1.016

orientation, engraving the continental shelf (Fig. 5). P follows a NE-SW orientation across the shelf, cutting through the northern CVF and upper slope, shifting to an E-W direction before merging with the Mannu Canyon (Fig. 5). It extends 56 km, from a water depth of –65 m to –2148 m (Fig. 5). The upper canyon has a V-shaped profile, with steep walls (14.5°), transitioning to U-shaped middle and lower sections, with gentler slopes (3° - 4.9°; Fig. 6f). The canyon widens downslope, with low relief and slope values in the middle and lower canyon (Table 2). The mean thalweg slope is 2.42°, highest in the upper canyon (Table 2). Sinuosity values are generally small (1.024 for the entire canyon), with the middle canyon reaching the highest value of 1.038 (Table 2), as confirmed by the sinuosity index, which also highlights thalwegs intersections (Fig. 6e). The longitudinal profile displays a linear, concave shape and contains several knickpoints distributed throughout the canyon (Fig. 5e).

P and SM cut through the slope, incising the PQ sequence between two structural highs. On the upper slope (Fig. 6a), the incisions are located in a topographically lower area, between the shelf to the south and a buried volcano to the north (Fig. 6a), which also separates the less deeply incised NM from the more pronounced SM. Further downslope (Fig. 6c), incisions are observed between the shelf to the southeast and the Putzu Idu Volcano to the north (Fig. 6c,d). The upper Putzu Idu Canyon is characterized by a gradually increasing incision moving westward, reaching a depth of –923 ms TWT (–730 m; Fig. 6b) with 229 ms (171 m) relief. The canyon evolves downslope, reaching –1193 ms TWT (–895 m), and shows the current (C1) and paleo (C2 and C3; Fig. 6c) incisions. Further north, on the upper slope, SM reaches a water depth of 1021 ms TWT (–765 m) and exhibits a relief of 223 ms TWT (167 m; Fig. 6a,b). Here, it displays its current, V-shaped incision (C1)

and the paleo-incision (C2; Fig. 6b). Downslope, it reaches a water depth of –1300 ms TWT (–975 m), with a relief of 310 ms TWT (232 m) and a wider U-shaped incision (Fig. 6c).

Seismic data show Quaternary sedimentary fill packages within P and SM (Fig. 6c), characterized by high amplitude, chaotic reflections, while the Pliocene sequence outside displays low-amplitude, continuous and parallel reflectors, which are horizontal in some areas (Fig. 6a,b) and gently inclined in others (Fig. 6c). In contrast, the Quaternary sequence is influenced by the incision process, as indicated by the erosional truncations in correspondence with the canyon (Fig. 6a,b,c). Locally, a plastered Quaternary sequence, more or less inclined, onlaps the underlying structures, such as the Putzu Idu Volcano (Fig. 6c). The plastered deposits present a uniform pattern of continuous reflectors of low to medium amplitude that follow the morphology of the coarse drift (Fig. 6c).

4.2.2. Oristano Canyon System (OCS)

The OCS (Figs. 5, 7, 8) exhibits an overall E-W orientation. The N-OCS (Fig. 7) extends for approximately 55 km, beginning at a depth of –77 m and terminating at –2030 m. It retains an E-W orientation and features a dendritic pattern, engraving both the upper slope and the shelf, reaching the CVF. The S-OCS (Fig. 8) spans about 35 km, originating at a depth of –338 m and joining the N-OCS at –1800 m. This branch follows a SSE-NNW orientation and carves the shelf, with its southernmost branches extending to the tilted outer shelf.

The N-OCS upper canyon (Fig. 7a) is marked by an inner incision (N-OCS_1) at –492 ms TWT (–369 m), with a relief of 266 ms TWT (200 m). Westward along the upper continental slope, it exhibits three V-shaped incisions, with steep, asymmetrical walls (Fig. 7b,g). Notably, N-OCS_1

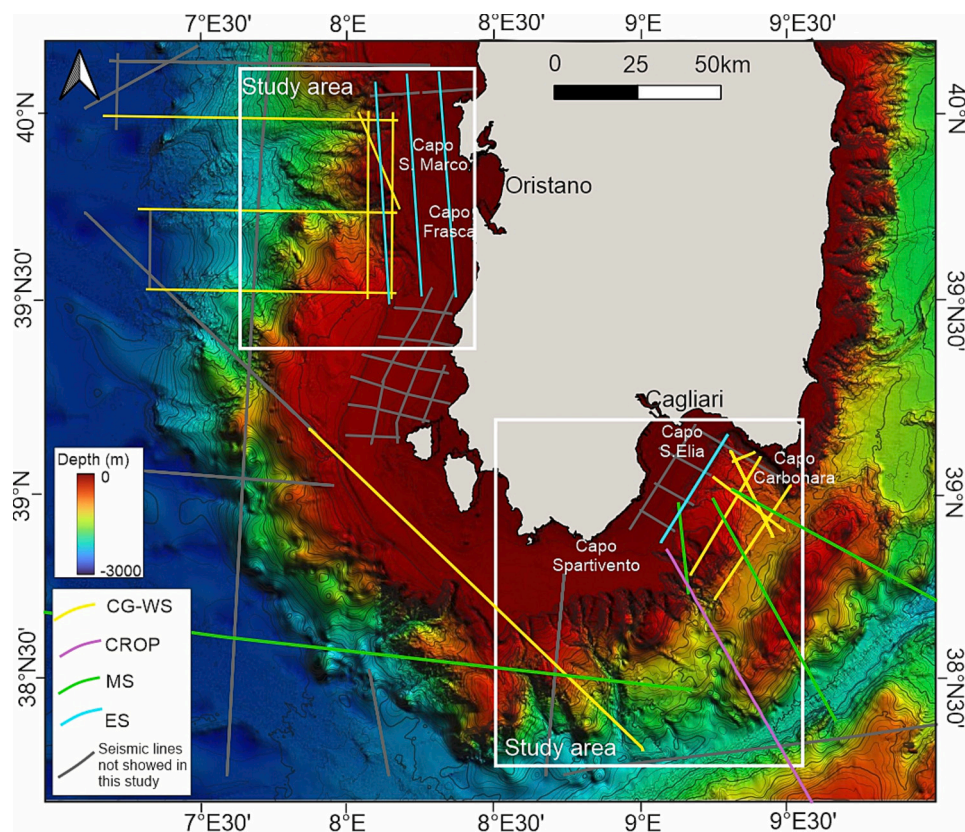


Fig. 3. White rectangles mark the study regions in west and south Sardinia, with the location of the seismic lines. The contour interval of the thickest bathymetric lines is 200 m.

reaches a water depth of -930 ms TWT (-697 m) and has a relief of 340 ms TWT (255 m), while N-OCS_2 and N-OCS_3 display lower reliefs of 156 and 186 ms TWT (117 and 139.5 m), respectively. The S-OCS features three E-W oriented incisions (S-OCS_1, S-OCS_2, S-OCS_3), with only the northernmost (S-OCS_3) reaching the shelf break (Figs. 5, 8). Further south, additional branches extend into a pockmark field (-200 to -600 m; Fig. 5). On the upper slope, S-OCS_1 presents a U-shaped incision (Fig. 8a) at -615 ms TWT (-461 m) with a relief of 75 ms TWT (56.25 m). Upper canyon walls are steep in both branches (Figs. 7g, 8f), though steeper in the N-OCS (Fig. 7g). Downslope, both branches transition into broader (Table 2), U-shaped canyon, with the N-OCS middle canyon exhibiting an asymmetrical profile (15.6° south wall, 7° north wall; Fig. 7g), whereas the S-OCS middle canyon is initially symmetrical with gently sloping walls, before turning asymmetrical downstream (Fig. 8f). After the confluence of N-OCS and S-OCS, the canyon maintains a U-shaped profile, with a steeper northern wall (9.6° ; Fig. 7g). Both branches are widest in the middle section, but while the N-OCS is accompanied by highest relief and sinuosity (Table 2), in the S-OCS relief is higher in the lower section and sinuosity in the upper (Table 2). In both branches, the lower section displays the lowest sinuosity and slope values (Table 2). The sinuosity index presents, in both branches, several peaks associated with branches convergence (Figs. 7f, 8f). The longitudinal profile presents a linear, concave structure with multiple knickpoints positioned throughout the canyon (Figs. 7f, 8e). Erosional features, paleo-incisions and infill patterns are observed in both branches. The N-OCS_1 branch exhibits paleo-incisions (C2 and C3), lateral erosional truncation of the PQ sequence, and high amplitude chaotic fill packages (Fig. 7a). This branch features well developed levees (Fig. 7b) and converges with the N-OCS_2 and N-OCS_3 branches into a wider channel exhibiting a relief of 400 ms TWT (approximately 300 m; Fig. 7c), where at least two erosion and filling cycles can be identified (C1, present; C2, paleo-incision; Fig. 7c). N-OCS_2 and N-

OCS_3 are currently inactive on the continental shelf, infilled with high-amplitude Quaternary deposits, but showing distinct paleo-activity cycles (Fig. 7a). Lateral erosional truncation of the southern wall and draping sediments on the northern wall (Fig. 7a,b,c) are also evident. Similarly, S-OCS_1 exhibits both current and paleo-incisions (C1, C2) filled with chaotic high-amplitude reflectors (Fig. 8a), bounded by Quaternary deposits in the north and lateral erosional truncation of the PQ sequence in the south. Downslope, S-OCS_1 reaches its deepest incision (-756 ms TWT; -567 m) with well-developed levees, while S-OCS_2 and S-OCS_3 remain shallower (Fig. 8b). On the middle slope, N-OCS converges with S-OCS (Figs. 7d, 8), displaying a reduced incision of 157 ms TWT (117.75 m). Here, it erodes the Pliocene unit and the Ms. reflector, while the Quaternary unit is absent (Fig. 7d). The geomorphology of the canyon is influenced by underlying structures, particularly in the southern branch, where the buried volcano (here named "Pistis"; Fig. 5) separates S-OCS_1 and S-OCS_2 from S-OCS_3 (Fig. 8b). This feature shapes canyon morphology, with S-OCS_1 and S-OCS_2 following a topographic low, before merging with S-OCS_3 into a broader channel with moderate incision (40 ms TWT; 30 m). Both N-OCS and S-OCS incise the Quaternary unit, with N-OCS eroding deeper into the Pliocene (Fig. 7b,c), whereas S-OCS never reaches the Ms. reflector (Fig. 8). Additionally, sediment drifts, including mounded elongated and plastered drifts, are present in both canyon systems, indicating complex sedimentary dynamics (Figs. 7c,d, 8a,c).

4.3. Southern Sardinia Canyons

The Southern Sardinian canyons are depicted in order, starting from Capo Carbonara and ending at Capo Spartivento. The Teulada, Spartivento and Pula (TCS, SpCS, PCS) canyon systems are sharper and deeper in the southern Sardinia offshore, near Capo Spartivento. These canyons are distinguished by their closer and narrower contour lines in

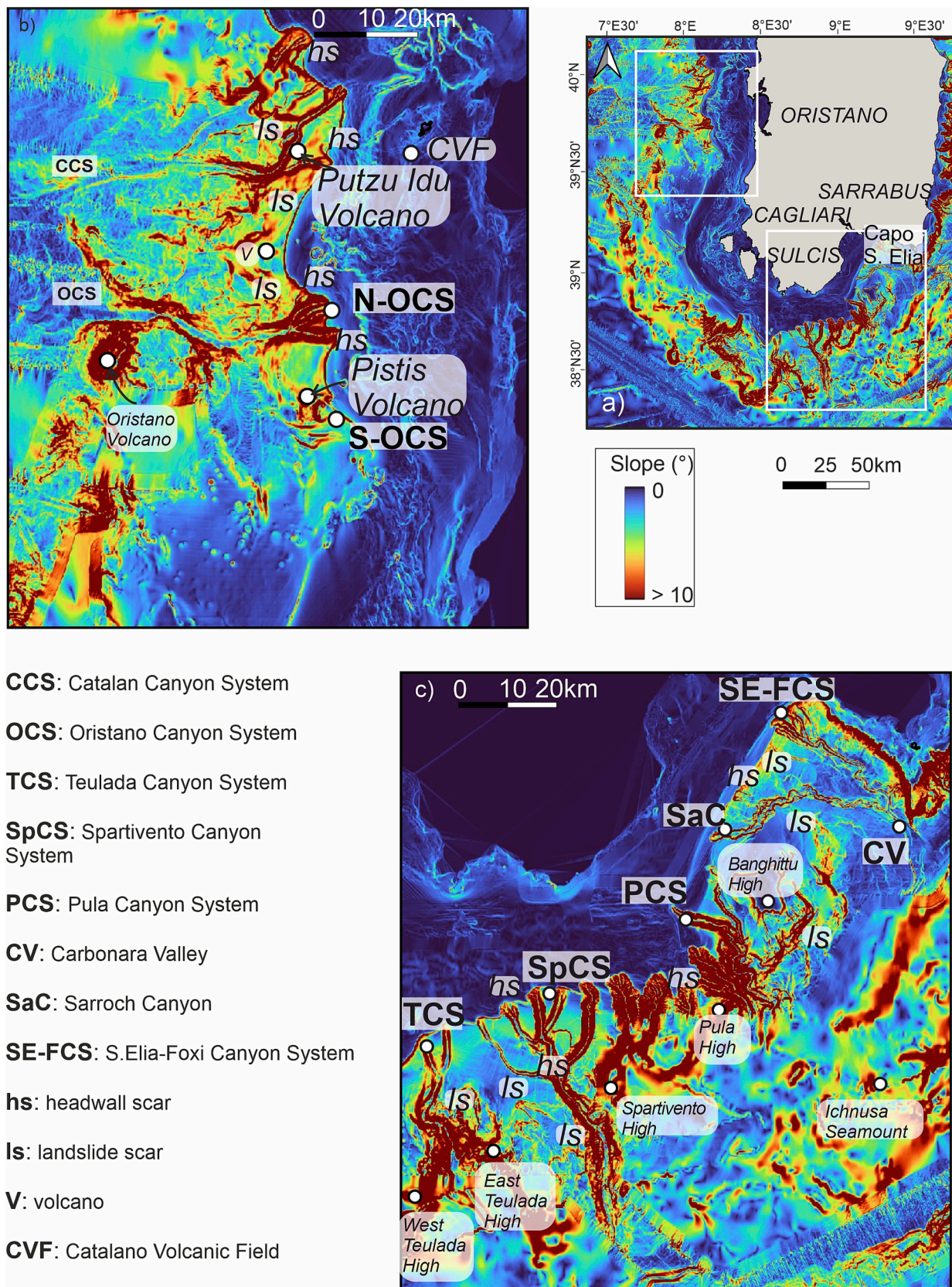


Fig. 4. Slope attribute of the bathymetry by EMODnet (2020); a) Map location; b) West margin; c) South margin.

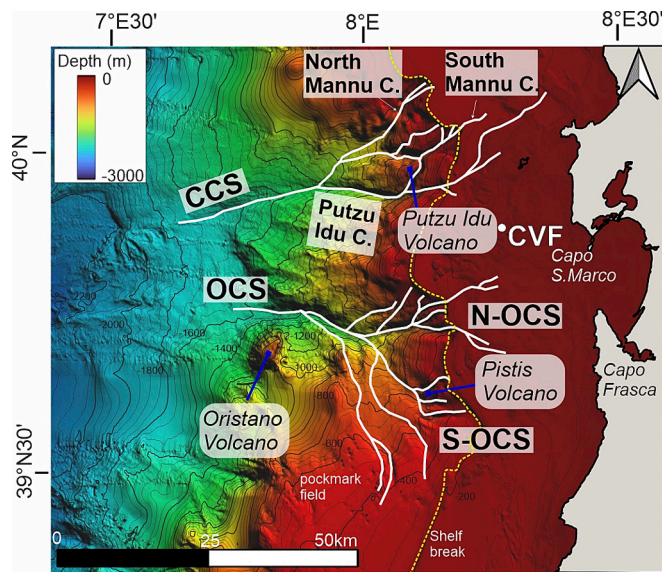


Fig. 5. Submarine Canyon pathway and main morphological structures in the western Sardinia margin.

comparison to the other three canyons in close proximity (Fig. 9). Additionally, structural highs (East and West Teulada highs, Spartivento High and Banghittu High) that face Capo Carbonara are observable on their slopes and are nearly aligned in a SW-NE direction. The Sarroch (SaC) and S.Elia-Foxi (SE-FCS) canyon systems, which converge in the distal domain to form the Carbonara Valley (CV), have more widely spaced contour lines and appear less sharp from an altimetric perspective.

4.3.1. S.Elia-Foxi Canyon System (SE-FCS)

The S.Elia-Foxi Canyon System (SE-FCS) extends NW-SE for approximately 30 km, beginning at -107 m and converging with the Sarroch Canyon (SaC) at -922 m (Fig. 9). It comprises four branches that form an amphitheatre-shaped head on the upper and steepest slope (7°). These branches converge into a single channel at -600 m, after 8 km.

The four branches (SE-FCS_1, 2, 3, 4) in the head domain and upper canyon exhibit a V-shaped incision (Fig. 10a,g), with steep walls (17° ; Fig. 10g). SE-FCS_3 is the most prominent incision (Fig. 10a), displays a relief of 150 m and evolves downslope into a U-shaped profile. Wall steepness decreases from 10° in the middle canyon to 5° in the lower canyon, where the relief is <60 m (Table 2). Width varies from 500 to 1500 m (Table 2), with the upper canyon being widest before narrowing in the middle canyon and slightly widening again in the lower section (Table 2; Fig. 10f). The overall slope angle is 1.6° , with the upper canyon reaching 3.9° before significantly decreasing downslope (Table 2; Fig. 10f). As slope values decrease, sinuosity increases for each segment of the canyon (Table 2; Fig. 10f). Furthermore, a sinuosity peak in the middle canyon, at ca. 10 km (Fig. 10f) corresponds to the intersection between the branches of the head domain, while another notable peak between 17 and 20 km coincides with a deviation in the canyon's direction (Fig. 10d). The longitudinal profile is concave with noticeable irregularities, featuring a few knickpoints along the canyon (Fig. 10f).

The SE-FCS engraves the PQ sequence in the upper canyon, but it does not reach the A_0 reflector downslope. Instead, it erodes only the plane-parallel reflectors of the Quaternary sequence, with clear lateral erosional truncation along its path (Fig. 10a,b,c,d). Levees and terraces indicate various phases of activity (Fig. 10b,c). Within the Quaternary sequence, a subtle morphological depression is observed at about 100 ms TWT below the canyon thalweg (Fig. 10b,c,d) and the parallel Pliocene sequence fills the incision of a Messinian paleo-canyon

(Fig. 10c).

4.3.2. Sarroch Canyon (SaC)

The Sarroch Canyon (SaC) originates at -135 m and extends for approximately 10 km along the upper slope in a W-E direction, running pseudo-parallel to the shelf edge, bounded to the south by the Banghittu High (Fig. 9). Downslope, it shifts to a NW-SE trend for 15 km along the lower slope, running orthogonal to the shelf and terminating at -922 m, where it merges with the SE-FCS. It is composed of a single, well-defined branch, with a V-shaped upper course and steep and asymmetrical walls (red profile; Fig. 11g). Progressing downslope, the canyon retains a V-shape and is highly asymmetric in the middle course, while it transitions to a symmetric, less steep profile in its lower course (Fig. 11g). Relief progressively decreases downslope, from approximately 130 m (Table 2; Fig. 11a) in the upper canyon, to around 50–80 m in the middle and lower canyon (Table 2; Fig. 11b,c,d). The canyon width varies between 500 and 1300 m, narrowing towards the lower canyon, where the average width is ca 650 m, correlating with decreasing relief (Table 2). The overall slope is 1.28° , the lowest among canyons of the western and southern Sardinian margins, with values decreasing from 2.02° in the upper canyon to 0.8° at its terminus (Table 2; Fig. 11f). Sinuosity is generally high (Table 2), peaking in the middle course (1.221) where the highest values correspond with thalweg intersections (Fig. 11f). The longitudinal profile displays a concave form with some irregularities, marked by a few knickpoints throughout the canyon (Fig. 11f). A key feature of the SaC is the progressive migration of its axis during the PQ sediments deposition, visible in the head domain and along the entire course, where also faults are imaged (Fig. 11b,c,d). Initially, the canyon migrates NW (C5 to C4), then SE (C4 to C1; Fig. 11b). Further paleo-canyons can be recognized lying on the flank of a deep structure (Fig. 11c) where a major fault is clearly identifiable. These paleo-canyons initially migrate SW (C8 to C6) until reaching a depth of about -1500 ms TWT, then they turn NE (C6 to C1; Fig. 11c), before realigning SE (C4 to C1; Fig. 11c,d). The present-day canyon, which erodes the Quaternary unit never reaching the A_0 reflector, along with the paleo-canyons, shows a high-amplitude erosional base, covered by the alternating phases of erosion and partial infill that have occurred repeatedly over time (Fig. 11b,c,d). The canyon fill is characterized by a chaotic, high amplitude internal seismic facies. A remarkable similarity, in morphology, seismic facies and internal stratigraphic architecture is evident between the paleo-canyons incising the PQ sequence and the present-day SaC.

4.3.3. Carbonara Valley (CV)

The convergence of the SE-FCS with the SaC leads to the formation of the Carbonara Valley (CV), a 64 km long structure extending from a water depth of -922 m to -1717 m. This valley consists of two sectors: a proximal, well-incised 6 km segment trending NW-SE near Capo Carbonara (Fig. 12a,b), and a distal segment that trends NE-SW, bordered to the SE by the Ichnusa Seamount and to the NW by the Banghittu High, where the relief is lower (Fig. 12c). Unlike the other canyon systems in this study, the CV has relatively low relief values (10 to 100 m), but considerable width (1000 to 3000 m; Table 2). It features a U-shaped profile, with asymmetrical, gently sloping walls (max. 6° ; Fig. 12g). Overall, the slope values are also low (Table 2; Fig. 12f), as the valley develops along the lowermost slope of southern Sardinia, extending parallel to the coastline in the deepest part of the basin. Sinuosity values (Table 2) range from 1.029 in the middle to 1.07 in the upper section, with the highest values typically associated with steeper slopes (Table 2).

Notably, slope values exhibit abrupt variations between 40 and 60 km (Fig. 12f), marking the transition where the valley is no longer confined by the Banghittu High and Ichnusa Seamount (Fig. 12e). The longitudinal profile displays an irregular, convex shape and is marked by several knickpoints throughout the entire canyon (Fig. 12f). The CV appears to have inherited some features from the Sarroch Canyon in its

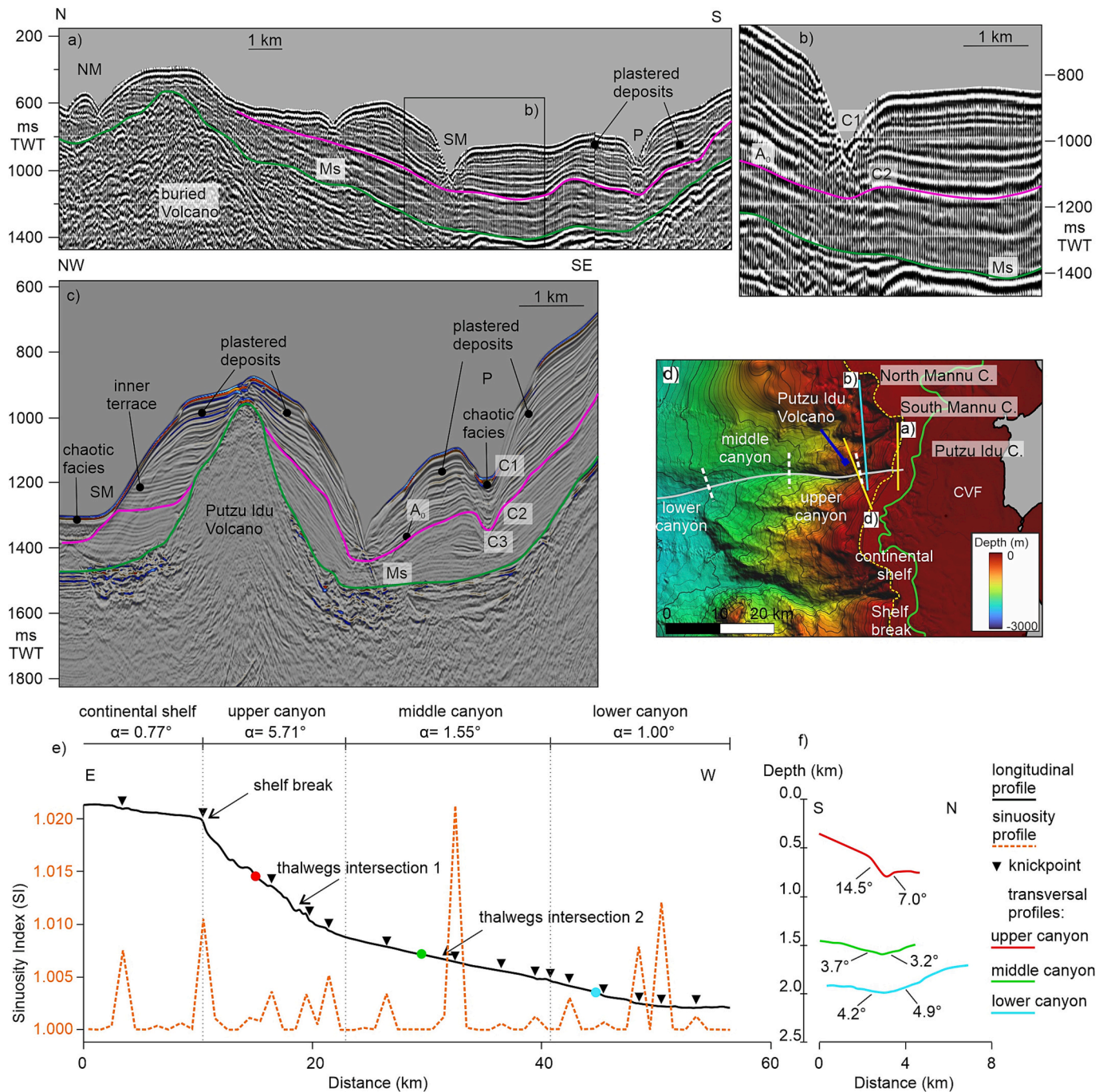


Fig. 6. Catalano Canyon System: seismic and morphological profiles. a) North (NM), South (SM) Mannu Canyon and Putzu Idu (P) Canyon incisions, on the uppermost slope; b) zoom of SM, showing different cycles of activity (C1 and C2); c) P and SM branches, P shows the current (C1) and the paleo-incisions (C2 and C3); d) map location; e) longitudinal profile and sinuosity index of the Putzu Idu Canyon; f) transversal profiles on the upper, middle and lower canyon (location as white dashed lines in d).

head domain, as indicated by lateral erosional truncation, the Quaternary high amplitude and chaotic seismic facies beneath the current incision, and the existence of paleo-incisions (Fig. 12a,b). Older incisions can be observed beneath the current one, affecting the Quaternary sequence (Fig. 12a,b). Where the CV is confined between the Banghittu High and the Ichnusa Seamount (Fig. 12d,e), the incision is characterized by directional changes. Several morphological lows are observed below the valley (Fig. 12c,d), suggesting structural control.

4.3.4. Pula Canyon System (PCS)

The Pula Canyon System (PCS) extends 40.5 km, from −116 m to

−1400 m, following a predominantly N-S trajectory. It consists of two main branches that converge at −810 m water depth (Fig. 13). The eastern branch (EPCS) follows a N-S trend and is less developed in the upper slope, near the Banghittu High, while the western branch (WPCS) follows a NW-SE trajectory, with a well-defined meandering pattern (Figs. 9, 13c). South of WPCS, two additional branches, which are also part of the PCS, incise the slope and extend to the shelf edge. Both branches exhibit meanders at comparable depths (−750 m, −870 m, −1100 m), particularly near the Pula High to the west. The PCS head domain incises the shelf edge, displaying a V-shaped profile that persists through the upper and middle canyon (WPCS1, PCS1, PCS2, PCS3;

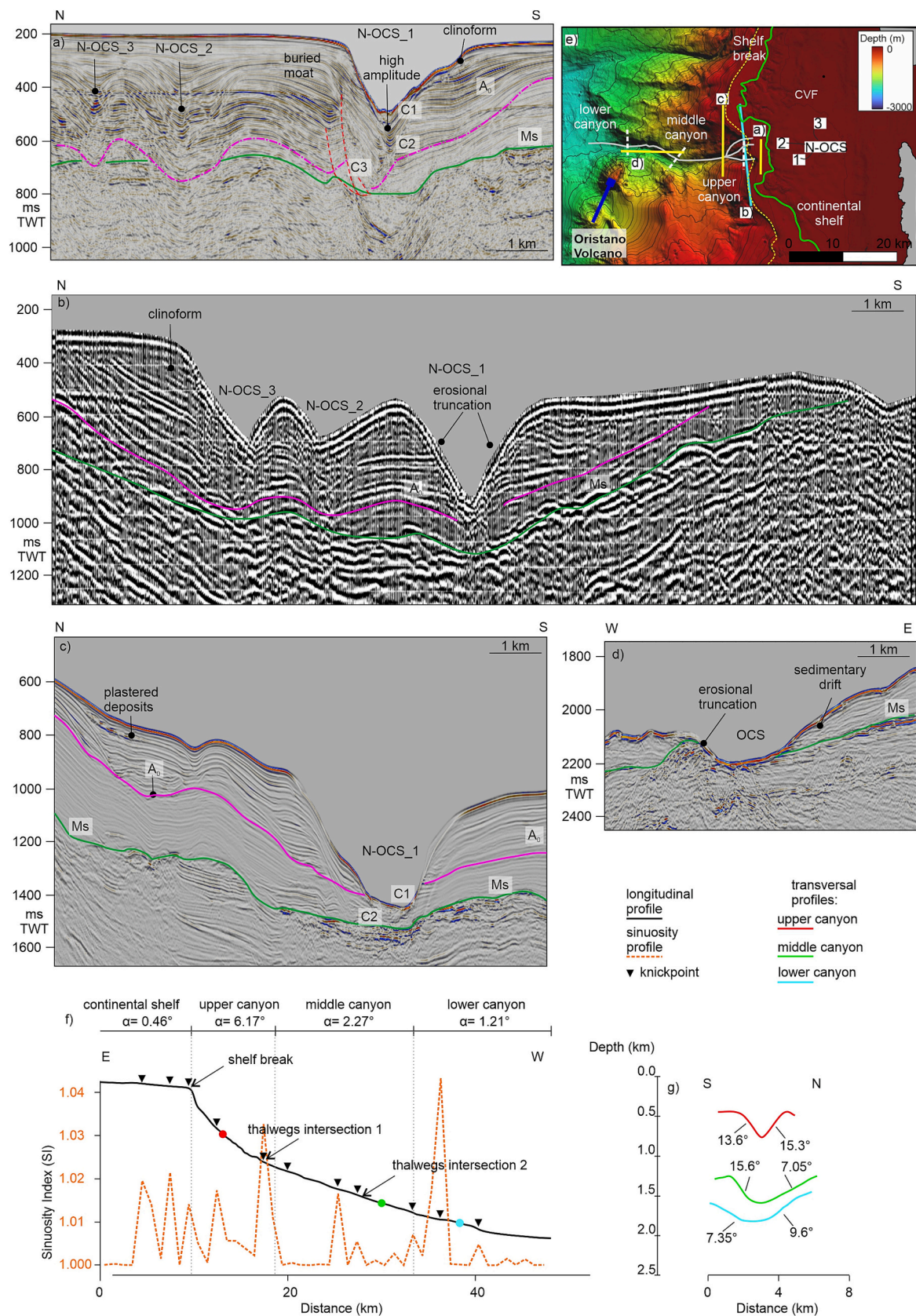


Fig. 7. Northern branch of the Oristano Canyon System: seismic and morphological profiles. a) N-OCS_1 on the uppermost slope, showing the current (C1) and the paleo-incisions (C2 and C3); b) N-OCS_1, 2, 3 branches of the canyon; c) N-OCS_1 resulting from the joining of the N-OCS_1, 2, 3; d) distal part of the OCS, after N- and S- join; e) map location; f) longitudinal profile and sinuosity index; g) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in e).

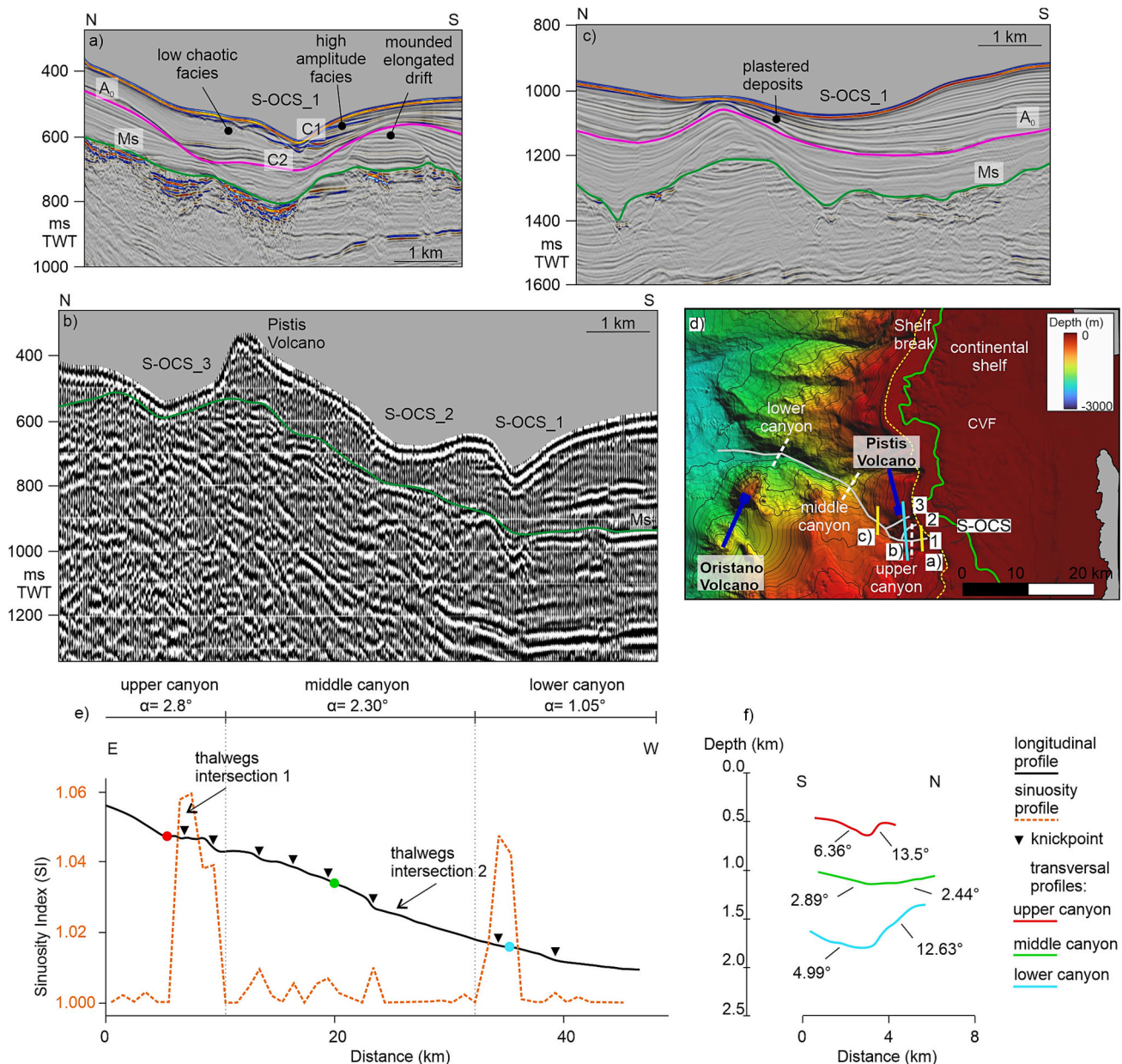


Fig. 8. Southern branch of the Oristano Canyon System: seismic and morphological profiles. a) current incision (C1) and paleo-incision (C2) on the upper slope; b) three main branches engraving the PQ sequence; c) S-OCS after the three branches join together; d) map location; e) longitudinal profile and sinuosity index; f) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in d).

Fig. 13a), before turning to a U-shaped morphology in the lower canyon (PCS4; Fig. 13a). In the middle sector, the canyon walls are highly asymmetrical, with slopes reaching 19° (Fig. 13e) and relief reaching 350 m (Table 2). In contrast, the upper canyon displays lower relief values, which correspond to narrower canyon widths (Table 2). The EPCS1 incision is relatively shallow (100 ms TWT; 75 m relief) in the upper slope, while WPCS1, also in the upper slope, exhibits significantly greater relief (ca. 500 ms TWT; 400 m) (Fig. 13a). The overall slope gradient is low (1.67°), with the steepest section in the middle canyon, where sinuosity also increases (Table 2). Sinuosity remains low in the canyon head (Table 2), rises after approximately 15 km before decreasing again in the lower canyon (Fig. 13d). Between 15 km and 30 km, multiple peaks in the sinuosity index profile (Fig. 13d) do not correlate with slope variations but instead reflect structural control from the Banghittu High (middle canyon) and Pula High (middle and lower canyon). The longitudinal profile displays an irregular, convex shape in

the upper and middle sections of the canyon, transitioning to linear thereafter, and features several knickpoints along its entire length (Fig. 13d). The canyon incisions overlie morphologically low areas, highlighted by the Ms. reflector. This latter is cut by the PCS1, PCS2 and PCS3 thalwegs in the upper canyon (Fig. 13a), while in the middle and lower canyon neither A_0 nor Ms. are incised, indicating that PSC erosion is confined to the Quaternary units.

4.3.5. Spartivento Canyon System (SpCS)

The Spartivento Canyon System (SpCS) extends 49.6 km, from -140 m to -2114 m, following a predominantly N-S trend. It is the most extensively branched canyon in this study, with five easternmost branches exhibiting deeper incisions, particularly in the amphitheatre head region. Several junction points are observed, such as at -800 m, where the second, third and fourth branches (from west to east) converge into a single channel, which then merges with two lateral

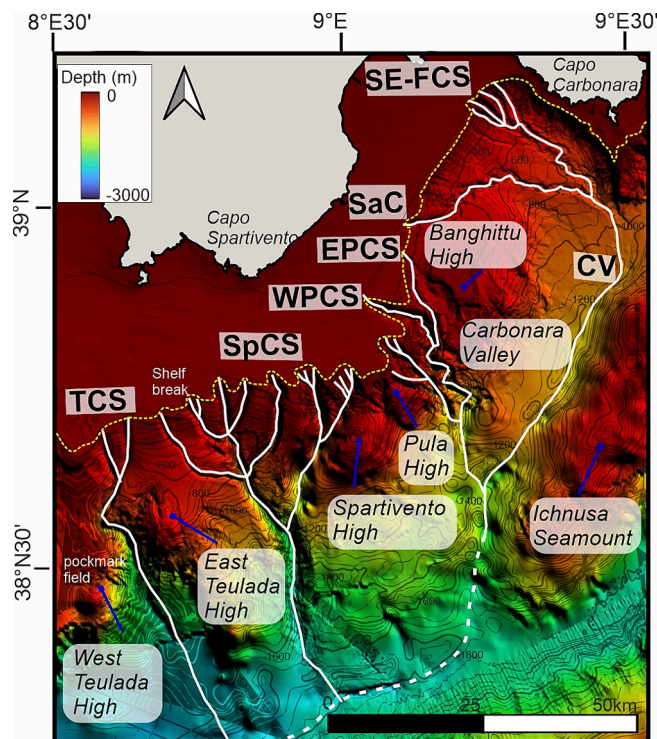


Fig. 9. Submarine Canyon pathway with the main geomorphological structures in the southern Sardinia margin.

branches at -1217 m. The two easternmost branches initially converge at -1134 m, forming a NE-SW oriented branch, which joins the SpCS at -1670 m, where the canyon assumes a N-S direction (Fig. 9). The SpCS features a V-shaped incision in its upper and middle courses, transitioning to a U-shaped profile downslope (Fig. 14f). In the upper course, the canyon walls are steep (19°) and largely symmetrical, but become asymmetrical in the middle and lower canyon (Fig. 14f), where the western walls are generally steeper than the eastern ones (Fig. 14a,f). The SpCS maintains consistently high relief values across all domains and exhibits a significant increase in width in the lower course, where slope gradients are at their lowest (Table 2). Conversely, steeper slopes characterize the upper and middle canyon (Table 2). The overall sinuosity is low, never exceeding 1.1 (Table 2), with localized increases (Fig. 14e) typically observed at thalweg intersections. The longitudinal profile presents a concave shape with some irregularities, characterized by several knickpoints (Fig. 14e).

The seismic profiles are in the central and distal area, leaving the head domain unexplored. In the central zone, a broad and deep incision cuts through the horizontal and parallel PQ package, the Ms. reflector and part of the pre-PQ sequence, reaching a depth of about -2250 ms TWT (Fig. 14a). Note that the synclinal geometry described by the horizons below the canyon is mainly due to a pull-down effect (Fig. 14a). The canyon is positioned within a morphological low in the distal zone (Fig. 14c). However, in this latter area, the incision does not reach the Ms. reflector and high amplitude, chaotic reflectors are imaged on the canyon thalweg (Fig. 14c).

4.3.6. Teulada Canyon System (TCS)

The Teulada Canyon System (TCS) follows a NE-SW trajectory along the upper slope for approximately 15 km before abruptly turning perpendicular to the shelf. It extends for 42.5 km, from -195 m to -2056 m. The canyon originates from two tributary branches that shape its head domain and incise the shelf edge. It has asymmetric walls, with the western wall steeper than the eastern one (Fig. 15f). In its upper course, it exhibits gentle V-shaped incisions, which transitions

downslope into broader U-shaped morphologies (Table 2; Fig. 15f). Relief variations range between 150 and 350 m, with the highest values in its middle sector (Table 2). The steeper sector is the upper canyon (3.6°) which exhibits low sinuosity (1.016). Similarly, the lower canyon maintains low sinuosity, although its slope gradually decreases to 1.3° (Table 2; Fig. 15e). The most pronounced sinuosity variation occurs in the middle canyon, where the TCS is confined by the West and East Teulada Highs (Fig. 15c,d). The longitudinal profile is irregular, with a convex shape marked by the presence of two knickpoints along its length (Fig. 15e).

The present-day TCS exhibits well-developed levees, with the western levee higher than the eastern one (Fig. 15a,b). Paleo-levees have been truncated by the new incision, and a high-amplitude reflector is observed at the canyon base. Below the current canyon, in its head domain, two PQ paleo-incisions (C2 and C3) are identifiable, both filled and subsequently abandoned (Fig. 15a,b). The infill facies displays a slightly chaotic pattern with high-amplitude reflections. The axis of the oldest canyon (C3) is located at approximately -1000 ms TWT and has migrated NW by roughly 1 km from the present canyon (C1), which lies at a depth of about -800 ms TWT (Fig. 15b). In the central, meandering section, the canyon is located on a morphological low, flanked by two structural highs, as evidenced by bathymetric data (Figs. 9, 15c,d). Here, the incision extends close to the Ms. reflector without fully reaching it (Fig. 15c).

5. Discussion

The current geomorphology of the western and southern slopes of Sardinia is the result of the interaction of cross-slope and downslope processes, including submarine canyon formation, slope instability and sediment transport mechanisms. The formation of submarine canyons is generally related to erosion by downslope-driven sediment flows or to widespread erosion related to retrogressive slope failure (Baztan et al., 2005; Harris and Whiteway, 2011).

5.1. Morphological characteristics of Canyons

The submarine canyon systems along the Sardinian margin display distinct morphological characteristics shaped by variations in slope gradient, sinuosity, and structural controls. Based on their morphological and architectural features, submarine canyons are often classified into two groups: erosional and depositional (Goff, 2001; Jobe et al., 2011).

Western Sardinian canyons are characterized by relatively high relief, averaging 260 m, and a thalweg gradient exceeding 2° (Table 2). These canyons exhibit smoother morphologies (Figs. 6f, 7a,c,g, 8) and well-preserved canyon-floor deposits (Figs. 6b,c, 7a,c, 8a), indicating the dominance of depositional processes. Paleo-incisions filled with chaotic, high-amplitude reflectors, alongside lateral erosional truncations within the PQ sequence, reflect a complex sedimentary history. Contourite drifts (Figs. 6c, 7a,c, 8a,b) further suggest the influence of bottom currents, which redistribute sediments, promote deposition, and stabilize canyon morphology (Esentia et al., 2018).

Southern Sardinian canyons exhibit significant morphological variability, which appears to be influenced by their geographic setting. Canyons exposed to the Teulada Valley (Fig. 1), specifically the TCS, SpCS, and PCS are characterized by high relief values, averaging 250 m (Table 2). In contrast, those located within the Gulf of Cagliari such as the SE-FCS, SaC and CV display lower relief values, averaging 113 m (Table 2). This morphological contrast is also reflected in their cross-sectional profiles: while some canyons exhibit U-shaped morphologies, indicative of dominant depositional processes (Figs. 11, 15), others preserve V-shaped incisions, suggesting high-energy erosional dynamics (Figs. 10, 13). The CV and TCS predominantly exhibit U-shaped incisions, suggesting a strong depositional influence. In the initial segment of the CV, this morphology is likely the result of the SE-FCS and SaC

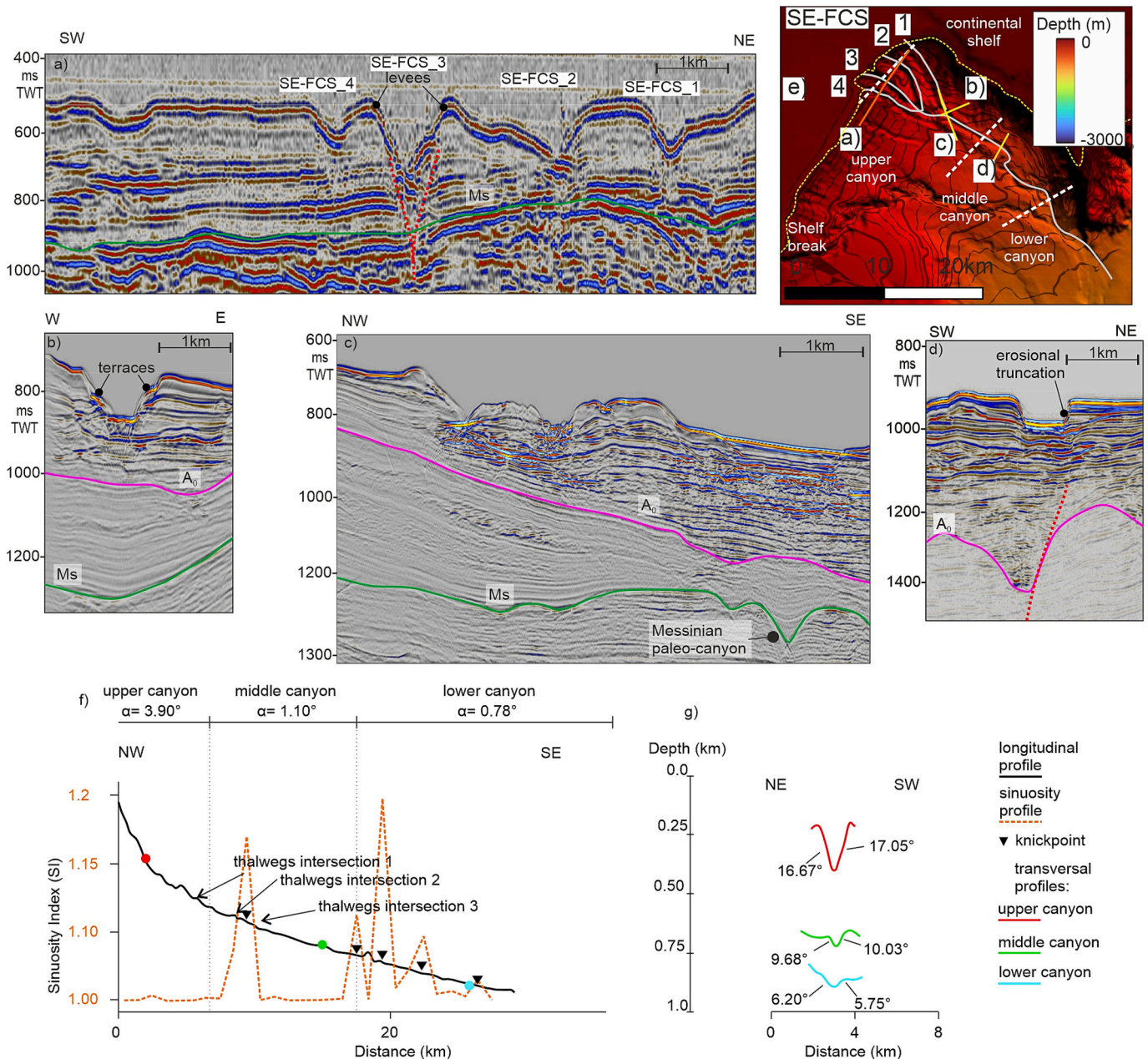


Fig. 10. S.Elia-Foxi Canyon System: seismic and morphological profiles. a) Head domain with four incisions; b) middle domain with terraces on the walls; c) the largest incision of the thalweg is in correspondence of a morphological depression related to previous Quaternary erosion; d) U-shaped incision in the distal part; e) map location; f) longitudinal profile and sinuosity index; g) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in e).

confluence, where flow energy variations at the merging point (Fig. 12a, b) favored the deposition of canyon fill sediments. A similar process is observed at the junction between the easternmost branch of the SE-FCS (SE-FCS_1) and its western counterparts, where internal terraces, levees and channel fill deposits indicate a complex depositional history influenced by previous erosional and sedimentary phases (Fig. 10b). The U-shaped incision observed in the TCS appears to be primarily depositional, as suggested by the morphology of the canyon walls, which is associated with overbank deposits (Fig. 15a,b), and by the presence of significant sedimentary infill beneath the canyon (Fig. 15a,b). Likewise, the SaC (Fig. 11) also displays U-shaped incisions along its course, with canyon fill deposits at its thalweg and terraces along its pathway (Fig. 11b,c,d). Notably, the SaC is the only system composed of a single branch, which may indicate a mature, highly depositional canyon evolution. This interpretation is supported by its PQ evolution, evidenced by

the numerous paleo-incisions imaged in the seismic profiles. Conversely, the SE-FCS and PCS mainly show V-shaped incisions (Figs. 10a,g, 13a,b, e), are tectonically controlled (Figs. 10a, 13a) and highly erosive, as confirmed by the erosional truncation of the PQ sediments (Figs. 10a,d, 13 a,b). Many canyons transition from V-shaped upper reaches to U-shaped lower sections (Figs. 6f, 7g, 10g, 11g, 13e, 14f), particularly after tributary convergence, as observed in the OCS (Figs. 7, 8). Notably, some distal U-shaped segments also show erosional truncations of the PQ sequence (Figs. 7d, 10d, 12d, 13a, 14c), suggesting a more complex dynamic, where these canyon function primarily as sediment bypass, transporting sediments to the abyssal plain rather than accumulating deposits (Cunningham et al., 2005), a pattern evident in the N-OCS and SpCS (Figs. 7d, 14c).

The morphometric analysis of the canyon sinuosity and slope provides insights into the processes controlling the canyon development.

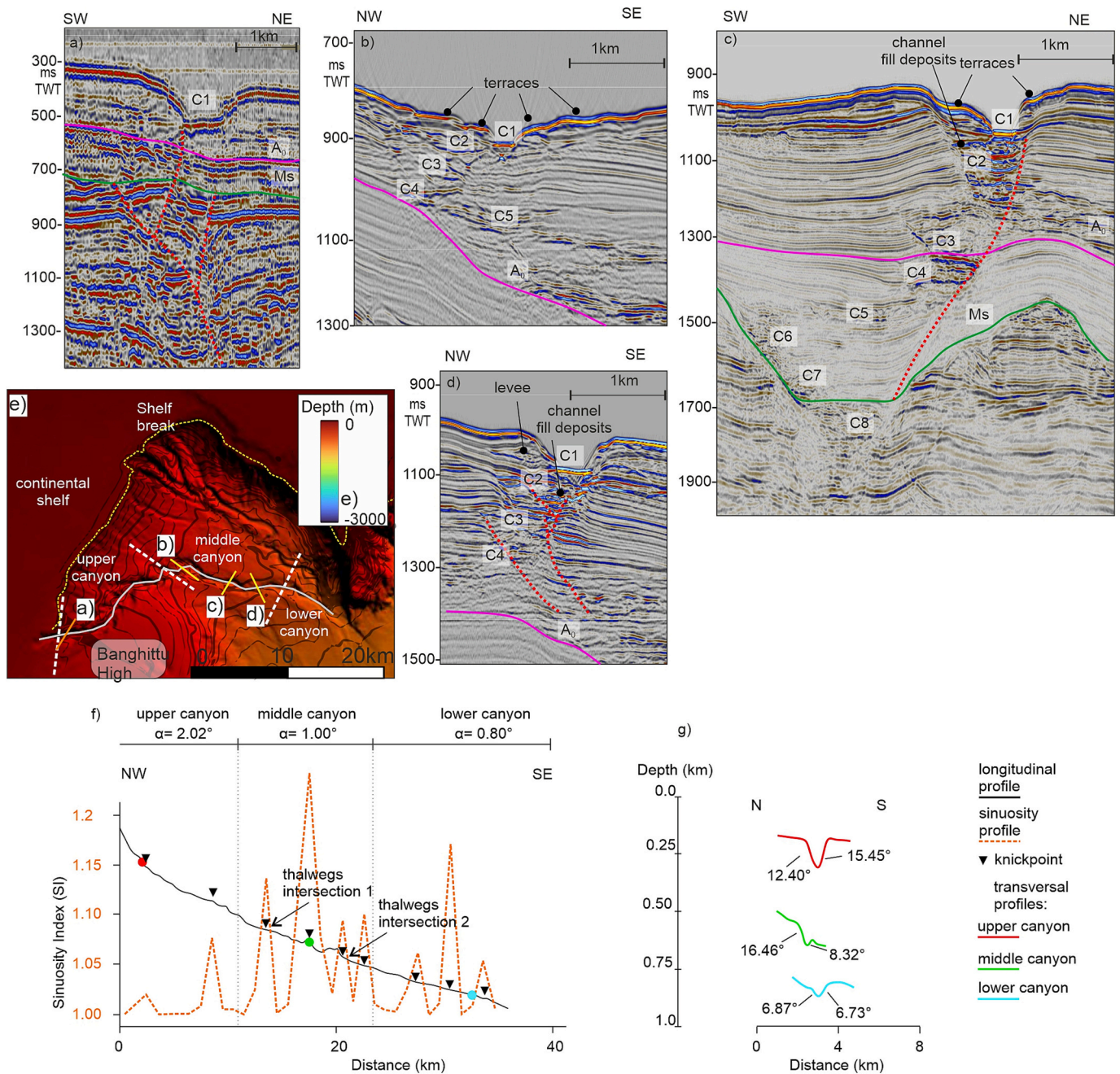


Fig. 11. Sarroch Canyon: seismic and morphological profiles. a) current head zone; b) and c) central zone. A major fault affected the PQ sequence bending several seismic units, and paleo-canyons lean on the flank of a deep structure; d) central zone paleo-canyons; e) map location; f) longitudinal profile and sinuosity index; g) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in e).

High sinuosity values are associated with low slope gradients, which favor low flow energy and the formation of meanders (Figs. 10e,f, 11e,f). However, along the Sardinian margins, sinuosity appears to be more influenced by morphological and structural features that constrain canyon pathways (Figs. 4, 5, 9) and by tributary junctions (Figs. 6e, 7f, 8e, 10b,f, 11f, 13f, 14e, 15e). Slope profiles analysis further confirms that the slope gradient is an important factor in controlling both the initiation and evolution of the canyon systems (Popescu et al., 2004; Baztan et al., 2005). In longitudinal profiles along canyon thalwegs, distinct gradient breaks known as knickpoints are observed. These knickpoints may arise from spatial variations in erosion resistance or the presence of underlying faults (Mitchell, 2006). Erosional and depositional processes within canyon systems shape a depth profile that tends towards equilibrium, where convex regions experience erosion while

concave regions accumulate sediments (Pirmez et al., 2000). Disruptions to this equilibrium can occur when tectonic deformation rates surpass sedimentary processes. An equilibrium channel exhibits a concave-up thalweg profile where erosional processes dominate and the channel is stable over time (Georgiopolou and Cartwright, 2013; Micallef et al., 2014a, 2014b). In contrast, a convex thalweg profile is the result of depositional processes or sediment accumulation. The presence of knickpoints and changes in concavity along thalweg profiles suggests disequilibrium state, where sedimentary disruptions or erosional base level variations influence the channel morphology. For instance, the CCS, N-OCS, SE-FCS, SaC and SpCS exhibit concave thalweg profiles, indicating that these systems are in a state of equilibrium, where ongoing erosional processes are the dominant forces shaping the channel. On the other hand, the S-OCS, PCS and TCS show convex profiles,

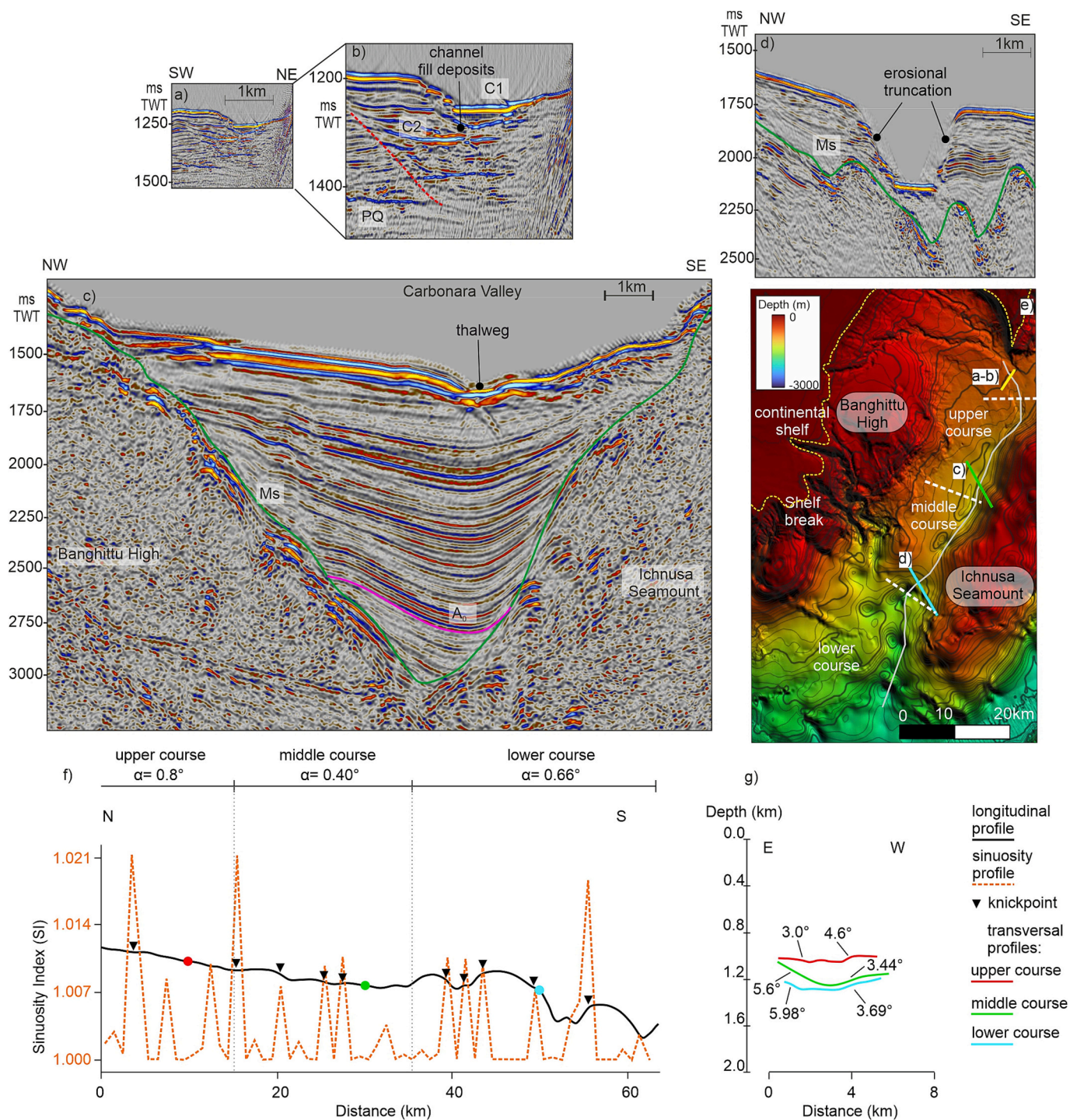


Fig. 12. Carbonara Valley: seismic and morphological profiles. a) area of origin; b) zoom of the paleo incision below the current one; c) Small incision in the CV; d) distal zone, deep incision; e) map location; f) longitudinal profile and sinuosity index; g) transversal profiles on the upper, middle and lower valley (sited on white dashed line in e).

suggesting disequilibrium, likely influenced by depositional controls, changes in sediment supply, or tectonic deformation. In addition, retrogressive erosion occurring at the heads of these canyons significantly influences their overall morphology. For instance, the heads of the SpCS branches display a retrograde pattern evidenced by seismic lines and bathymetry analysis (Fig. 9), indicating that instability processes are dominant and suggesting that this canyon evolution is mainly controlled by the steep gradient (Fig. 14) and its direct connection with the basin. Similar retrogressive pattern affects also the SE-FCS and

western margin, often facilitated by gravitational processes, related to the slope values (Fig. 4). Furthermore, the direct linkage between the southwestern flank of Sardinia and the deeper margin regions results from retrograde erosion caused by the CV (Lecca et al., 1998). In contrast, the Gulf of Cagliari is shielded by the Banghittu and Ichnusa highs (Figs. 9, 12).

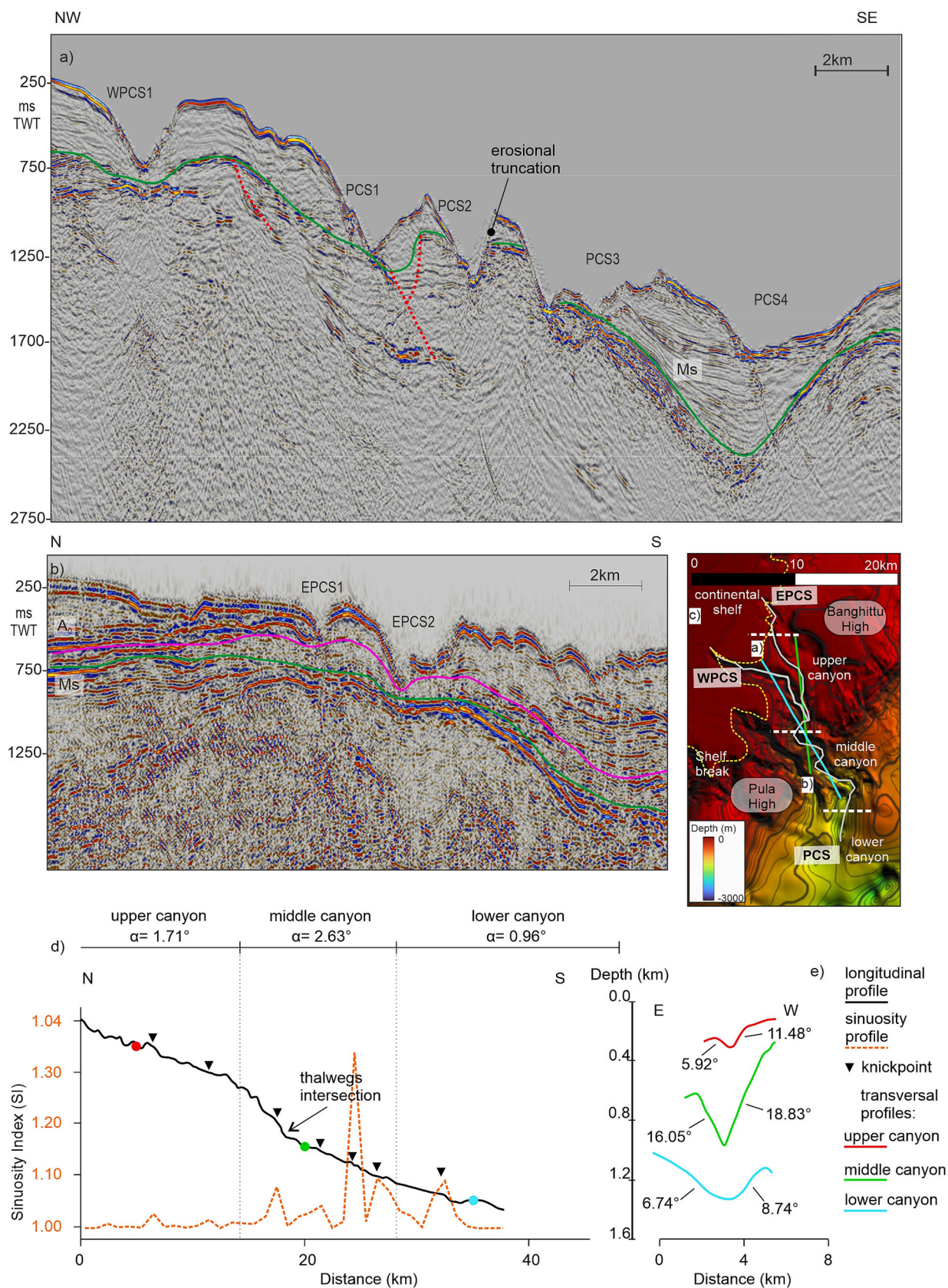


Fig. 13. Pula Canyon System: seismic and morphological profiles. a) and b) The seismic sections cut the canyon several times; c) map location; d) longitudinal profile and sinuosity index; e) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in c).

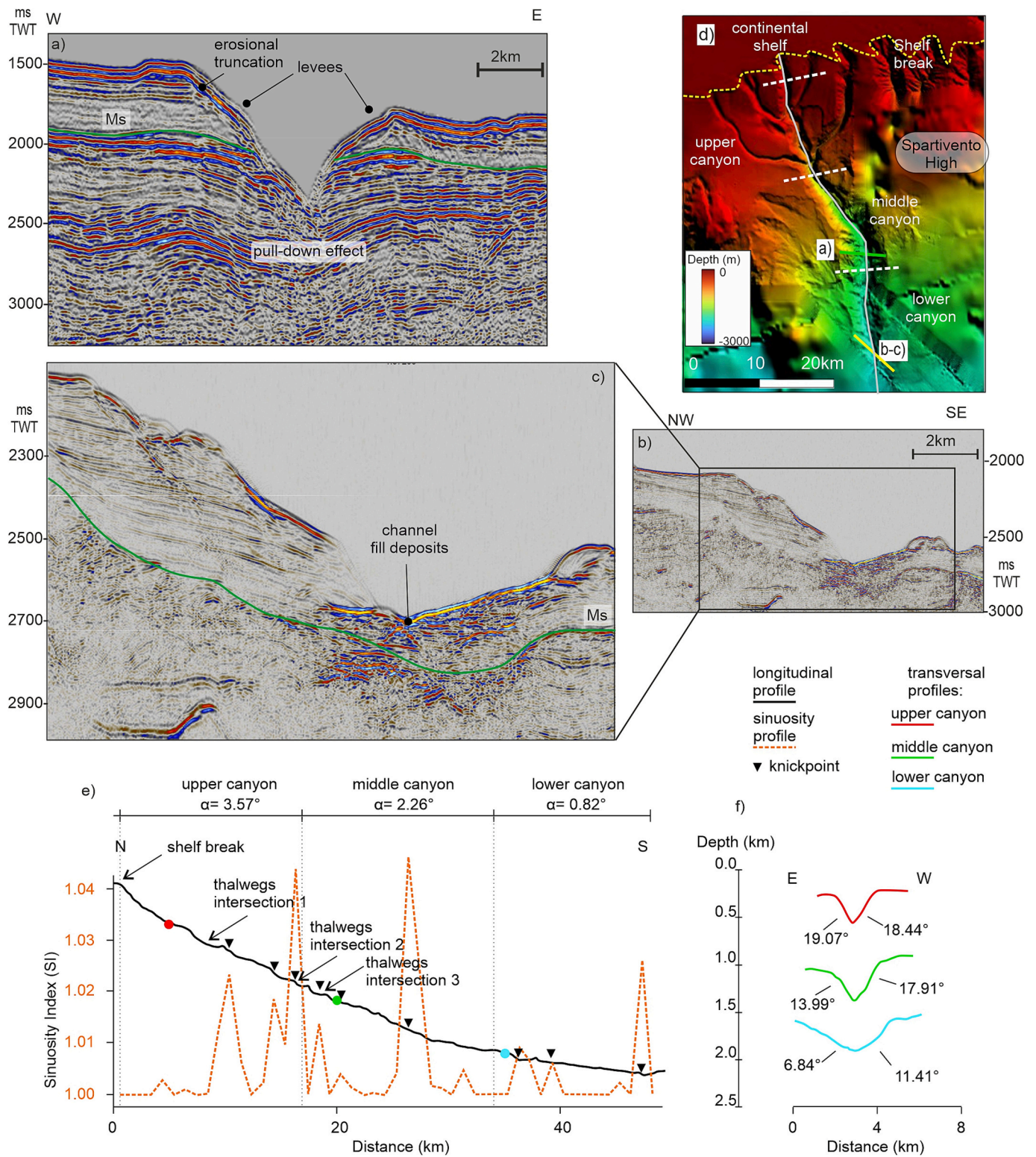


Fig. 14. Spartivento Canyon System: seismic and morphological profiles. a) Central zone showing deep incision that cuts the PQ base; b) distal zone; c) zoom of b showing a deeper incision that cuts the PQ sequence; d) map location; e) longitudinal profile and sinuosity index; f) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in d).

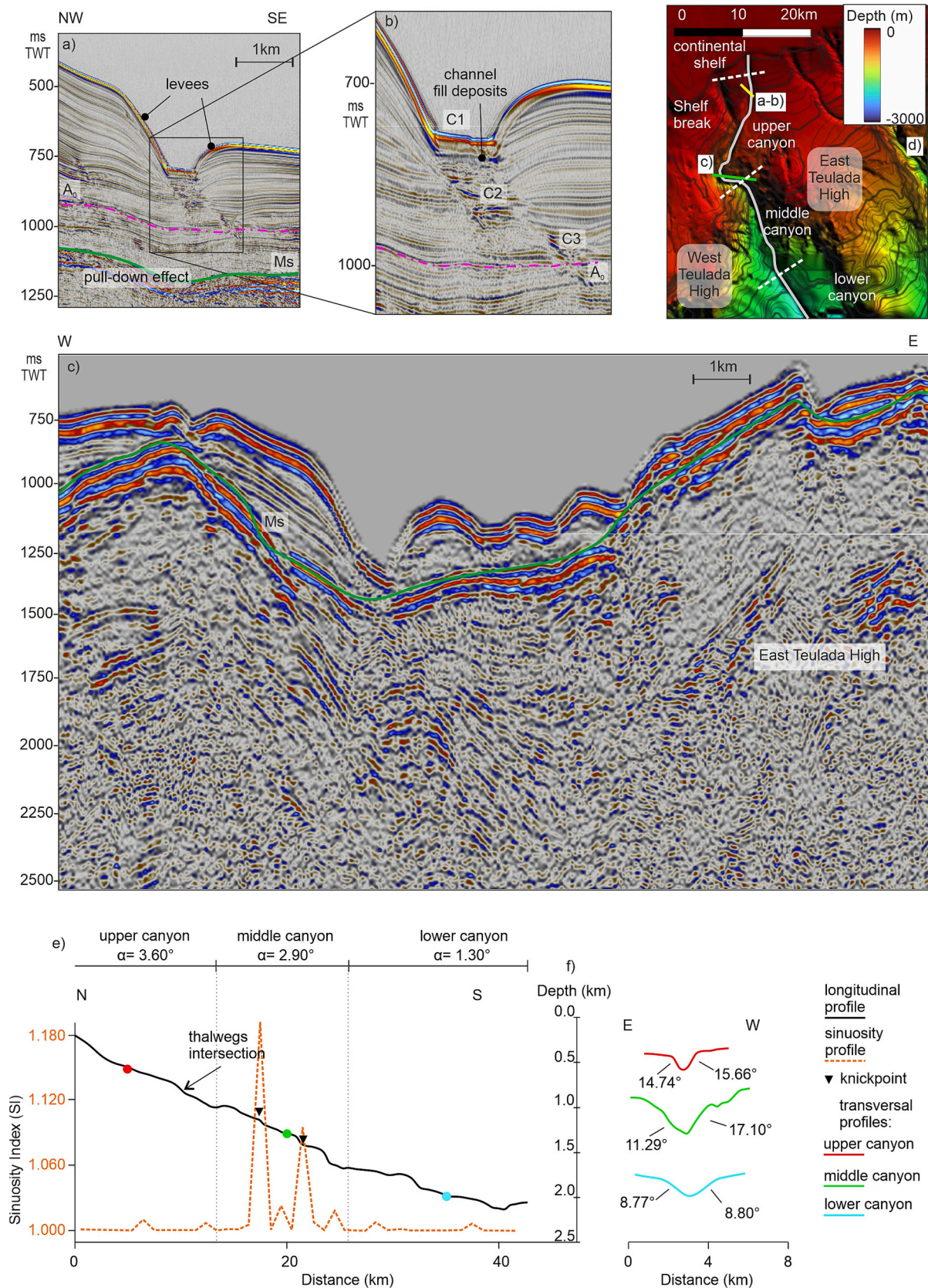


Fig. 15. Teulada Canyon System: seismic and morphologic profiles. a) Canyon head; b) Zoom of a) showing migration and filling of the canyon in the PQ sequence towards NW; c) deep incision of the canyon set between two structural highs; d) map location; f) longitudinal profile and sinuosity index; g) transversal profiles on the upper, middle and lower canyon (sited on white dashed line in d).

5.2. Controlling factors on the evolution of Sardinian submarine canyon systems

The development of submarine canyons along the Sardinian margin has been influenced by tectonic and volcanic structures, slope morphology, sediment transport processes and sea level fluctuations. Each of these factors plays a critical role in the initiation, modification, and long-term evolution of the canyon system.

5.2.1. The role of tectonic and volcanic structures

Todde (2012) distinguished the southern Sardinian canyons based on their morphological characteristics, identifying tectonic (SE-FCS), erosional (SaC), or mixed (PCS) controls. Our research intends to refine this classification by integrating new seismic and geomorphic data.

As evidenced by seismic imaging (Fig. 10), the SE-FCS is weakly affected by faults, which appear to constrain the canyon path in the upper canyon branches (Fig. 10a). The CG profiles (Fig. 10b,c,d) generally show that the A_0 reflector is often tilted, sometimes marking the Quaternary base as an erosional surface, but it is never cut by faults, meaning that the upper faults below the SE-FCS are not related to tectonics. Anyway, tectonic events affected the study area during the Quaternary, in fact the PCS appears to be structurally controlled, with normal faults affecting both the PQ and pre-PQ sequence (Fig. 13a). Similarly, the asymmetry of canyon walls (Fig. 14f) in the middle and lower SpCS is likely related to the increasing dipping of the underlying basement (Fig. 14b,c).

Evidences of canyon axis migration indicate a dynamic and extended evolutionary history. In the SaC (Fig. 11b,c,d) and TCS (Fig. 15a,b), this migration is driven by the presence of buried structural anticlines that also characterize the shape of the overlying sedimentary layers, affected by draping deposition and differential compaction. In particular, in the middle TCS canyon (Fig. 15c), the East and West Teulada highs limited its development and longitudinal trajectory, thereby impacting its sinuosity (Fig. 15e). Similarly, the PCS is predominantly shaped by the presence of the Banghittu and Pula Highs (Fig. 13c), which drive its meandering course. Moreover, the morpho-bathymetric map (Fig. 5b) and seismic analysis (Fig. 12) show how the Banghittu and Ichnusa uplift has played a critical role in shaping the CV (Fig. 12c,e). Therefore, on the southern margin, the ENE-WSW alignment of morphological and structural highs runs parallel to the Ichnusa Seamount and continental shelf (Fig. 9), incorporating features such as the East and West Teulada highs, and the Spartivento, Pula, and Banghittu highs, delineating the boundaries and pathways of the canyon systems.

In the western Sardinian canyons, the morphology is largely influenced by volcanic structures. For instance, the CCS is shaped by the Putzu Idu Volcano (Fig. 6c,d), which is likely of early Pliocene origin, as suggested by the deformation of the surrounding stratigraphic sequence and the presence of overlying plastered deposits. Similarly, the southern branch of the OCS is controlled by the Pistis Volcano (Fig. 8b). Furthermore, outcropping morphological features of the CVF control the sinuosity of both the CCS and N-OCS (Figs. 5, 6d, 7e) along the West Sardinian continental shelf, as confirmed by the sinuosity profiles.

5.2.2. Slope morphology, instability processes and sediment transport

A key factor controlling the origin of canyons on the Sardinian margin is the slope gradient, influenced by sea-level changes which destabilize the slope, triggering slope failure and retrogressive erosion (Pratson and Coakley, 1996; Harris and Whiteway, 2011). Tectonic uplift, including late Miocene inversion of the OM rift fill (Casula et al., 2001) and recent tilting of the West Sardinian margin (Frisicchio et al., 2025), has further modified the slope, accelerating erosion on both the OCS and CCS. The western and southern Sardinian margins exhibit slopes lower than 3° , with slightly higher values in the Sulcis sector (3° – 4°). In particular, the PCS is characterized by high values in its middle section, which, together with the high relief values and the absence of depositional features, evidence how the slope gradient was crucial for its

development, with active sediment transport (Fig. 13a,b).

Slope instability is generally caused by sea-level fluctuations, whose effect in the southern Sardinian margin was enhanced by the tectonic activity associated with the last phase of the Campidano Graben extension and the transpressive phase related to the Sardinia-Africa collision. Further landslides, triggered by high slope values (Soulet et al., 2016), were identified by the MaGIC project around the head of canyon systems subject to active retrograde erosion. They can be considered as a trigger mechanism for the canyon development, as already suggested by Johnson et al. (2011), Todde (2012) and Meleddu et al. (2016) for the SE-FCS and SaC (Figs. 10, 11), and consistent with classical models of canyon formation (Farre et al., 1983; Green et al., 2007). Furthermore, high slope values can favor the downslope movement of gravity-driven currents, which have the potential to reshape canyon heads and drive canyon migration (Shepard, 1981; Harris and Whiteway, 2011). Our data further reveals that sediment transport mechanisms, such as mass flow and bottom currents played a key role in shaping the OCS and CCS systems (Figs. 6c, 7a,c, 8a,c), in particular, the presence of contouritic drifts indicates bottom currents activity (Rebesco et al., 2014) which contributed to the lateral migration of paleo-incision (Mao et al., 2014) in Western Sardinia (Figs. 6, 7, 8). For instance, in the N-OCS system (Fig. 7a), branches 2 and 3 are filled with plastered deposits, while branch 1, still active, lies on 2 paleo-incisions that appear to be coeval with the contouritic drifts found in the adjacent sediments. Similarly, plastered deposits on the SM branch of CCS seem to be responsible for filling the paleo-incisions C2 and C3 (Fig. 6c). Furthermore, shelf bottom currents interact with the CVF and Putzu Idu volcano in the OCS and CCS respectively, further influencing the paths of these canyons.

5.2.3. Sea level fluctuations

Quaternary climatic oscillations, particularly the Last Glacial Maximum (LGM), have led to significant changes in the slope morphology of both Western and Southern Sardinia. This is supported by the fast erosional lowstand phase and subsequent eustatic sea-level rise, with markers such as the Younger Dryas paleo-coastlines and relict coastal beach rocks in the southern Sardinian margin (Deiana et al., 2021). Significant sea-level fluctuations are also evidenced by the regressive clinoform system (Frisicchio et al., 2025), which plays a crucial role in shaping the region's geomorphological features during the LGM (Aiello, 2022).

The TCS and its paleo-incisions (C2 and C3; Fig. 15b) do not affect the Pliocene unit (Fig. 15), indicating a Quaternary erosional activity. The SaC seems to be influenced by the pre-Messinian Banghittu structure (Figs. 4, 11c), which drove it initially in a ENE direction. The identified paleo-incisions emphasize changes in flow dynamics with alternating phases of erosion and sediment infill (Fig. 11b,c,d). This last is associated with non-continuous high amplitude reflectors that usually indicate coarse-grained deposits. Continuous and cyclic stacking of lowstand systems creates buried paleo-canyons (Fig. 11b,c,d), documenting the glacio-eustatic control in the infilling of the basin floor (Lecca et al., 1998).

We classify the Sardinian canyons as type 2 systems—i.e. canyons that cut into the shelf without a connection to major fluvial systems (Figs. 5, 9). The earlier classifications of the southern Sardinian canyons as type 1 systems (Harris and Whiteway, 2011), in fact, seem not to be supported by either our data or existing literature, both not providing clear evidence of present-day fluvial systems on the shelf. The only documented case is reported by Deiana et al. (2021) on the southwestern Sardinian shelf, in an area not analyzed in this study. Consequently, our findings suggest that their development was primarily controlled by the interplay of currents, tectonics, and slope instability, rather than by fluvial connections.

5.3. Timing of Sardinian canyons

The age and evolutionary history of Sardinian canyons provide critical insights into their formation mechanisms. While previous studies suggested that the MSC played a key role in the formation of Mediterranean canyons (Harris and Whiteway, 2011; Migeon et al., 2012), our analysis indicates that these canyons, although influenced by Miocene topography, developed more recently, within the PQ sequence. Seismic data show that the incision is generally limited to the upper PQ sequence, reaching the Ms. horizon only when the recent incision affects all the PQ sequence, resulting from a combination of heightened energy levels and a decreased thickness of the PQ sediments (Figs. 7d, 14a). This pattern has been previously observed by Frisicchio et al. (2025) in the western Sardinian margin and is further supported by our findings in the southern sector. More frequently the current incision does not even reach the A₀ reflector (Figs. 6c, 7a, 8a,b, 10b,c,d, 11, 12c, 15). However, several paleo-incisions have been identified within various canyon systems (Figs. 6b,c, 7a,c, 8a, 11b,c,d, 12a,b, 15b), which were active during the Quaternary glacio-eustatic oscillations (Figs. 6, 7). Their migration (Fig. 11c,d,e) generally developed on the flanks of structures produced by the Messinian erosion (Fig. 11c, 12d) and PQ deformation (Fig. 12c, d), or both processes (Figs. 7, 8, 11c, 12a). The Pliocene sediments underlying these incisions often exhibit parallel and sub-horizontal geometries (part of the effect of the pull-down velocity, Fig. 14a), indicating a lack of post-MSC erosive activity and suggesting that the development of these canyons is relatively recent. Some canyons in southern Sardinia, such as the SaC, exhibit long-term episodic reactivation with numerous stacked paleo-incisions (Fig. 11). In contrast, western Sardinian canyons exhibit stronger depositional influences, with contourite drift deposits suggesting a key role of bottom-current activity in infilling paleo-incisions (Figs. 6, 7, 8).

5.4. Comparison with other shelf incised canyons

The studied canyons display spatial patterns and dimensions that align with the average characteristics of Mediterranean canyons, which have a mean length of approximately 30 km (Harris et al., 2014) and a mean width of about 8 km (Harris and Macmillan-Lawler, 2015). The canyons analyzed in this study show geomorphological values consistent with the Mediterranean canyon averages (Table 2). Shelf-incised canyons commonly widen downslope (Lastras et al., 2007, 2009; Wiles et al., 2019), a pattern observed in the Western Sardinian margin, as well as in the PCS, SpCS and TCS in Southern Sardinia (Table 2). Additionally, canyon relief generally decrease downstream (Baztan et al., 2005; Puga-Bernabéu et al., 2013; Micallef et al., 2014b), a trend evident in the N-OCS, SE-FC, SaC and SpCS (Table 2).

Baztan et al. (2005) describe axial incision processes in the Gulf of Lion, emphasizing the presence of multiple paleo-incisions and the lateral canyon migration driven by alternating erosion and sediment infill due to sea-level fluctuations. A similar pattern is observed for the CCS and OCS in Western Sardinia and the PCS, TCS and SaC in Southern Sardinia, where paleo-incisions suggest episodic erosional events and the lateral shift of canyon axes indicates canyon reorganization in response to changing sedimentary regimes. Marchès et al. (2007) highlight the role of sedimentary infill in shaping the Portimão Canyon, where contourite deposits significantly contribute to the progressive smoothing of canyon relief. A similar process occurs in western Sardinia canyons, where contourites reduce relief contrasts and gradually bury older canyon features (Figs. 6a, 7a).

6. Conclusions

This study highlights the complex interplay between geomorphology, tectonics and sea-level fluctuations in shaping the submarine canyon systems of the western and southern Sardinian margins. The primary element is represented by the slope gradient of the margins,

which increased during the PQ, and by the important eustatic variations of sea-level, which were particularly active during the MSC and the Quaternary ice-age. Slope instabilities strongly affect the morphology and development of the canyons, triggering downslope sedimentary flows and slope failure processes, such as retrogressive erosion at the canyon heads. Tectonic highs in the southern margin and volcanoes in the western margin control the paths and sinuosity of these canyons. In the study area, sediment transport and canyon incision are driven by mass flows, gravity currents and bottom currents, rather than by fluvial inputs, which are very scarce in western and southern Sardinian margins. This absence of major rivers suggests that Sardinian canyons fit within type 2; however, a more detailed analysis of the continental shelf using higher-resolution bathymetric and seismic data could assess potential subtle fluvial influences not evident at the current resolution. We establish that the current Sardinian canyons are recent and represent the evolution of alternating erosion and filling phases. The canyons developed during the Quaternary, often on the flanks of morphological and structural features, sometimes influenced by buried structures produced by the Messinian erosion. The incision only occasionally extends to the Pliocene and rarely reaches the Messinian surface, suggesting that recent geological processes, related to slope morphology (e.g. margin tilting in the western margin) and influenced by sea-level fluctuations (e.g. SaC paleo-canyons in the southern margin), are the primary drivers of incision and sediment transport. This study enhances our understanding of the evolution of these complex submarine systems and underlines the ongoing influence of geological forces in shaping the Sardinian margin. Future research should explore the role of these canyons in supporting benthic ecosystems, assess the accumulation of pollutants, and examine how climate change and anthropogenic activities affect their dynamics.

CRedit authorship contribution statement

Maria Cristina Caradonna: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Veronica Frisicchio:** Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Anna Del Ben:** Writing – review & editing, Validation, Supervision, Conceptualization. **Riccardo Geletti:** Writing – review & editing, Visualization, Resources, Data curation.

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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Data Availability

The seismic data are available at the Seismic data Network Access Point (SNAP). URL: <https://snap.ogs.trieste.it/>

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