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Tectonic Interplay in the Gulf of Cagliari (Italy): Extension, Compression and Strike-Slip Movements

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ABSTRACT

The Gulf of Cagliari (CG) region has been shaped by a combination of extensional and compressional tectonics, sometimes accompanied by transpression, since at least the Paleogene. The Corso-Sardinia Plate underwent counterclockwise rotation during the Late Oligocene-Early Miocene and coeval extensional tectonics formed the Sardinian Rift, which propagated into the present-day CG region. Simultaneously, compressional structures developed at the southeastern margin, starting the collision with the northern Africa margin. The Banghittu and Ichnusa highs, underlain by Palaeozoic basement, were uplifted and subsequently partially buried by thick Oligo-Miocene (OM) sedimentary wedges. Starting in the Late Miocene onwards, the southern Campidano Graben partially reactivated the pre-existing faults of the Sardinian Rift in the CG area. A Messinian evaporitic sequence (200–300 ms TWT of gypsum thickness) was deposited, thinning toward the margins. At the Last Messinian, a deep canyon eroded the gypsum within the graben depocenter, which was subsequently filled by Pliocene sediments. Compressional tectonics resumed at the Pliocene-Quaternary boundary (Ao phase), probably due to collision with a thick African continental foreland. The Banghittu High, ENE-WSW trending, was disrupted by the extensional deformation of the Campidano Graben and is now mostly buried below the Plio-Quaternary (PQ) sediments partially transported through recent canyons. In contrast, the Ichnusa High remains exposed, shaping the southern margin of the gulf with its NE-SE elongated form related to SE-ward compression. Its approximately symmetrical section also suggests a Quaternary strike-slip component. During the Quaternary, a canyon system was re-established, with trajectories partially determined by the previous structural highs.

1 | Introduction

The Gulf of Cagliari is situated in the northern sector of the Sardinia Channel, an area primarily consisting of the Sardinian and African continental shelves and slopes. Beneath these, nappes and deformed continental blocks form a structural boundary separating the Algerian and Tyrrhenian oceanic basins.

Multiple tectonic phases can be identified in the Gulf of Cagliari, reflecting a series of extensional and compressional events that occurred throughout the Cenozoic. Corti et al. (2006), analysing

Abbreviations: Ao, base of Quaternary; BH, Banghittu High; Bv, base volcanic unit; CG, Gulf of Cagliari; CV, Carbonara Valley; DMC, Deep Messinian Canyon; IH, Ichnusa High; m, multiple; Ms., Messinian top erosional truncation/Base of left-lateral Pliocene; MSC, Messinian Salinity Crisis; OM, Oligo-Miocene; PQ, Plio-Quaternary; Tv, top volcanic unit; TWT, two way travel time; Z, Hercynian unconformity.

Highlights

- The development of the Sardinian Rift and Campidano Graben had a significant impact on the structural evolution of the Gulf of Cagliari.
- During the Oligo-Miocene, compressional tectonics led to the uplift of the Banghittu and Ichnusa highs, which at that stage were not yet distinctly separated.
- These earlier thrust structures were reactivated at the end of the Pliocene and by a more recent transpressional tectonics.
- During the Messinian salinity crisis, evaporitic layers were deposited on the Cagliari continental slope.

the coexistence of extensional and compressional processes in the NW Sicily Channel, suggest a connection between the extensional systems of the Campidano Graben and the Sicily Channel, which is intersected by the coeval Apennines-Maghrebides accretionary prism.

The coexistence of extensional, compressional and strike-slip tectonics in this sector of the Mediterranean was already described by Torelli et al. (1990) as the result of a large-scale alternation of tectonic regime: contraction during the Corso-Sardinia microplate rotation; extension and strike-slip tectonics during the initial opening of the Tyrrhenian Sea; and subsequent compression and transpression.

Compressional events were already active during the Palaeozoic Hercynian orogeny with Southern Sardinia representing the foreland zone (Franceschelli et al. 2005). Consequently, Alpine tectonics affected present SW Sardinia with eastern Pyrenean compression (Barca and Costamagna 1997). Alpine compressions are interpreted as due to the counterclockwise rotations of Corso-Sardinian and African plates (Westaway 1990), also associated with sinistral transpressive faults of incipient Apennine Chain (Carmignani et al. 1994). In the Gulf of Cagliari area, these compressive phases resulted in the uplift of a Palaeozoic basement, which now crops out in Sulcis and Sarrabus-Gerrei regions, located to the west and east of Campidano Graben, respectively (Cherchi and Murru 1985).

The northern Gulf of Cagliari was investigated by Lecca et al. (1986, 1998), who employed analog single-channel Sparker, Uniboom and Sub-Bottom profiling systems, which provided high-resolution data of the sedimentary sequence to a depth of several tens of meters. Casula et al. (2001) analysed the entire Campidano Graben using multiple NE–SW-trending seismic profiles, extending to the continental shelf of the Gulf of Cagliari, based on publicly available ES seismic data and extending to the continental shelf of the Gulf of Cagliari. More recently, Allevi et al. (2025) interpreted the Sardinia Rift as a failed arm of the West Mediterranean rifting, reactivated and inverted by transpression, which produced the Campidano Graben.

To enhance our understanding of previously unexplored, buried geological structures along the continental slope of southern Sardinia, a seismic dataset (CG profiles) was acquired in 2010 by the National Institute of Oceanography and Applied Geophysics (OGS), in collaboration with the Universities of Trieste and Cagliari (Zgur et al. 2011). Owing to carefully selected acquisition parameters, the dataset delivers high-resolution imaging of the Plio-Quaternary (PQ) sequence and the upper portion of the pre-Pliocene deposits, with particular emphasis on the identification of neotectonic features. In regions with relatively minor deformations, the seismic profiles image deeper and older reflectors which have been identified in the lower-resolution/deeper-penetrating MS and CROP seismic profiles, which provide valuable insights into the deeper structural framework. Integrating datasets with different resolutions enables a more comprehensive understanding of the relationships between shallow/recent and deeper/older geological structures in the northern sector of the Sardinia Channel, providing new constraints on the tectonic evolution of this complex area since the Oligocene.

2 | Geological Setting

The Gulf of Cagliari represents a transitional zone between the extensional systems of the Campidano Graben, primarily developed in onshore Sardinia and the collisional domain involving the Corso-Sardinia and African plates in the Sardinia Channel (Caire 1970; Grandjacquet and Mascle 1978; Bouillin 1984; Bouillin et al. 1986). Several authors (Assorgia et al. 1997; Cherchi 1985; Cherchi et al. 2008; Pala 1982; Pecorini and Pomesano Cherchi 1969; Savelli et al. 1979; Spano et al. 2002) have proposed main evolutionary stages of the area, using biostratigraphic and radiometric data to calibrate geological formations and related events.

Onshore Sardinia is predominantly composed of extensively exposed Palaeozoic units, strongly overprinted by Cenozoic tectonics phases. These include compressional events related to the Apennine-Maghrebian orogeny, followed by extensional episodes that led to the formation of nearby sedimentary basins. In the onshore Gulf of Orosei, Arragoni et al. (2016) identify remnants of a fold-and-thrust belt involving both the Palaeozoic basement and its Mesozoic sedimentary cover, interpreted as the Cenozoic southward continuation of the Alpine Corsica collisional chain. In the south-western Sardinia, the presence of positive flower structures associated with sinistral transpressive fault systems has been interpreted by Carmignani et al. (1994) as systems controlling the Late Eocene-Early Miocene thrusting of the Palaeozoic basement over the Mesozoic and Tertiary cover.

In southern Sardinia, the Hercynian orogeny is interpreted as the driving force behind the emplacement of the external nappes of the Sarrabus-Gerrei region (Conti and Patta 1998) to the southeast and the Sulcis region (Carmignani et al. 2004) to the southwest (Figure 1). From a paleogeographic perspective, the Palaeozoic basement (Carmignani et al. 2004) of south-western Sardinia is comparable to coeval sequences in France and Spain, with which Sardinia remained connected until the Late Eocene (Barca and Costamagna 1997; Carmignani et al. 2004). Barca and Costamagna (1997) suggest a pre-Miocene position of the Corso-Sardinia Plate in the south-Pyrenean zone, so that in the Middle-Upper Eocene, the Pyrenaic tectonics also affected the southern Sulcis region, as evidenced by exposed Meso-Cenozoic

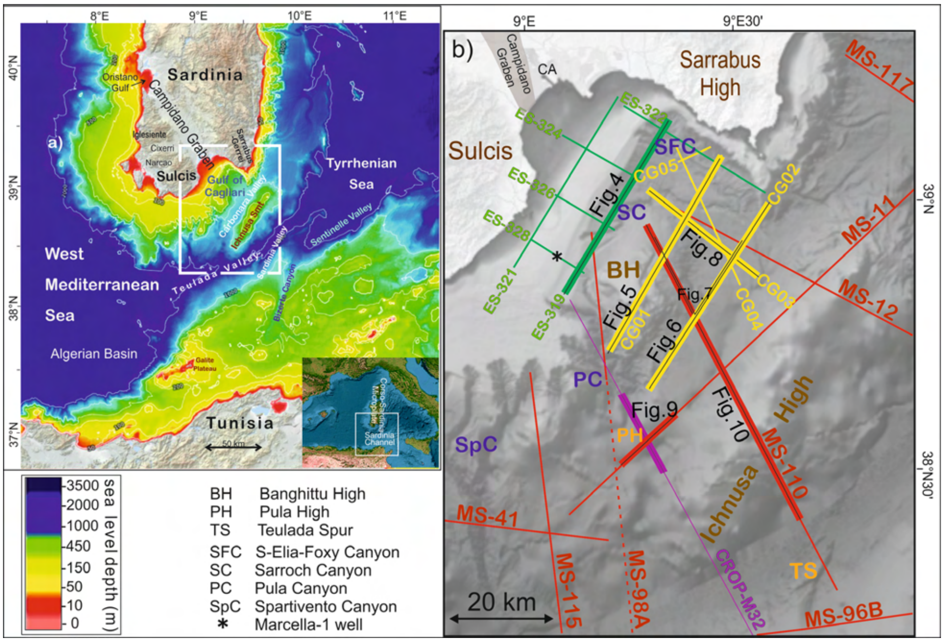

FIGURE 1 | (a) Regional map of the study area. Bathymetry by Emodnet; (b) detail of the study area with position of the interpreted seismic profiles. BH and IH are respectively the Banghittu and Ichnusa highs; PH is the Pula High; TS is the Teulada Spur by Mascle et al. (2004); SpC, PC, SC and SFC are respectively the Spartivento, Pula, Sarroch and S.Elia-Foxy canyons by MaGic Project; * is the Marcella-1 well position by the ViDEPI Project. Note that in (a), Sarrabus-Gerrei indicates the union of two areas, while in (b), Sarrabus indicates the Sarrabus High.

sedimentary successions. In this area, Eocene marine deposits and fluvial sandstones and claystones of the Cixerri Formation (Middle Eocene to Early Oligocene) are well documented (Assorgia et al. 1992; Costamagna and Schäfer 2013).

During the Oligocene, the rotations of the Corso-Sardinia Plate and the Apennine Chain, with the east-verging Alpine subduction, culminated in continental collision with the Adria Plate. This led to the opening of the Balearic-Provençal basin and to the Sardinia Rift during the Late Oligocene-Early Miocene (Maldonado et al. 1992; Watts et al. 1993; Mauffret et al. 2004). Furthermore, it triggered back-thrusts within the Alpine orogenic belt and Oligocene-Aquitanian compression in the Northern Apennines. According to Carmignani et al. (2004), the E-W oriented Cixerri and Narcao basins, located within the Sulcis-Iglesiente structural high, formed as a result of this compressive regime, combined with right-lateral strike-slip tectonics associated with the collision between the Southern European and Adria margins.

From the Late Oligocene onward, the Western Mediterranean—including the Valencia, Provençal, Algerian and Alboran basins—evolved above the subducting Tethyan slab (Roca and Desegaulx 1992; Sàbat et al. 1997; Jolivet and Faccenna 2000) as a result of back-arc extension progressing from west to east, during the counterclockwise rotation of the Corso-Sardinia Plate. Simultaneously, the Sardinia Rift developed for over 200 km in length as a north–south-oriented intracontinental graben (Cherchi and Montadert 1982; Sau et al. 2005), from the Rupelian (Reuter et al. 2017) or Aquitanian (Montigny et al. 1981) to the Middle Burdigalian (Letouzey et al. 1982; Cherchi and Tremolieres 1984). This rift separates two regional horsts composed of Palaeozoic rocks (Pala et al. 1982): a more continuous eastern horst and a more irregular western horst, along whose margin significant calc-alkaline volcanism occurred (Assorgia et al. 1997; Lecca et al. 1997). Late Oligocene-Aquitanian andesitic volcanism also affected the southern Sulcis block, as testified by its presence in the deep part of the AGIP Marcella-1well (www.videpi.com) in the Gulf of Cagliari. The southern onshore segment of the Sardinia Rift was filled with approximately 500 m of syntectonic, coarse-grained fluvial sediments of the Ussana Formation (Balia et al. 1991), in addition to sandstones and bioclastic to biothermal temperate-water limestones deposited on the continental shelf. Further Late Oligocene marine sediments contributed to ~800 m of additional thickness.

Episodes of calc-alkaline and alkaline volcanism, primarily along the western margins of the Corso-Sardinia Plate, were triggered by roughly 800 km of eastward migration of the Apennine-Maghrebian Arc from the Late Oligocene to the present. This coincided with the Tyrrhenian Sea opening from the Late Miocene (Kastens et al. 1988) into the Quaternary. At the same time, the Campidano Graben began to subside, overlapping the southern sector of the pre-existing Sardinian Rift. Structurally, it is characterized by a northeast-dipping master fault and northwest-dipping antithetic faults (Finetti et al. 2005; Lecca et al. 1998). The graben extends in a NNW–SSE direction from the Gulf of Oristano to the Gulf of Cagliari and is filled with approximately 500 m of clays, sands and fluvio-lacustrine conglomerates, attributed to the Late Pliocene-Quaternary Samassi syntectonic Formation (Balia et al. 1991).

Between Sardinia and Africa lies a south-verging, Late Cenozoic orogenic prism composed of crystalline basement rocks with European and Kabylo-Calabrian affinities, which tectonically overlies the sedimentary covers of the African margin (Catalano

TABLE 1 | acquisition parameters of the multichannel seismic profiles (MCS) used in this study.

MCS profiles	CG	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 (11 L)	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 ± 0.5 m	10 m	10 m	
Source depth	4 ± 0.5 m	14 m	5 m	

et al. 1989; Compagnoni et al. 1989). This structure continued to evolve after the cessation of the Corso-Sardinia rotation, which occurred no earlier than 16 Ma (Speranza et al. 2002). The Ichnusa High represents the most prominent structural feature in the study area, with its top located less than 200 m below sea level (EMODnet 2023). Its basement is composed of metasediments and Palaeozoic granitoids, overlain by sedimentary and post-Palaeozoic volcanic sequences associated with southern Sardinia (Compagnoni et al. 1989).

To the south of the Ichnusa High, the Sardinia Channel is characterized by an asymmetric WSW-ENE-oriented depression, exceeding 2000 m in depth. The crustal thickening, associated with the Apennine-Maghrebian Chain concurrent with the rotation of the Corso-Sardinia Plate, was followed by moderate crustal thinning related to Tyrrhenian rifting, which began during the Tortonian (Kastens et al. 1988). The African plate is anticlockwise rotating relative to Europe, around an Euler pole in the eastern Atlantic (Westaway 1990), causing regions of collision between the two megaplates. In this area, extensional and compressional processes often occurred simultaneously (Horvath and Berckhemer 1982) and minor tectonic inversions have been documented in the Algerian Basin since the Tortonian and within the PQ sequence of the Sardinia Channel (Torelli et al. 1992; Tricart et al. 1994; Depardon 1995). Transtensional to extensional tectonics, followed by Messinian erosional events (Casula et al. 2001; Finetti et al. 2005; Lecca et al. 1986; Lecca 2000), reactivated earlier extensional features. Fault kinematic indicators analysed by Camafort et al. (2022) suggest a transpressional regime dominated by a major NE–SW-trending sinistral strike-slip fault, linked to the early-middle Miocene fold-thrust belt system. The slow Africa–Eurasia convergence (~4 mm/year) is accommodated, from the Algeria margin to northern Sicily, by a transition from compression in Algeria to transpression in Tunisia and transtension in the Pelagian Platform (Rabaute and Chamot-Rooke 2019). This west to east transition developed along the STEP fault that controlled the opening of the Algerian and subsequently the Tyrrhenian basins.

Mauffret (2007) interpret the North African margin as an incipient active margin, where slow Africa-Eurasia convergence is accommodated by recent northward thrusting and transpression across the broad deformed zone of the southern Sardinia Channel.

3 | Data and Methods

3.1 | Data

The interpreted seismic profiles originate from distinct datasets. Although they exhibit limited continuity, their different resolutions enhance the ability to identify features of different scales and depths. Table 1 summarizes their acquisition parameters, while Figure 1b illustrates their spatial distribution.

Several seismic datasets have been interpreted as follows:

i. The Aquapulse ES lines (ViDEPI project), located near the gulf coast (Figure 3), were acquired by AGIP for the purpose of hydrocarbon exploration. These profiles clearly display the deep OM reflectors and the geological basement. In contrast, the PQ sequence is characterized by medium-to-low resolution (30–70 m).

ii. The CG profiles (e.g., Figure 4) consist of five multichannel seismic reflection lines acquired by the research vessel N/R OGS Explora in September 2010 (Zgur et al. 2011). The resolution and penetration depth of these lines depend primarily on the characteristics of the source. The acquisition settings, including source and streamer depths, produced a notch frequency of 150 Hz. Assuming an average seismic velocity of 2000 m/s (Figure 2), the theoretical vertical resolution within the PQ sequence, can therefore not be finer than 3–4 m. The resolution remains high throughout the PQ sequence, while the seismic signal within the OM sequence progressively attenuates.

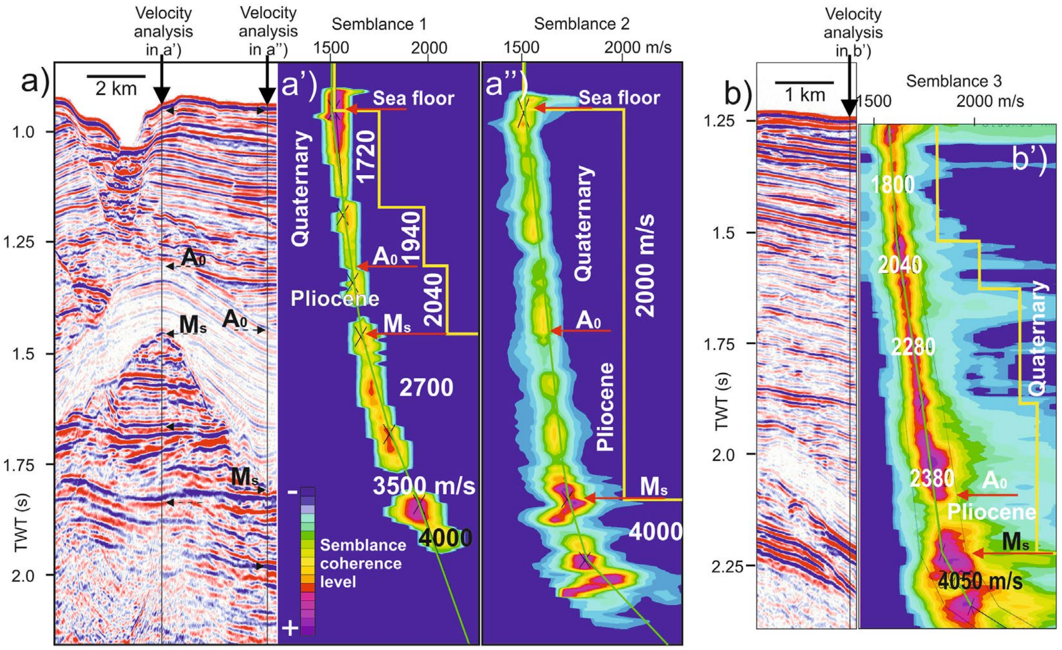

FIGURE 2 | (a) Segment of the CG-1 seismic section. The CDP gathers, indicated by the vertical lines (black arrows), correspond to the velocity spectrum panels in (a′) and (a″). Panel (a′) presents a detailed velocity analysis in the PQ sequence, while (a″) illustrates a broader velocity picking (green lines) to obtain the average interval velocity of the PQ (yellow stepped line), which can be assumed to be 2 km/s. (b) Segment of the CG-3 seismic section and its corresponding velocity spectrum panel (b′), highlighting the interval velocities of PQ and upper pre-Pliocene sequences. Ao, top of the Pliocene; Ms, Messinian unconformity.

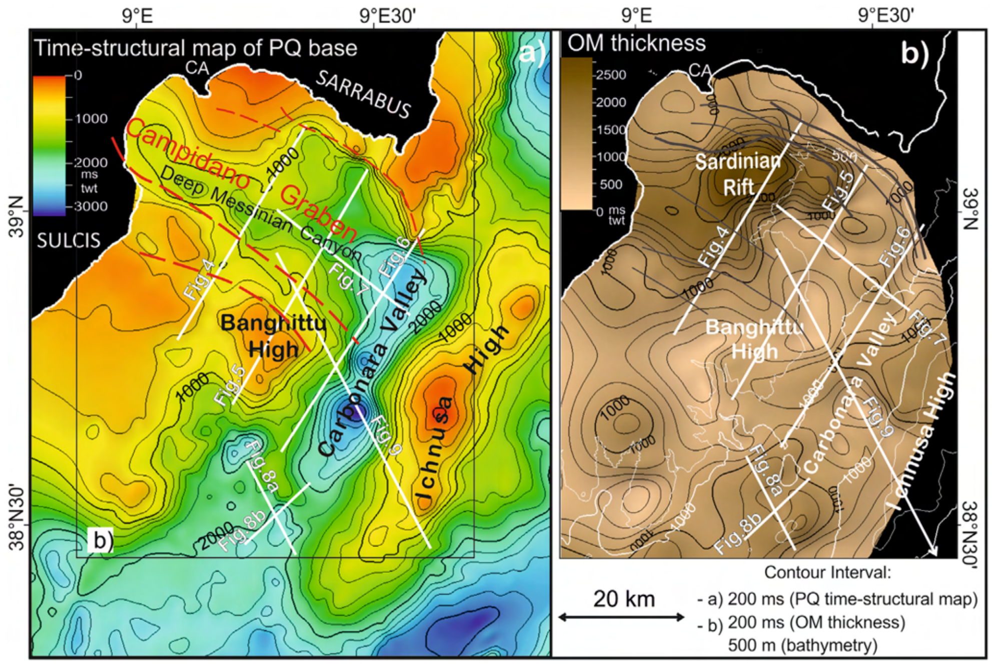

FIGURE 3 | (a) Time-structural map of the Ms reflector (base of PQ). The main faults forming the graben and the location of the interpreted seismic profiles are indicated. The Deep Messinian Canyon coincides with the depocenter of the Campidano Graben. (b) Isochron map of OM thickness (sequence between the Ms and Tv reflectors) with bathymetric lines, and location of seismic profiles (in white). The Campidano Graben converges orthogonally with the Carbonara Valley, which is prominently outlined in (a) and barely distinguishable in (b).

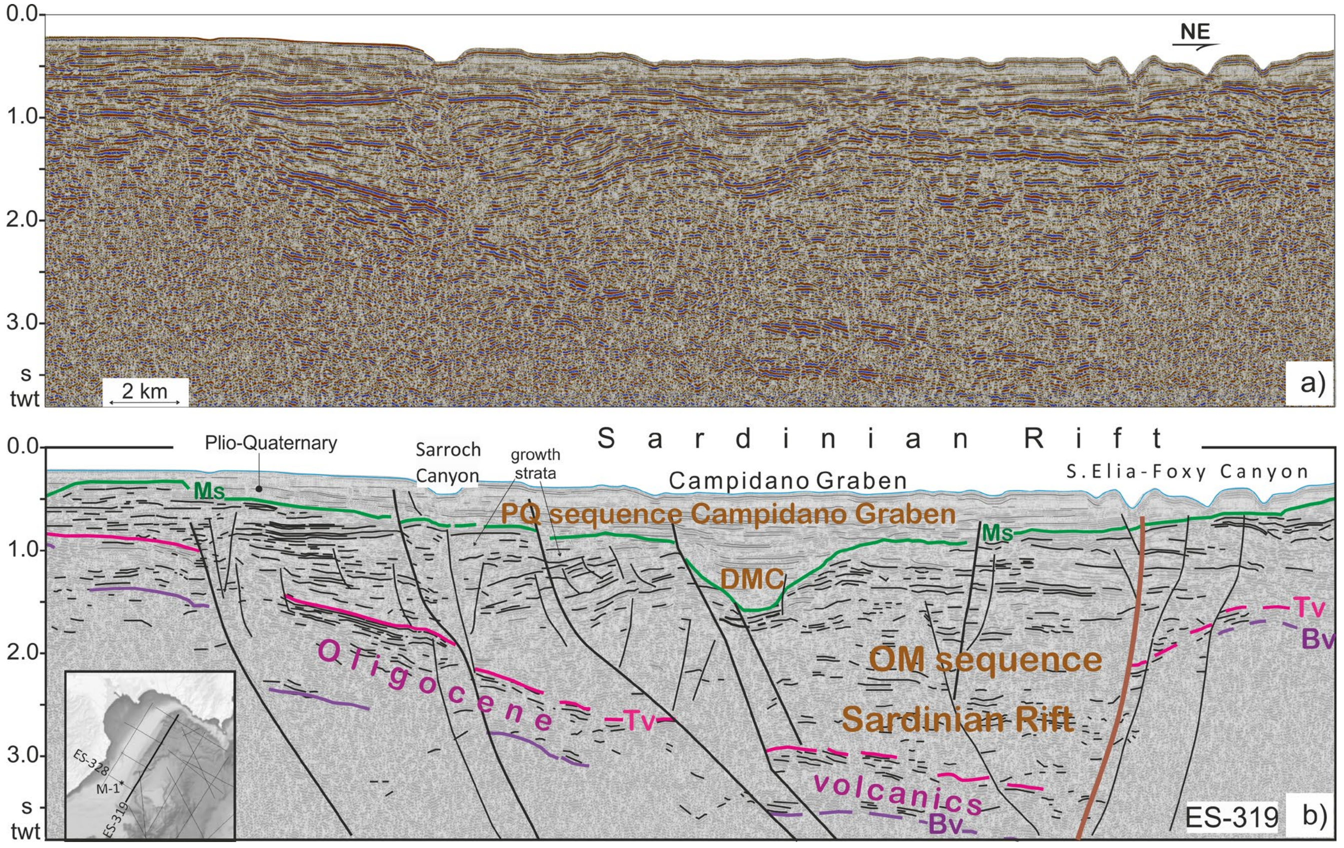

FIGURE 4 | The ES-319 seismic profile (a) in the Cagliari Shelf, close and approximately parallel to the shelf break, crosses the offshore Campidano Graben, which is a younger structure superimposed on the older Sardinian Rift. The interpreted profile (b) highlights main sequences identified and indirectly calibrated by the Marcella-1 well (M-1 *). The Deep Messinian Canyon (DMC) coincides with the graben depocenter. Inset shows location of both the ES-319 profile and the Marcella-1 well, which is about 5 km away, crossed by the NW-SE ES-328 profile.

iii. The MS profiles (Figure 6c,d) are old regional lines that effectively image buried regional structures along the continental slope; however, the seismic resolution within the PQ sequence is medium to low.

iv. The CROP-M profiles (Figure 6b), which have been acquired by the OGS since the 1990s to investigate the full crustal thickness, overlap the CG profiles and provide valuable insights into deeper geological structures. However, they have a lower resolution.

The Marcella-1 well, drilled by AGIP in 1974 and located in the southwestern sector of the continental shelf, (Cherchi and Murru 1985; Lecca et al. 1986; Pala et al. 1982), acts as a stratigraphic tie-point, reaching the Oligocene sequence, at a depth of 2440 m. The well documents approximately 350 m of PQ deposits, consisting of marine sandstone-marl succession of Aquitanian-Tortonian age (350–1265 m). This interval is underlain by the Ussana Formation (1265–1785 m), a continental clastic unit of Oligocene-Aquitanian age (Pecorini and Pomesano Cherchi 1969) and by an andesitic volcanic complex attributed to the OM age (1785–2456 m).

3.2 | Methods

The CG data employed in this study consists of 2D seismic profiles processed at OGS using Echos industrial software by Aspen Technology Inc. The data were processed according to the flowchart of Geletti et al. (2014), Frisicchio et al. (2025), Caradonna, Del Ben, et al. (2025), Caradonna, Frisicchio, et al. (2025). This dataset was integrated with vintage ES, MS and CROP-M profiles and imported into a seismic interpretation project based on the Schlumberger's Petrel E&P software platform available at the University of Trieste.

The processing of the CG lines allowed us to derive interval velocities for the shallower sequences (Late Miocene and PQ) by analysing the velocity spectra (Figure 2), with a high degree of reliability. The interval velocities calculated with the Dix (1955) formula often provide valuable insights into the lithology of the uncalibrated sediments. Specifically, an average velocity of approximately 2000 m/s was confirmed for the thicker PQ sequence (Figure 2). In addition, the seismic facies and interval velocities (4000 m/s) of the pre-Pliocene sequence (Figure 2b) appear to support the hypothesis of the presence of Messinian evaporites in the gulf.

To exploit the high resolution bathymetry provided by the European Marine Observation and Data Network (EMODnet, http://www.emodnet.eu), bathymetric depths were converted from m to ms TWT. In this way it is possible to use the same unit of measurements for the seabed and the deeper reflectors, which allows the calculation of isopach maps in TWT.

The calibration based on Marcella-1 well serves as a calibration point for the ES-328 seismic profile. Occasional time-to-depth conversions for certain sedimentary units were performed by assigning compressional wave velocity (Vp) values derived from velocity analyses conducted during seismic data processing. The available data and their interpretation enabled the creation of time-structural maps of the Ms. reflector (which marks the base of the PQ sequence, Figure 3a) and the isochrone map for the OM sedimentary sequence (Figure 3b). A map of fault patterns for the study area was also proposed.

Seismic data coverage is limited and seismic horizons are often distinctly identifiable only in selected profiles. Time-structural maps were generated using the 'convergent interpolation' algorithm with an automatic 50 m grid. A smoothed bathymetric map, which is necessary to reduce the effects of the canyon systems, was used as a guide for the Ms. reflector (Figure 3a). This method allowed a better constraint of contour lines in areas with insufficient data coverage.

The selected colour scale emphasizes zones of maximum thicknesses, typically associated with subsiding basins, fault-controlled depressions and foredeep basins. Minimum thicknesses are generally observed above structural highs (e.g., the continental shelf and the Banghittu and Ichnusa highs).

Horizontal (km) and vertical (second TWT) scales are generally indicated on the seismic profiles. Interpretation software typically provides an accurate vertical exaggeration value only for depth-migrated or depth-converted profiles; in contrast, for TWT profiles, we have to consider that the exaggeration factor varies continuously due to changes in Vp.

3.2.1 | Seismic Stratigraphy

The main stratigraphic markers were identified on the basis of field observations and data from hydrocarbon exploration wells described in the literature (Assorgia et al. 1988, 1992, 1997; Pala et al. 1982; Pecorini 1966; Pecorini and Pomesano Cherchi 1969). Particular attention was given to data from the southern sector of onshore Sardinia (Barca and Costamagna 1997, 2000, 2010; Spano and Barca 2002; Costamagna and Schäfer 2013).

Across the available seismic profiles (ES, CG, MS and CROP) regionally traceable units are characterized by significant acoustic impedance contrasts and/or by boundaries between distinct seismic facies. In particular, the following have been distinguished: the boundary between Quaternary and Pliocene units (Ao reflector); the base of the PQ sequence (Ms reflector); and the package of high amplitude seismic reflectors corresponding to volcanic layers associated with the first Oligocene rifting phase (Tv as top reflector and Bv as bottom reflector). The Tv reflector also represents the base of the OM sedimentary sequence mapped in Figure 3b. In general, the pre-Messinian horizons—more deformed and discontinuous—have often been more difficult to recognize. Seismic evidence beneath the Oligocene volcanic formation has been observed only sporadically and remains largely undefined. Particularly, the Ms. is a characteristic reflector in the Mediterranean Sea, corresponding to the top of the Messinian evaporites on the lower continental slope and deep basin, or the Messinian erosional truncation on the upper slope and shelf (Lofi et al. 2018). It was recognized as the main reflector in all the Mediterranean basins since the first seismic reflection acquisition (reflector 'A' in Finetti and Morelli 1972).

While Casula et al. (2001) and Cherchi et al. (2008) report the presence of continental deposits within the late Miocene sequence, they are not identified in our seismic analysis. We therefore conclude that such continental sediments were either not deposited, have been eroded, or are not seismically detectable due to their limited thickness in the Gulf of Cagliari. In contrast, a Messinian evaporite sequence has been hypothesized, consisting of well-stratified gypsum.

The CG seismic profiles (Figures 5, 6a, 7 and 8), which feature higher frequencies and resolution compared to the ES profiles, offer a clearer imaging of the PQ sequence. In the offshore sector of the southern Campidano Graben, this sequence displays significant thickness and can be subdivided into a lower, low-amplitude stratified facies and an upper, high-amplitude stratified facies. These distinct seismic facies are widely recognized across the western and central Mediterranean Sea, including the Sardinian Margin and Sardo-Provençal Basin (Geletti et al. 2014; Dal Cin et al. 2016; Frisicchio et al. 2025), the Balearic Basin (Blondel et al. 2022), the Tyrrhenian Basin (Selli and Fabbri 1971), the Sicily Channel (Civile et al. 2013), the Ionian Basin (Volpi et al. 2017) and the Adriatic Sea (Del Ben et al. 2018). Frisicchio et al. (2025), by correlating a seismic profile from the West Sardinian offshore with the ECORS profile calibrated by Leroux et al. (2017), assigned a 'very Late Pliocene' age to the boundary between the two stratigraphic units. Ercilla et al. (2022) assumed this marker as the base of Quaternary. We therefore assign a Pliocene age to the low-amplitude unit, and a mainly Quaternary age to the high-amplitude unit. The boundary separating these units, referred to as Ao reflector, is generally well identified across all CG profiles, although it is only locally discernible in lower resolution datasets.

4 | Seismic Interpretation

We distinguish three main morphological domains in the study area, which have been investigated by different seismic datasets:

i. The *continental shelf*, primarily investigated through the ES profiles;

ii. The *northern continental slope*, mainly explored by the CG profiles and partially by the ES, MS and CROP profiles;

iii. The *outer domain*, comprising the southern continental slope and the Ichnusa High, is predominantly analysed using the MS and CROP profiles.

Each dataset provides different levels of resolution and depth of investigation, necessitating a comparative and integrative approach. Accordingly, the interpretation focused on correlating the identified structures across profiles to reconstruct the tectonic evolution of the study area.

The Ms reflector, marking the base of the PQ sequence, is generally well defined across the majority of the profiles. Along the

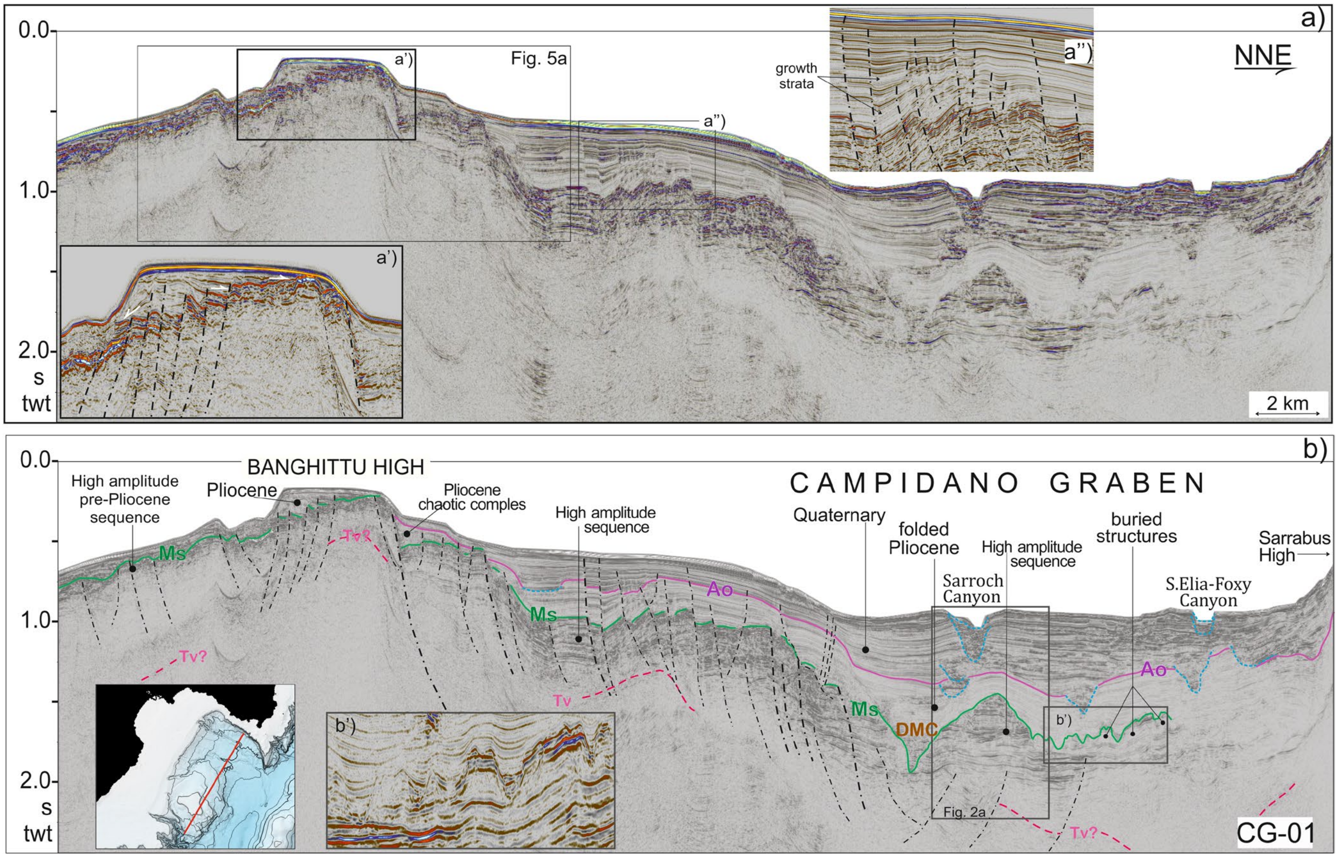

FIGURE 5 | Uninterpreted (a) and interpreted (b) seismic profile CG-01 crossing the Banghittu High and the southern Campidano Graben. The Ao reflector separates Quaternary and Pliocene units. In the upper Banghittu High, Pliocene reflectors exhibit downlap and onlap terminations (white arrows in a′), while the Ms reflector (green) marks the top of the pre-Pliocene high-amplitude sequence, affected by PQ normal faults (detail a′). In the Campidano Graben, Ms reflector represents a major erosional truncation, related to submarine Messinian canyons, as the incision of the Deep Messinian Canyon (DMC), later infilled by Pliocene sediments; a younger canyon system developed during the Quaternary (blue). Several buried, likely Messinian structures are highlighted in b′. The Tv reflector has been tentatively interpreted locally.

CG lines, we were also able to interpret the Ao reflector (top of the Pliocene unit), which is typically not well resolved in lower-resolution datasets. Deeper reflectors—such as the top (Tv) and base (Bv) of the Oligocene volcanic sequence—and more rarely, the top of the geological basement are only sporadically visible and locally correlated.

The time-structural map of the PQ base (Figure 3a) and the isochore map of the OM sequence (Figure 3b) provide valuable insight into the tectono-sedimentary evolution of the area. These maps highlight the structures most affected by PQ deformation, as well as the spatial variability in sediment accumulation during the deposition of the OM sequence.

The structural architecture is defined by the interplay of several major tectonic features that contribute to a regional compartmentalization of sedimentary deposition. They are: the southern Campidano Graben, trending NW-SE; the Carbonara Valley (CV), trending NE–SW; the Banghittu High (BH), a morphologically irregular structure dissected by canyons that induce significant local thinning and disruption of the PQ sequence; and the Ichnusa High (IH), an elongated structural high trending NE–SW.

4.1 | The Continental Shelf

The ES seismic profiles crossing the continental shelf have been calibrated using data from the Marcella-1 well (Figure 1). At a broader tectono-stratigraphic scale, the prominent normal fault system of the Sardinian Rift, has caused significant tilting of the high-amplitude seismic package of the Oligocene volcanic layer. A huge vertical displacement of the volcanic sequence defines a half graben structure controlled by a SW-verging master fault, accompanied by several oppositely-verging conjugate faults. This major displacement highlights the regional role of rifting in controlling the OM accommodation space.

The pronounced tilting of the Oligocene volcanic unit was followed by the OM onlapping sedimentary sequence, mainly composed of subparallel internal reflectors (Figure 4). The OM wedge has undergone extensive fracturing due to the Upper Miocene to Quaternary Campidano extensional system. This younger extensional phase defines a half-graben structure with vergence opposite to that of the Sardinian Rift. The Campidano extensional system partially overprints the earlier rift architecture and reactivates a significant portion of the pre-existing fault network.

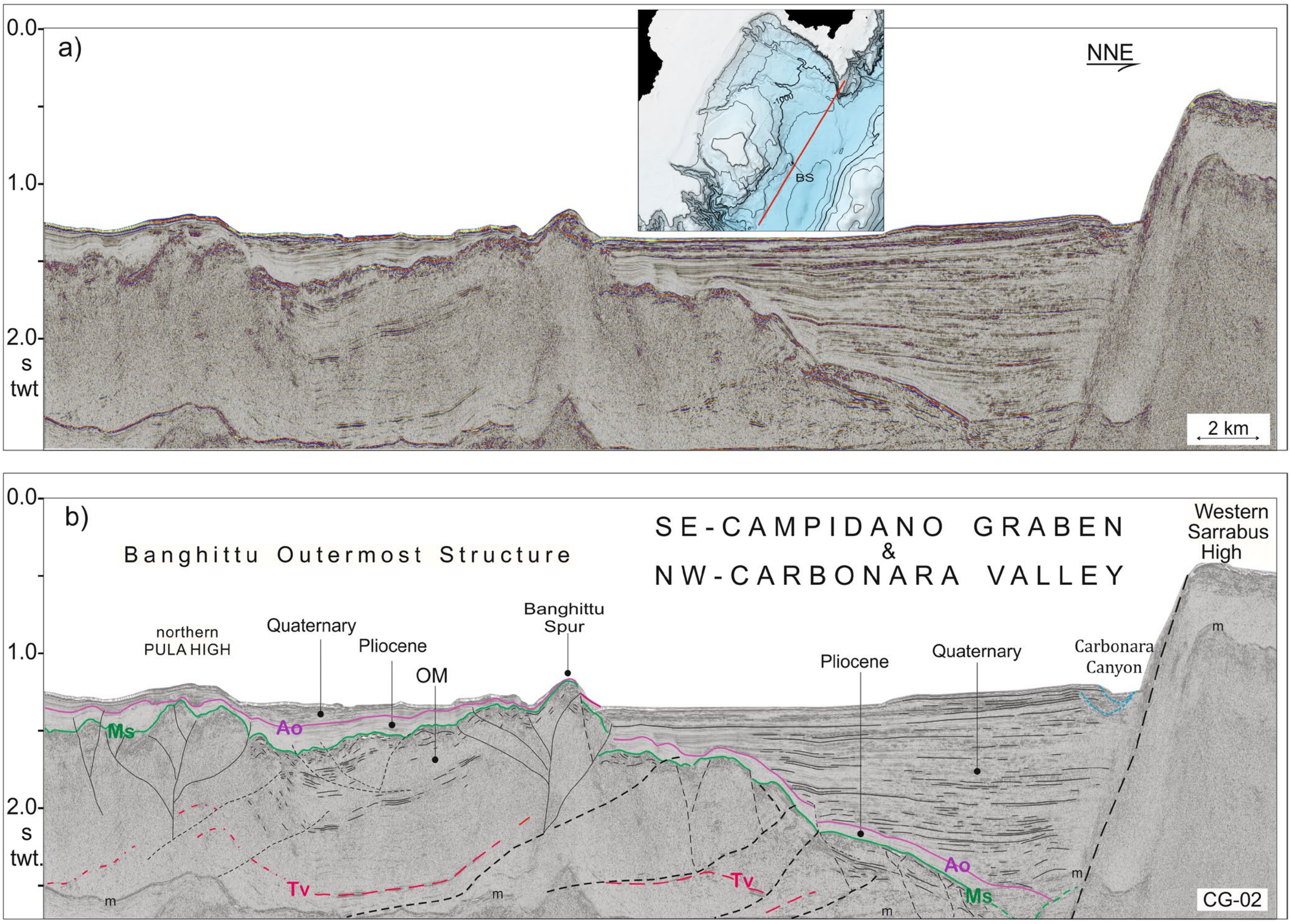

FIGURE 6 | The CG-02 profile is almost parallel to the Banghittu thrusts which are therefore partially sub-horizontal (black dotted lines). The Pliocene unit is mainly parallel to the Ms reflector, both deformed and tilted. The sub-horizontal reflectors of the Quaternary unit, onlapping the Ao reflector, reach a thickness of 1200 ms TWT at the confluence between the southern Campidano Graben and the Carbonara Valley (position in the inset, where BS and PH indicate the Banghittu Spur and the Pula High respectively).

Some pre-Pliocene growth-strata provide evidence of Late Miocene tectonic activity, while a high amplitude seismic reflector typically marks the Messinian erosional unconformity (Ms), which contributed to the deepening of the Campidano Graben depocenter in the Deep Messinian Canyon (DMC), where the PQ sequence exceeds 1 s TWT in thickness.

Outside the Campidano Graben depocenter, significant erosion of the PQ sequence is mainly associated with recent canyon incisions (Figures 1 and 4), which are not directly correlated to the Messinian erosion. The PQ sequence is thin (generally about 200 ms TWT) and characterized by low-amplitude reflectors, suggesting a predominantly Pliocene age.

4.2 | The Northern Continental Slope: Campidano Graben and Banghittu High

The continental slope extends from the shelf break down to the Ichnusa High, and is intersected by the southern ends of the NW-SE-trending ES profiles, all five CG profiles, as well as the northern sectors of four MS profiles and one CROP profile (Figure 1). To the northeast, the slope is bounded by the Sarrabus High and incorporates the intermediate Banghittu High, a roughly triangular bathymetric plateau characterized by a notably flat seafloor (Figure 1). At the base of the Sarrabus High, the Sarroch and S.Elia-Foxy canyons converge, with their orientation shifting from NW-SE to NE–SW as they enter the Carbonara Valley (Figure 1). Further southwest, the Pula and Teulada canyons also merge within the same valley.

From a stratigraphic perspective, seismic data acquired along the CG profiles (Figures 5, 6 and 8) clearly reveal two distinct seismic facies corresponding to the Pliocene and Quaternary units, separated by the Ao unconformity. Within the offshore sector of the Campidano Graben, numerous normal faults displace both the PQ and pre-Ms sequences, resulting in tilted fault blocks at the base of the Banghittu High (Figure 5). Notably, growth-strata are also well developed in the lower Quaternary unit (Figure 5a″). The seafloor is incised by recent canyons which developed during the Quaternary and locally incise the upper Pliocene unit. These canyons are infilled by high seismic amplitude, triangular-shaped seismic bodies onlapping the underlying erosional surface (blue reflectors in Figure 5b). In the Sarroch and S.Elia-Foxy canyons, the triangular-shaped bodies appear to be filled with geometries typical of levee-channel systems, suggesting changes in sediment supply. In the depocenter of the Campidano Graben, the Quaternary unit is characterized

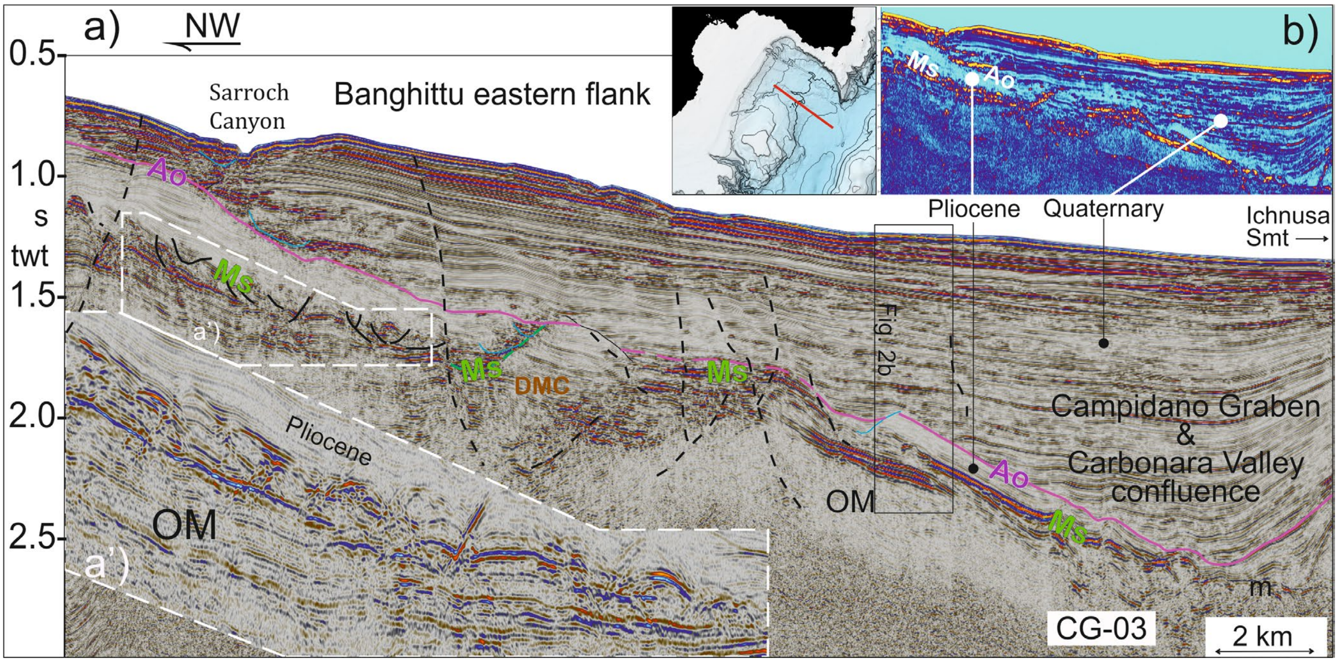

FIGURE 7 | The NW-SE profile CG-03 crosses the Campidano Graben, where Quaternary layers onlap the Ao unconformity and are only folded by the Ichnusa uplift (at the right end). In (a) the pre-Pliocene unit slides down through roll-over structures. In (b) the 'RMS Amplitude iterative' seismic attribute highlights the seismic facies variation between the high amplitude Quaternary and low amplitude Pliocene units and the thickening of the Pliocene on the upper flank of the Banghittu High.

by parallel horizontal reflectors, indicating a stable undeformed depositional setting. It onlaps the Pliocene unit, which is identified by low amplitude, parallel reflectors that are partially fractured (Figure 5a″) and weakly folded (Figure 5a,b). Beneath the Campidano depocenter, they initially infill a buried canyon system (note particularly the DMC), generated by the Messinian erosion event.

The planar Banghittu High bathymetry is shaped by PQ layers (Figures 5 and 9) that onlap its irregular south-western flank (Figure 5a′). Based on the low-amplitude seismic signals, this shallow unit is interpreted as Pliocene in age, overlain by a very thin Quaternary unit.

The Ms. reflector exhibits pronounced deepening, from approximately 200 ms to nearly 1100 ms TWT, controlled by steeply dipping NE-verging normal faults that nearly reach the present-day seafloor (Figure 5). Further northwest, the reflector reaches a depth of 1800 ms TWT due to a combined effect of faulting, PQ subsidence and Messinian erosion. This erosional surface represents a significant unconformity that sharply truncated the pre-Pliocene sequence. Between the Banghittu High and the Campidano Graben depocenter, the high-amplitude pre-Pliocene package appears intensely fractured and its thickness varies significantly: from less than 100 ms TWT over the Banghittu High, to 250 on its fractured eastern flank and exceeding 500 ms in the deeper sector of the graben, where high variations are primarily due to intense incision during the Messinian erosional phase.

In the central-eastern sector of the depocenter, the presence of the high-amplitude, subparallel reflectors directly below the Ms. unconformity (Figure 5) is interpreted as Messinian gypsum, alternated with different lithologies. This ascription to an evaporate layer is also supported by its high interval velocities (Figure 2).

In profile CG-02 (Figure 6) a thick Quaternary wedge, composed of sub-horizontal reflectors, shows only minor growth-strata. It onlaps the Ao reflector, top of the Pliocene unit, which is relatively thin (up to 100 ms TWT), at the confluence of the Campidano Graben with the Carbonara Valley. The Pliocene unit thickens progressively toward the southwest, above the outer structures of the Banghittu High. Its internal reflectors are conformable to Ms., and do not show evidence of erosional truncation at the top, indicating that the main tectonic activity (referred to as the Ao phase) occurred during the Late Pliocene to Early Quaternary age. The tilted Ao horizon is observed at a depth ranging from approximately 1200 ms TWT at the emerging peak of the southern extremity of the Banghittu High to about 2500 ms TWT at the base of the Sarrabus High, over a relatively short distance of just 11 km. The associated depocenter, infilled by Quaternary deposits, reaches a maximum thickness of 1250 ms TWT. The tilting observed in the pre-Quaternary succession, characterized mainly by subparallel layers, appears to be linked to sub-horizontal deep-seated thrusts that were active at the end of Pliocene. These compressive structures likely initiated during the OM period, when likely significant horizontal displacement occurred. The thrust faults cut through the Messinian sequence and conformably deform the overlying Pliocene unit. As also suggested by roll-over structures in the profile shown in Figure 7, this Pliocene unit is locally offset by normal faults that appear to detach at, or within, the Messinian gypsum layers.

Some of the compressional faults appear to have been partially reactivated in recent times under a transpressional

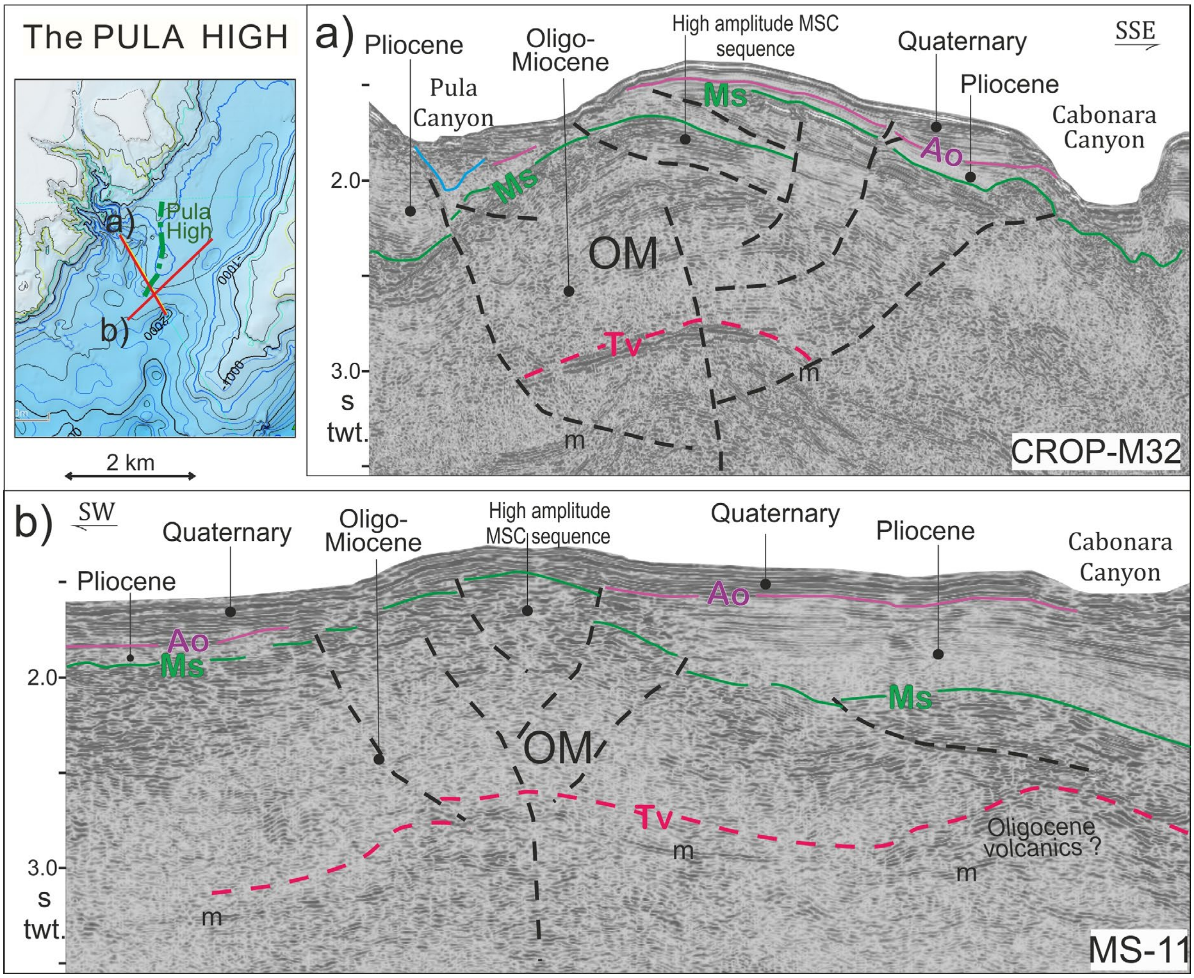

FIGURE 8 | The Pula High is bounded by the Pula and Carbonara canyons. The Quaternary unit onlaps the Ao reflector (a) and is folded to describe a positive flower structure in (a) and (b).

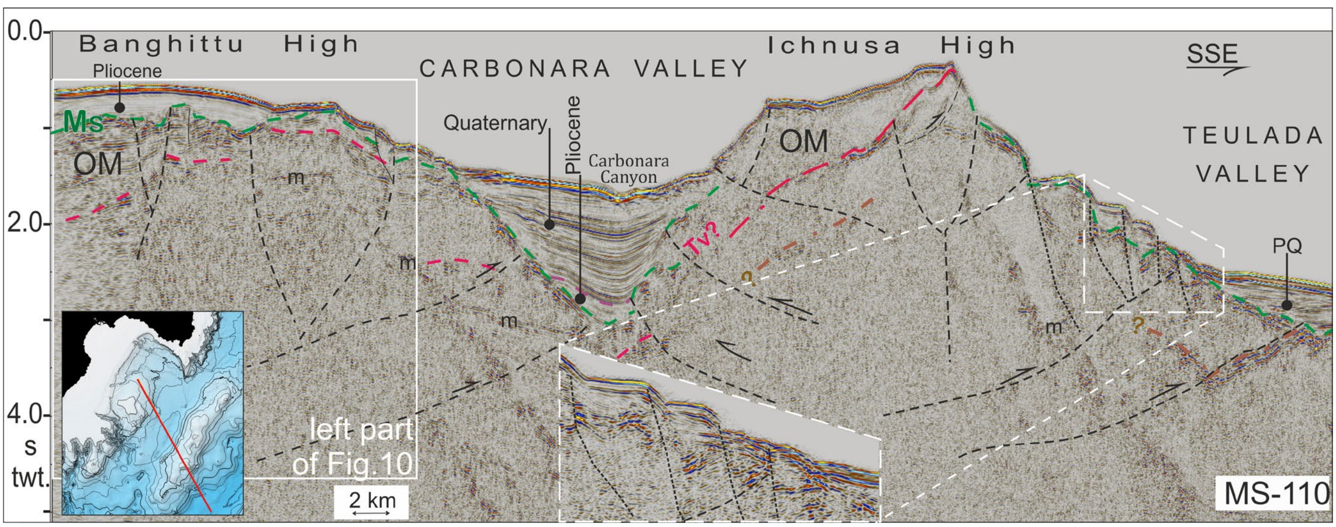

FIGURE 9 | Seismic profile MS 110 highlights the largest regional structures within the study area. From left to right, these are the Banghittu High, the Carbonara Valley (filled by the Quaternary unit and recently eroded by the Carbonara Canyon), the Ichnusa High and the eastern Teulada Valley. The OM sedimentary wedges indicate uplift events for both highs, while the partially deformed Quaternary unit infilling the Carbonara Valley is associated with recent uplift.

regime. This interpretation is supported by the interpretation of positive flower structures, which are typically formed in transpressional domains. These features have been identified in the structures referred to here as the Pula High and the Banghittu Spur (Figure 6). Toward the eastern end of the profile, a prominent structural step leads to the offshore Sarrabus High, where the Palaeozoic crystalline basement is exposed at the surface.

Deep reflectors are sporadically identified along the MS and CROP profiles, and are also imaged with sufficient resolution on the CG-02 profile (Figure 6). The isochrone map between Tv and Ms. has been tentatively generated (Figure 3b) to reconstruct the post-volcanic sedimentary infill (OM sequence) following the volcanic event controlled by the Sardinian Rift and the early pre-Pliocene Campidano extensional phase.

The profile in Figure 7 and its RMS Amplitude attribute (Figure 7b) further highlights the thinning of the Pliocene unit in the deepest part of the basin, although this unit appears to be not affected by erosion. This observation is consistent with what was already observed in the orthogonal crossing profile CG-02 (Figure 5).

4.3 | The Southern Continental Slope

The southern continental shelf is structurally dominated by the NE–SW-oriented Ichnusa High, flanked by two parallel, elongated basins: the Carbonara Valley to the northwest and the Teulada-Sardinia Valley (also referred to as the Sardinia Channel) to the southeast. These structural elements are intersected by four seismic profiles MS-12, MS-110 and CROP-M32 orthogonally and MS-11 obliquely (Figure 1). The maps (Figure 3a) indicate a structural connection between the NNE–SSW-striking Pula High (Figure 9a,b) and the south-western peak of the Banghittu High. In this area, the pre-Pliocene high-amplitude package is overlain by the Pliocene unit which is partially onlapped by the sub-horizontal Quaternary unit (Figure 8). The seafloor is incised by the Pula and Carbonara canyons, which is driven but also partially influenced the present morphology of the structure. Transpression, which folds the entire succession up to the seabed, is suggested by the positive flower structure.

The Carbonara Valley is bounded to the southeast by the Ichnusa High, which has been uplifted by SE-verging main thrusts (Figure 9). The imbrication and uplift of pre-Pliocene sequences has caused the top of Oligocene volcanics (Tv) to rise from a depth of about 3.3 s TWT beneath the Carbonara Valley to the crest of the Ichnusa High, at a depth of 400 ms TWT. The OM thickness exceeds 1 s TWT on the northern flank of the Ichnusa High. The Ms. locally crops out or is more commonly overlain by a very thin PQ sequence at the southern flanks of both the Banghittu and Ichnusa highs. Between the two highs, the Quaternary and a thin Pliocene fill the Carbonara Valley onlapping the Ms. reflector. Some back-thrusts cut the pre-Messinian and fold the PQ sequences, contributing to the current steep slope. The southern flank of the Ichnusa High is cut by recent active south-verging normal faults.

In Figure 10 the composite section includes segments of the seismic profiles shown in Figures 6 and 9, highlighting the connection between the Banghittu High and the thrusts in the profile in Figure 6.

4.4 | The Messinian Erosion

A high-amplitude seismic package is often recognized below the Ms. reflector in the analysed seismic profiles. These reflectors are generally interpreted as Messinian evaporate. The associated seismic facies suggest an alternation of salt, salt-bearing clay and anhydrite gypsum, as described by Gorini et al. (2005) in the Gulf of Lions or, alternatively, an alternation of marly beds, dolomitic and gypsiferous layers, as calibrated by DSDP wells in the western Mediterranean (Ryan et al. 1973).

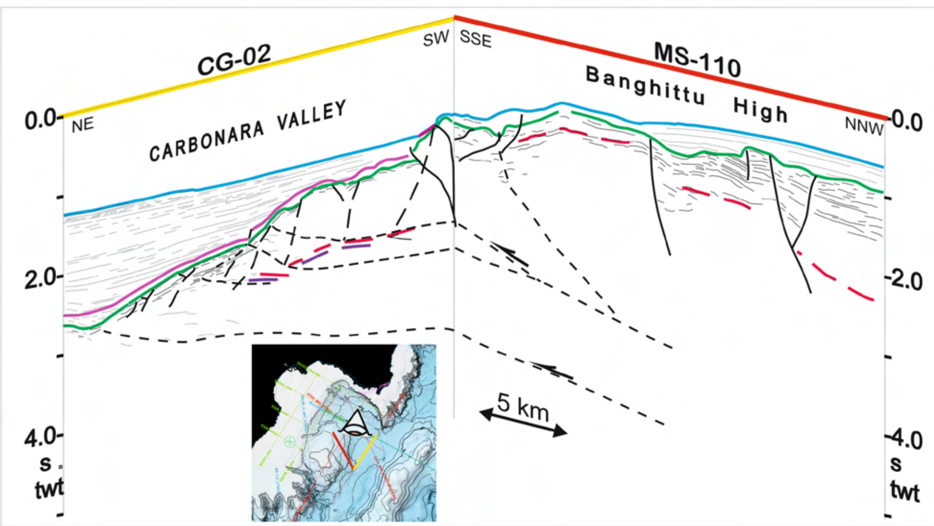

FIGURE 10 | Line drawing of the composite profile obtained by the NNW–SSE-trending MS-110 profile (part of section in Figure 9) and the NE–SW-trending CG-02 profile (part of section in Figure 6) evidences the direct relation between the thrusts already interpreted in Figure 6b (on the right) and the Banghittu High (on the left).

Toward the continental platform, this package progressively thins and ultimately reduces to a single high-amplitude reflector, locally showing evidence of erosional truncation. On the continental shelf (Figure 4) and slope (SSW sector of Figure 5, NNW of Figure 6d, SSW of Figure 7), truncation surfaces affect thin Messinian or directly pre-Messinian deposits, locally transitioning upward into conformable geometries.

In the northwestern part of the profile shown in Figure 8, the irregular morphology of the Ms. reflector is interpreted as the result of gravity-driven sliding involving the evaporate layers. In the deeper areas, the high-amplitude package is significantly thicker and is largely unaffected by erosion, except for abrupt V-shaped incisions produced by the Deep Messinian Canyon (DPM; Figure 5). As illustrated in the map of Figure 3a, this canyon developed during the latest Messinian and was likely controlled by the incipient tectonics of the Campidano Graben (Figure 4), which promoted deep incision of the evaporitic succession at the foot of the Banghittu High (Figure 6). The canyon system here coalesced with tributaries sourced from the Sarrabus High, widening toward its base. Subsequently, it deflected along a NE–SW trend within the Carbonara Trough, a structural depression located northwest of the Ichnusa High that has been active since at least the Oligo-Miocene and experienced marked tectonic accentuation during the Quaternary.

5 | Discussion

As shown in the literature (Mascle et al. 2001; Fais et al. 2002; Casula et al. 2001; Finetti et al. 2005), the Sardinia Rift and the Campidano Graben are linked to the regional extensional systems of the Sardo-Provençal Basin and the Tyrrhenian opening, respectively. The interpreted data presented here clearly reveal the effects of these extension phases in the study area, which alternated and often coexisted with compressive deformations.

5.1 | Seismic Stratigraphy and Geodynamic Significance of Key Reflectors in the Gulf of Cagliari

A significant limitation in the geological reconstruction of this region is the scarcity of well data. The Marcella-1 well is the key calibration point, providing stratigraphic constraints for some major unconformities associated with the OM and PQ tectonic phases. The recently acquired CG profiles provide clear evidence of the PQ sequence, based on the Ms. reflector, commonly recognized by truncation evidence and/or high seismic amplitude. Within this PQ sequence, the Ao reflector separates the Pliocene and Quaternary deposits and is interpreted as a regional significant Mediterranean unconformity (Figures 5–7 and 10). The Ao reflector has been variously attributed to different processes across the Mediterranean Sea, including change in seismic facies (in the Ionian Sea, by Camerlenghi et al. (2019); in the Adriatic Sea, by Spelic et al. (2021); in the Sardo-Provençal Basin, by Frisicchio et al. (2025)), compressional tectonics (e.g., Calabrian Accretionary Wedge in the Ionian Sea by Volpi et al. (2017); Upper Pliocene Tectonic Phase in the Apennine Chain, by Patacca et al. (2008)), extensional events (e.g., Middle Pliocene unconformity 'X' in the Tyrrhenian Sea by Selli and Fabbri (1971); Bacini Sedimentari (1980)), erosional surfaces (e.g., Pliocene erosional surface in Sardinia by Cocco 2013) and sea level fluctuations (e.g., BQD reflector in the Alboran Sea, by Juan et al. 2016). It remains a very intriguing question, already partially discussed by Frisicchio et al. (2025) which associated it with the intensification of the Northern Hemisphere Glaciations. In the study area, Ao represents an important geodynamic phase, characterized not only by a change in seismic facies but also by deformation of the underlying Pliocene sequence. This is particularly evident in the offshore sector of the Campidano Graben, with consequent sub-horizontal onlap termination of the Quaternary layers. This stratigraphic relationship constrains the timing of deformation between the Late Pliocene and Early Quaternary, after which sedimentation resumed under more stable tectonic conditions.

At the base of the Pliocene unit, the Ms. reflector (green reflector in Figures 4–10) is generally recognized as the main seismic reflector in the Mediterranean Sea (variously referred to in literature, e.g., Lofi et al. 2018; see for a synoptic discussion). It is typically associated either with the erosional surface of the Messinian affecting the OM sequence, or with the top of the Messinian evaporites that were eventually deposited. On the Cagliari Shelf, Casula et al. (2001) and Cherchi et al. (2008) reported the presence of continental deposits within the late Miocene sequence. However, these deposits are not evident in the interpreted seismic profiles, suggesting they were either eroded or are too thin to be resolved seismically.

In the northern sector of the gulf, the OM sequence—where evidenced by seismic markers, more clearly interpreted in Figures 4, 6, 8 and 9—forms a sedimentary wedge lying above the Oligocene volcanic unit. This unit, bounded by the Bv and Tv reflectors, is imaged in several profiles (Figures 5–7) as a package of high amplitude parallel reflectors tilted to the north and reaching a maximum depth of 3700 ms TWT (Figure 6f).

Below Bv, tilted reflectors characterized by low continuity and amplitude, with chaotic facies, indicate a highly tectonized environment. Considering the geological context of the study area, and following the results of Fais et al. (1999) and Finetti et al. (2005), it is reasonable to correlate these reflectors with the Palaeozoic basement (Figure 4).

5.2 | Fault Pattern in the Study Area

The main interpreted faults in the study area have been mapped (Figure 11) in relation to the Ms. reflector, revealing a complex tectonic evolution resulting from alternating and overlapping extensional, compressional and strike-slip regimes. The OM normal faults generated by the Sardinian Rift (brown colour) exhibit predominantly E-W or ENE-WSW direction to the south of Cagliari, behind the buried Banghittu High (Figure 3b). The Sardinian Rift is dominated here by south- or southwest-verging master faults (Figures 4 and 11), which partially deviate from the N-S trend that regionally crosses the entire Sardinia Island from the Asinara Gulf to the Cagliari Gulf (Cherchi and Montadert 1982). A significant portion of the Sardinian Rift faults have been reactivated by the Campidano faults (yellow), which represent the southeast continuation of the southern Sardinia onshore extensional

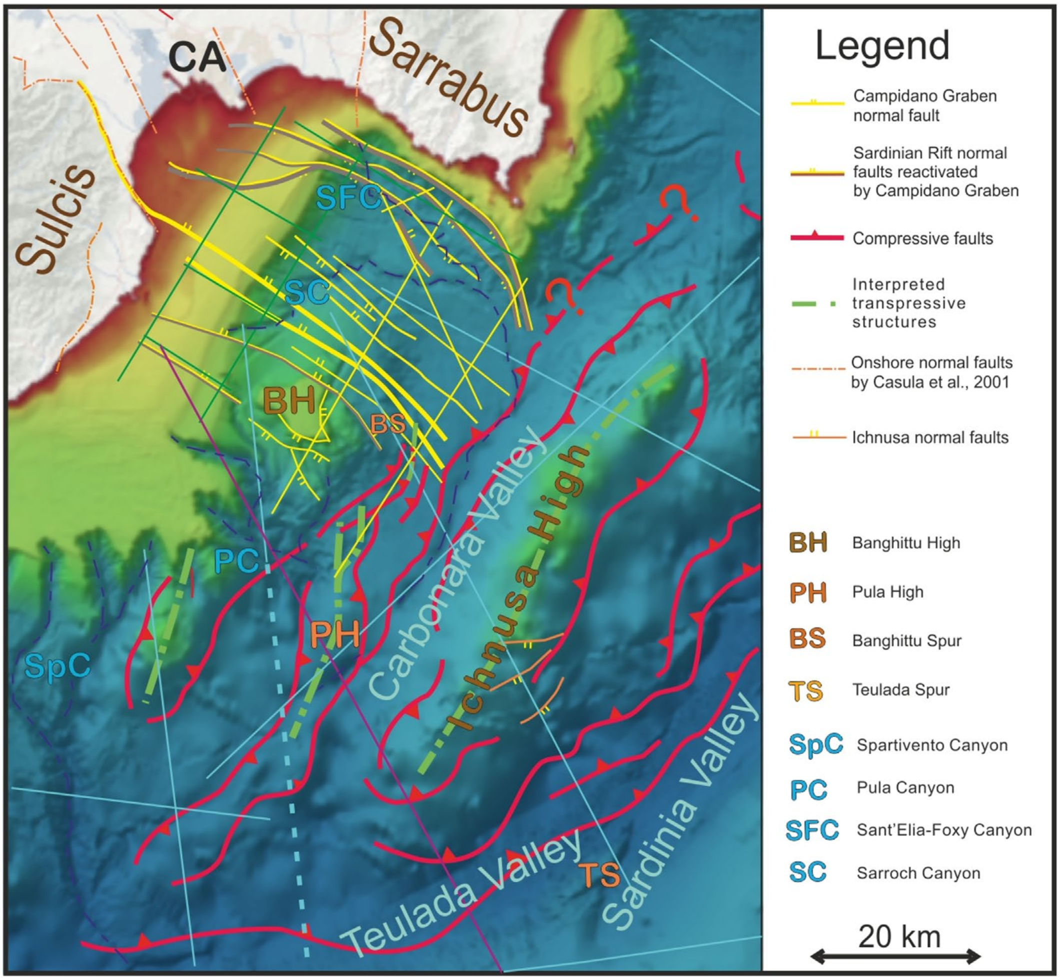

FIGURE 11 | Map of the main faults interpreted in the study area. BH is the Banghittu High; PH is the Pula High; TS is the Teulada Spur (Mascle et al. 2004); SpC, PC, SC and SFC are the Spartivento, Pula, Sarroch and S.Elia-Foxy canyons, respectively, from the MaGic Project. Coloured lines indicate the locations of the seismic profiles, as in Figure 1.

system described in the literature (Balia et al. 1991; Casula et al. 2001). The Campidano Graben is generally characterized by a main northeast-verging throw of the Ms., with significant activity during the PQ until the present.

Seafloor deformation and development of morphological steps are commonly associated with this ongoing activity (Figures 4–8). The normal faults of the Campidano Graben extend into the gulf area to the foot of the Sarrabus High and terminate north of the outer Banghittu thrusts. This configuration indicates strong structural inheritance, with the younger extensional deformation significantly controlled by the pre-existing tectonic framework.

Southwest of the Campidano Graben, a compressional regime appears to dominate. Some positive flower structures suggest localized transpression (Figures 6, 8 and 11), which, on a broader scale, seems to also affect the Ichnusa High (Figures 9 and 11).

The recent transpressional reactivation along the Campidano Graben faults, proposed by Allevi et al. (2025) for the onshore sector, has not been identified along the seismic profiles in the study. The interpreted main extensional tectonics of the Gulf of Cagliari appear, in our opinion, consistent with the southernmost seismic profile presented by the same authors (see their figure 16).

In contrast, the positive flower structures observed in the Ichnusa High and parts of the Banghittu High indicate a localized transpressional component that could be associated with a recent phase of transpression involving the NE–SW-trending structures inherited from the Africa–Sardinia collision.

The interpreted thrusts (red lines) suggest that the Banghittu and Ichnusa highs represent the effect of several compressional events:

i. during the Late Oligocene-Early Miocene, as suggested by the sedimentary wedge on the Ichnusa High (Figure 10), partially simultaneous to the Sardinian Rift;
ii. at the end of the Pliocene, as highlighted by the Ao unconformity (Figures 6–9), simultaneously with an important offshore extension of the Campidano Graben;
iii. during the Quaternary, with transpression highlighted by elongated and approximately symmetrical flower structures (Figures 6 and 9, green dotted lines in Figure 11), which can also be interpreted along the Ichnusa High

(Figure 10). This phase represents the most recent tectonics in the area. The transpressive structures (SE-Banghittu in Figure 7, Pula High in Figures 7 and 9) are likely the result of the interaction between major right-lateral strike-slip faulting observed onshore (Carmignani et al. 2004; Allevi et al. 2025) and ENE-WSW-oriented compressional structures related to the Africa-Europe convergence.

The pre-Oligocene volcanic faults are poorly recognized and not mapped.

5.3 | Campidano Graben

The present-day shape of the Gulf of Cagliari is primarily controlled by the structure of the Campidano Graben, which developed onshore as a half-graben since the Upper Miocene (Balia et al. 1991). A shift in the polarity of the master faults (Cherchi and Montadert 1982; Casula et al. 2001) has been associated with PQ transtensional tectonics by Viti et al. (2021).

Offshore Cagliari, significant extension occurred during the Plio-Quaternary period. On the continental shelf and upper slope, NE-verging master faults exhibit considerable vertical displacement. When combined with the 500 ms due to Messinian erosion, this displacement results in a marked vertical step of the Ms. unconformity, from approximately 200 ms TWT at the Banghittu High to nearly 2000 ms TWT south of Sarrabus High, across just 17 km (Figure 5).

The prominent buried channel at the base of the Campidano master fault (Deep Messinian Canyon, DMC; Figures 3a, 4 and 5) was carved by this Messinian erosion, which likely occurred shortly after the deposition of the Messinian evaporite sequence. Gypsum is hypothesized to correspond to the underlying high-amplitude seismic package.

Between the emerging Banghittu High and the Sarrabus High, normal faults cut through the entire sedimentary sequence. These structures appear to have mainly developed during the Pliocene and, in some cases, remained active until the Early Quaternary (Figure 5). Toward the SE, normal faults become less frequent and are primarily associated with sliding along the evaporitic unit, which was deformed during the Ao phase. In this sector, the Campidano Graben merges with the approximately orthogonal Carbonara Valley, which is mainly related to the uplift of Banghittu and Ichnusa highs (Figure 6).

5.4 | Sardinian Rift

The Sardinian Rift fault system describes a half-graben geometry, as evidenced by the tilting of the top of the Oligocene volcanic unit (Figure 3). As already discussed in the literature (Casula et al. 2001; Fais et al. 2002; Finetti et al. 2005), the offshore Sardinian Rift formed during the OM extensional phase. It developed along with the Corso-Sardinia Plate rotation producing a complex system of conjugate faults with a regional N-S arrangement (Casula et al. 2001). Allevi et al. (2025) interprets it as a failed arm of the West Mediterranean rifting.

In the Gulf of Cagliari, we analysed the southern offshore continuation of this rift (Figure 4), which shows a half-graben structure with a local south-verging master fault, parallel to the Cagliari coast, then transitioning into a southwest-verging orientation, parallel to the Sarrabus slope.

Seismic profiles across this area (e.g., profile in Figure 4) show parallel subhorizontal reflectors within the OM sediments, without evidence of growth strata. This suggests that a very rapid tilting occurred immediately after the Oligocene volcanic event, followed by weak tectonic activity and the progressive filling of the half-graben.

The OM isochrone map (Figure 3b) further highlights a thick OM sedimentary accumulation within the locally E-W-oriented Sardinian Rift. This is consistent with the deviation of the main coeval faults in the northern sector of the gulf (Figure 11), behind the SE-verging thrusts of the Banghittu High.

5.5 | Banghittu High

The buried Banghittu High is partially masked by the PQ sedimentary cover. This high appears as a plateau generated by subhorizontal PQ reflectors onlapping and downlapping the old, partially eroded, anticlinal buried structure, which is cut by several normal faults (Figure 5). The last tectonics, likely still active, seem to be associated with strike-slip dynamics affecting secondary structures, such as the Banghittu Spur (Figure 6) and the Pula High (Figure 8).

Although the CG-01 profile (Figure 5) does not penetrate enough to image the deeper reflectors, the outermost thrusts of the Banghittu system are recognizable and interpreted in the CG-02 and MS-110 seismic profiles (Figures 6 and 9). Structural deformation was active prior to the Messinian event, as indicated by differentiated erosional truncation of the tilted pre-Pliocene sequences (Figures 6 and 7). Further evidence of important tectonic activity during the Plio-Quaternary is given by the tilted Pliocene layers, conformable to the Ms. horizon (Figure 7), and covered by subhorizontal Quaternary reflectors onlapping the Ao unconformity. This configuration indicates a very rapid event, here defined as the 'Ao phase', often associated with a major hiatus in the Early Quaternary (Figures 5 and 10). The conformable relationship between the Pliocene units and the underlying Messinian layers suggests that the compressional regime prevailed during the Ao phase. The Pliocene unit appears to be plastically deformed and is locally affected by gravity-sliding associated with listric normal faults.

The seismic profiles shown in Figures 5 and 6 illustrate the juxtaposition and southward transition from the extensional tectonic setting of the Campidano Graben to the piggyback basin of the Carbonara Valley. The latter developed between the Banghittu and the Ichnusa highs in the Pliocene, but predominantly during the Quaternary.

The intersection of the 2D profiles in Figure 7 suggests that the current Banghittu High is a remnant of an older E-W compressional system, partially masked by the PQ normal faults of the Campidano Graben (Figure 5) and, more recently, by several canyons (Figures 5–7) that incise the Quaternary unit. The thrust system has been active since the pre-Pliocene times in connection with the Corso-Sardinia rotation. Possibly, the uplift could be started with the compressional phase previously hypothesized by Carmignani et al. (2004) in the Sulcis area, related to the collision between the Sardinia and the Adria plates (Figure 12).

Compression was subsequently reactivated during the Ao phase, leading to significant uplift of both the basement and the overlying sedimentary succession. The structure was later overprinted by localized tranpression, predominantly oriented NNE–SSW (Figures 6 and 9) during more recent time.

5.6 | The Carbonara Valley and the Ichnusa High

Above the tilted basement of the Ichnusa thrust system, the OM sedimentary wedge (Figures 3 and 9) indicates that uplift and tilting of the structure also occurred during the southeast-directed compression of the Late Oligocene-Early Miocene. In addition, the OM isochrone map (Figure 3b) and the Pliocene unit (Figures 6 and 9) highlight the poorly structured Carbonara Valley, located between the Banghittu and Ichnusa highs, suggesting that the Carbonara Valley had not yet fully developed until the Ao phase.

The Carbonara Valley exhibits a maximum Quaternary thickness of about 1100 ms TWT (approximately equivalent to 1100 m), which is only superficially incised by the Carbonara Canyon (Figures 6 and 9). Internal reflectors onlapping the buried flanks of the Carbonara Valley provide seismic evidence that uplift of the highs persisted after the Ao phase. The Ichnusa flank displays north-verging back-thrust faults (Figures 8 and 10) which contributed to the nearly symmetrical geometry of the structure, suggesting a transpressional component that continues to the present.

5.7 | Comparison Between Maps

A comparative analysis of the time-structural map of the PQ base and the isochore map of the OM sequence (Figure 3a,b) has been used to integrate and validate interpretations derived from the seismic profiles. The PQ base (Figure 3a) describes the effect of the PQ deformations, which are related (i) to the last extensional tectonic of the Campidano Graben, strongly affecting the Cagliari continental shelf; (ii) to the uplift of the Banghittu and Ichnusa highs, with the subsidence of the intermediate Carbonara Valley; (iii) to the recent transpressive tectonics.

The OM isochore map shows no evidence of thickening in the Carbonara Valley, indicating that this depression had not yet formed (Figure 3b). The subsidence occurred during the Ao phase, as suggested by the age of the southern Campidano normal faults (Figure 5) and by the thin and southward thinning Pliocene unit in the Carbonara Valley (Figures 7 and 8). After the Ao phase, Quaternary deposition filled the structural depressions with subhorizontal layers characterized by high seismic amplitude, consistent with glacial–interglacial sedimentation patterns of the Quaternary.

The OM Isochore map also highlights a thicker OM sequence near the Cagliari coast, corresponding to the locally E-W elongated basin produced by the combined effects of the southern Sardinian Rift subsidence (Figure 4) and by the back-limb of the Banghittu-Ichnusa compression (Figure 7).

6 | Conclusions

This study reconstructs the tectono-stratigraphic evolution of the Gulf of Cagliari from the Oligocene to the present, highlighting the interplay among extensional, compressional and transpressional processes.

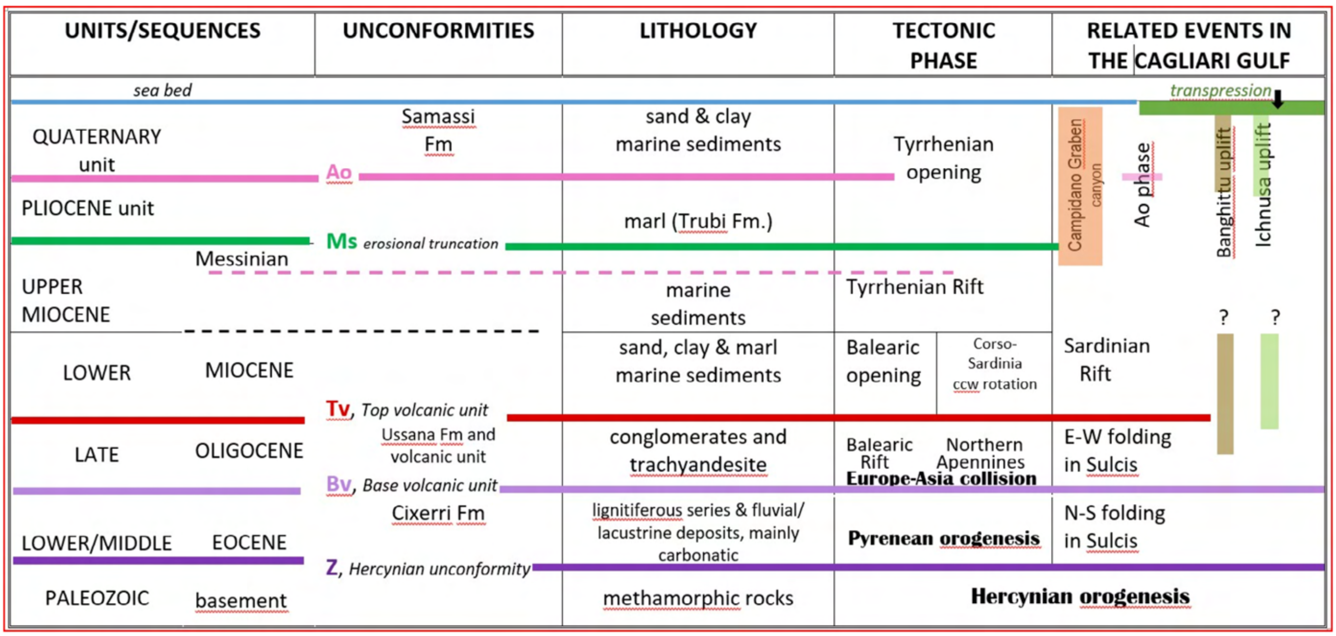

FIGURE 12 | Main stratigraphic sequences calibrated in the study area with the interpreted unconformities and their correlation with the main tectonic phases.

During the Oligocene–Early Miocene extension related to the Sardinian Rift dominated, leading to the offshore development of a half-graben system influenced by pre-existing E–W compressional structures. The tilted Oligocene volcanic unit is overlain by onlapping sub-horizontal OM deposits. The Banghittu and Ichnusa highs, which were not yet separated by the Carbonara Valley, were affected by compressional deformation and covered by sedimentary wedges.

In the Middle Miocene, the cessation of the Sardinia Rift coincided with the end of the Corso–Sardinia rotation. At the same time, the continued northward motion of the African Plate likely maintained a compressional regime in the southern Gulf of Cagliari.

In the Late Miocene, Tyrrhenian rifting reactivated inherited structures and promoted the formation of the Campidano Graben, with its offshore continuation as a half-graben with NE-verging master faults. Messinian evaporite deposition and the development of deeply incised canyon systems mark this stage.

The Pliocene began with the infilling of Messinian incisions and a gradual transition from extension of the Campidano Graben, which disrupted the east–west Banghittu thrust system, to compression of the Banghittu and Ichnusa highs and the initial development of the Carbonara Valley between them.

At the Pliocene–Quaternary boundary (Ao phase), thrust systems experienced a brief but important compressional event that also generated back-thrusting, resulting in further uplift of the Banghittu and Ichnusa highs and subsidence of the Carbonara Valley. We hypothesize that this activity may be linked to ongoing Sardinia-Africa convergence.

During the Quaternary, sedimentation progressively filled the Carbonara Valley, while tectonic activity evolved toward a predominantly transpressional regime. Shallow buried structures influenced the development and orientation of younger canyon systems.

Overall, the evolution of the Gulf of Cagliari reflects the strong control exerted by inherited tectonic structures and the alternation and coexistence of different geodynamic regimes, which governed both basin architecture and sedimentary processes over time.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in SNAP seismic database of OGS at https://snap.ogs.it/cache/index.jsp.

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