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Preservation of Transgressive System Tract Geomorphic Elements during the Holocene Sea Level Rise in the South-Eastern Sicilian Tyrrhenian Margin

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Abstract: Understanding of complex sedimentary records formed by transgressive systems is critical because they provide information on sea level changes which control the evolution of the coastal environment. This paper discusses the preservation of the Transgressive System Tracts (TST) in the south-eastern Sicilian Tyrrhenian margin during the last Holocene eustatic cycle. The available dataset consists of high-resolution bathymetry (multibeam), whose description and interpretation through a Digital Elevation Model (DEM) has been integrated with six seismic profiles (CHIRP). Within the whole study area, four bathymetric contours (−120 m, −100 m, −80 m and −70 m) were identified and assumed as the markers of the main locations of the paleo-coastlines, corresponding with the steps of the main changes in the sea level. The transgressive deposits are preferentially preserved in the 70–100 m bathymetric range, bounded at the top by the maximum flooding surface and consisting of the relict geomorphic elements that represent past landscapes (coastal barrier lagoons, transgressive sheet areas, cuspate beaches, transgressive dune-field systems). Furthermore, with the support of 3D bathymetric maps, a reconstruction of the geomorphological evolution of the past coastal systems during the last transgressive stage is also provided.

Keywords: Transgressive System Tract; multibeam data; CHIRP seismic profiles; continental shelf

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1. Introduction

Continental shelves are the submarine areas closest to land and their stratigraphy and morphology record the interplay between oceanographic processes and fluvial sediment transport to the offshore. Waves, currents and gravity-driven flows play a fundamental role in the redistribution of river-borne sediments across and along the shelf, creating sediment transport gradients. They combine with sea-level and climate changes and tectonics, to determine the nature and the geometries of the continental shelf sedimentary successions [1–5]. Morphologic and sedimentary characteristics vary considerably along the entire shelf [6,7]. The continental shelf is very sensitive to sea level variations, which are expressed with the landward or seaward migration of the coastline [8,9]. During landward shifts, transgressive deposits can form: coastal barrier-lagoons [6,7,10,11], transgressive sheet areas [12], cuspate beaches [13] and transgressive dune-field systems [14,15]. They develop in fully marine, estuarine/lagoonal and fluvial systems and can include several sedimentological facies [6,7,16,17]. Their variability is driven by changes in the rate of sea level rise and by the balance between sediment supply and accommodation space [10]. The latter determine the morphology and development of transgressive landforms, in combination with other factors such as the aeolian sedimentary activity that control the distribution of vegetation [18]. The landward coastline migration is often associated with: (i) an increase in sedimentation within the alluvial and coastal plain, (ii) a decrease in the sediment influx to the basin, and (iii) the ravinement of ancient deposits [6,7,10]. Research on ancient and recent transgressive successions is a key issue for reconstructions of eustatic sea-level behavior.

The north-eastern sector of the Sicilian continental shelf represents an excellent site, for the study of the transgressive geomorphic elements, in relation to the last eustatic cycle. In this area, in fact, the numerous Transgressive System Tract (TST) geomorphic characters stand out spectacularly on the seafloor, as they are well-imaged through the multibeam data and high-resolution seismic profiles (CHIRP system). In particular, our morpho-stratigraphic analysis focusses in the area comprised between the villages of Spadafora and Villafranca (Figure 1a,b).

The focus of this work is the description and interpretation of numerous geomorphic relict elements connected with the last Transgressive cycle lying on an offshore portion (about 15 km^2) of the Tyrrhenian continental shelf of the north-eastern Sicilian margin (Figure 1b). Such geomorphic elements provide a valuable archive of the geological processes associated with the last eustatic cycle. Developed on a regional erosional surface, the sedimentary deposits detected in the study area belong to the last transgressive and, in sub-order, highstand wedges.

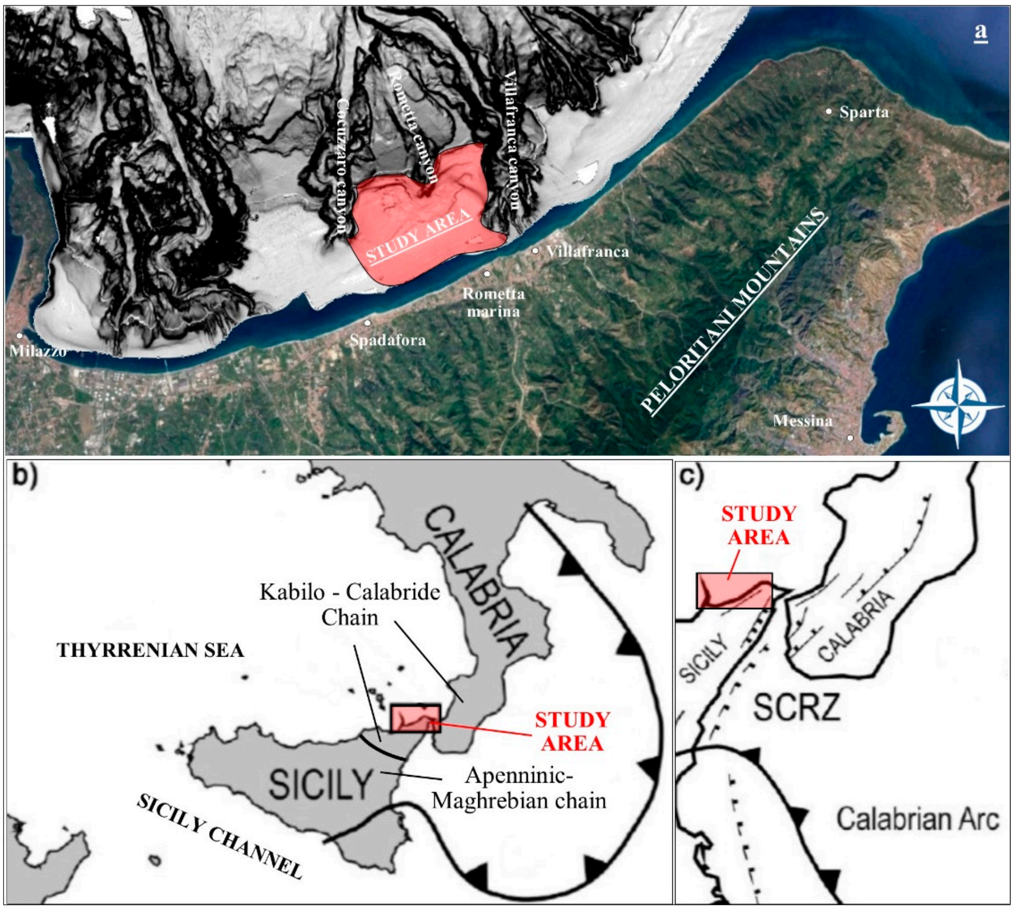


Figure 1. (**a**) Geographic map (WGS84) of north-eastern Sicily and the offshore sector (red area) investigated in the present study through a bathymetric survey (multibeam data). (**b**) Regional location of the study area; the black arrows show the extensional regime responsible for the Siculo-Calabrian Rift Zone above the Calabrian Arc subduction zone. (**c**) Schematic reconstruction of the Siculo-Calabrian Rift Zone (SCRZ) in north-east Sicily and in Calabria.

2. Geological Setting

The study area lies in the north-eastern Sicily offshore (Figure 1), within a crucial stratigraphic–tectonic setting of the central Mediterranean orogeny, derived from the

Neogene–Quaternary convergence between the European and African plates [19–21]. The area is characterized by two structural domains, belonging respectively to the Kabilo-Calabride and Appenninic-Maghrebian chains [22,23].

The Peloritani Mountains are cut by ramps linking with a floor-thrust underlying the Kabilo-Calabride Chain; this crops out at the southern margin [24]. The geometry of the thrusts has been partly modified by recent dextral strike-slip faulting, connected to regional collisional tectonics that displaced pre-existing tectonic elements. Within this complex tectonic setting, the largest tectonic feature of the Calabrian Arc is the Siculo-Calabrian Rift Zone (SCRZ; Figure 1c), a 370 km long belt that runs continuously along the inner side of the Calabrian Arc [25,26]. The tectonic pattern controls the development of the hydrographic network of the northeast of Sicily, with rivers that are short with small drainage basins on the eastern side and become progressively longer with larger drainage basins to the west [26].

The Peloritani Mountains, dissected by a deeply entrenched drainage system, shows a regional divide markedly shifted towards the Ionian coast. Thus, the north side of the ridge of the Peloritani Mountains hosts very short and steep rivers that form a NW-directed and consequently, a poorly hierarchized fluvial pattern [27].

The northeastern Sicilian margin is dominated by canyons that in some cases have their heads in proximity to the coast (Corriolo, Niceto and Villafranca Canyon), and in other cases (Cocuzzaro and Rometta Canyon) at almost 3 km from the Sicilian coastline and, therefore, at a significant distance from the river mouths [2,3,26].

3. Materials and Methods

The Digital Terrain Model (DTM) presented in this work and used for geomorphological analysis consists of high-resolution bathymetric data acquired during two cruises around the north-eastern Sicilian offshore shelf area, carried out on board R/V Mariagrazia in 2009 and 2010 using a hull-mounted Kongsberg EM3002D (300 kHz) and a pole-mounted Reson 7111 (100 kHz) multibeam system respectively [18].

All the multibeam data have been merged and post-processed using CARIS HIPS and SIPS software; a 5 m-resolution DTM was produced for the shelf area, while a 20 m-resolution DTM was attained for the slope area [28]. The high-resolution CHIRP seismic profiles were acquired in 2009 on board R/V Mariagrazia and Urania with a hull-mounted Teledyne BENTHOS III CHIRP system (frequency modulation between 2 and 20 kHz). They are spaced at about 2 km and have 0.5 m-vertical resolution (Figure 2). The seismic profiles, acquired in the SEG-Y format, were processed and interpreted using the GeoSuite Allworks software (2020R2 version). Initially, a standard processing sequence was applied to all seismic profiles. The Debias operator was used to remove the DC (Digital Circuit) component, which usually affects the seismic data. The Infinite Impulse Response (IIR) filter module was employed to attenuate any undesired frequency content of the signal spectrum (e.g., electrical low frequency noise). Trace equalization was applied to compensate amplitude variations across the profile. Finally, a constant Gain (50 dB) has been applied, increasing the amplitude of the acoustic signals. The seismic profiles (about 150 ms TWT) have high resolution (<1 m), allowing the imaging of upper part of the sedimentary succession of the Marzamemi offshore. The analysis of all the available profiles was initially aimed at recognizing the main seismic reflectors that allow for the sub-division of different seismo-stratigraphic units. They were digitalized by means of the "horizon-picking" phase. Thanks to a sequence stratigraphic approach, the more recent units, on the basis of their reciprocal geometric relationships, were assigned to different stages of the last cycle of sea level, making it possible to identify the boundary surfaces of the Lowstand and Falling Stage System Tract (LST and FSST), Transgressive System Tract (TST) and Highstand System Tract (HST).

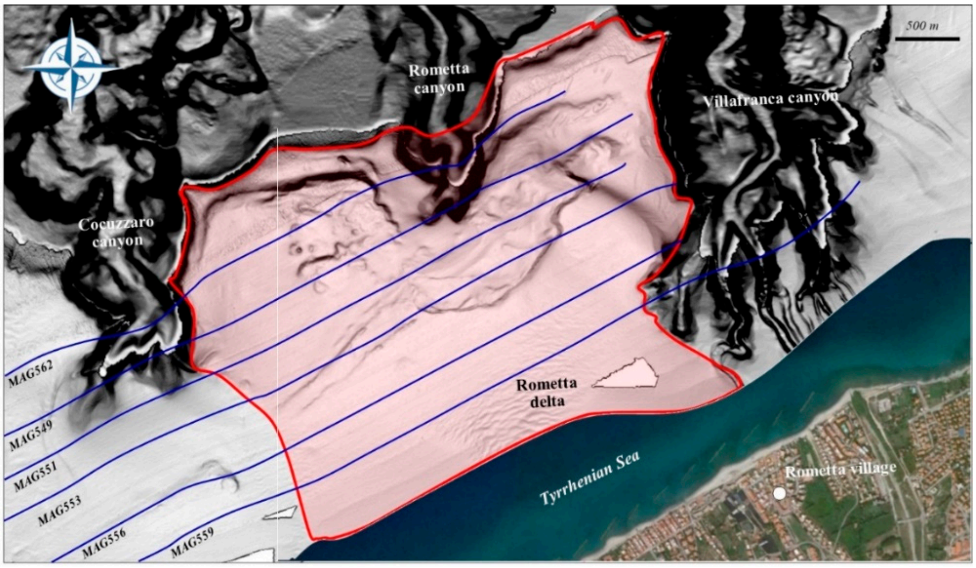


Figure 2. Overlapping of the dataset analyzed for the geomorphological reconstruction of northeastern Sicilian offshore: the bathymetric data (multibeam) and the traces of seismic profiles (CHIRP).

4. Seismic-Stratigraphic Analysis

Through the CHIRP seismic profiles interpretation, two main widespread reflectors, characterized by an intense contrast of acoustic impedance, have been recognized (Figure 3).

The first main reflector (named here L-reflector) is laterally continuous and has an erosional character and is the top of the lowstand succession and the base of the transgressive wedge. The L-reflector is well-imaged, especially in the northern portion of the study area (MAG562 and MAG549; Figure 3a). Conversely, in the central portion and moving towards the coastline, the L-reflector and the underlying deposits are rarely imaged due to the coverage of coarse deposits of the TST succession that do not allow for the penetration of the acoustic signal.

In the northern portions, the analysis of the MAG562, MAG549 and MAG551 profiles reveals the acoustic facies and the-stratigraphic setting of the LST deposits (Figure 3a). Here locally the reflectors show a discrete continuity and a depositional setting that varies from sub-vertical to sub-horizontal and/or slightly wavy. Upwards, these reflectors are always cut by the erosive surface corresponding with L-reflector. The LST succession is interpreted as being characterized by the foreset of the prograding clinoforms of the northeastern Sicilian continental margin.

The transgressive (TST) deposits lie above the L-reflector and are characterized by high-amplitude facies (Table 1). In the northern portions, the thickness of the TST deposits is strongly irregular, whereas in the southern portions it is undefined due to the low penetration of the acoustic signal. The TST deposits cover a large part of the underlying LST succession, outcropping on the seabed in the central and in northern sector of the study area. Again locally, the TST deposits constitute some irregular geomorphic elements characterized by a poorly stratified acoustic facies with reflections to high amplitude, attributable to extended biogenic coverage (Figure 3b).

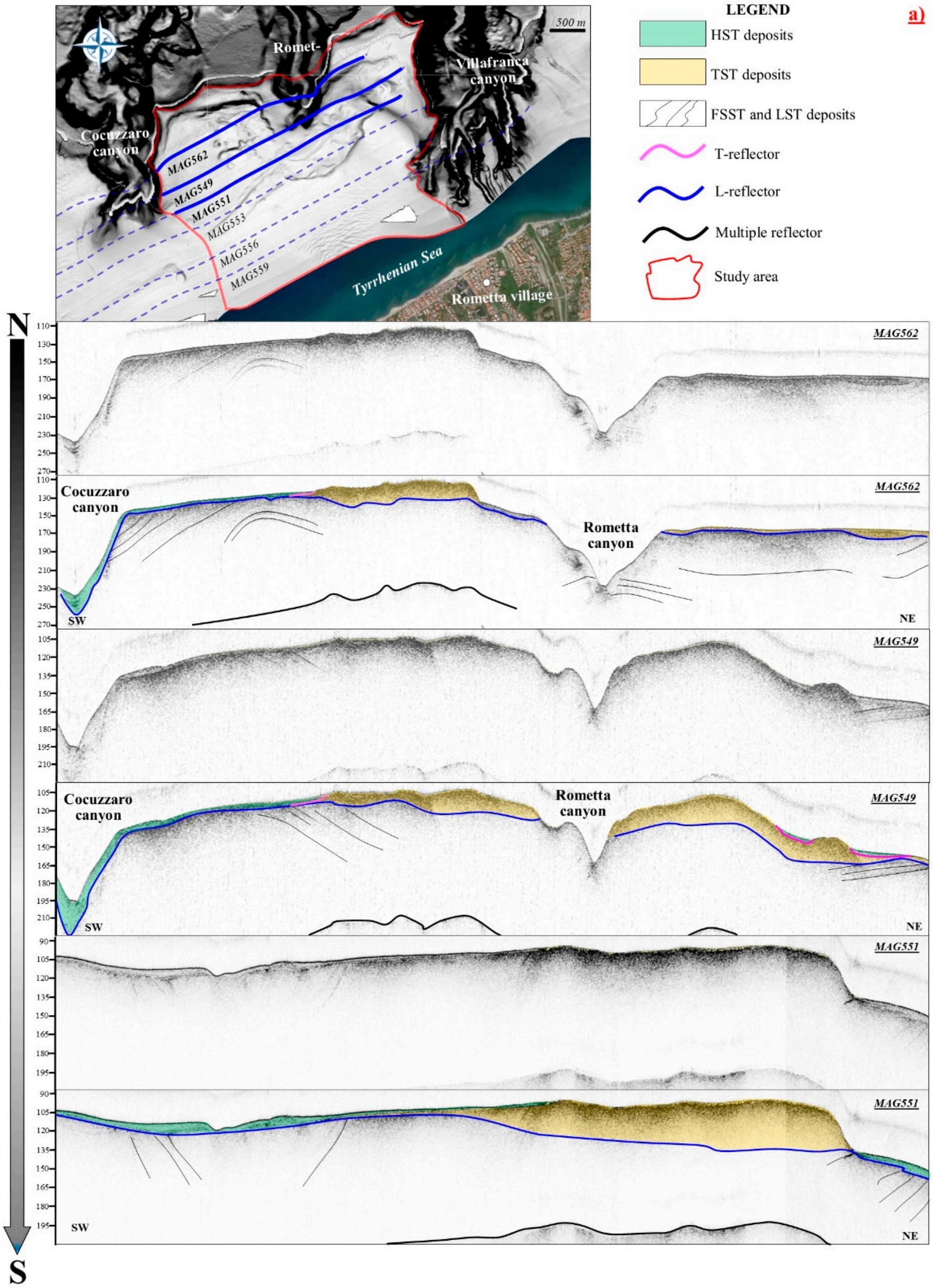


Figure 3. *Cont.*

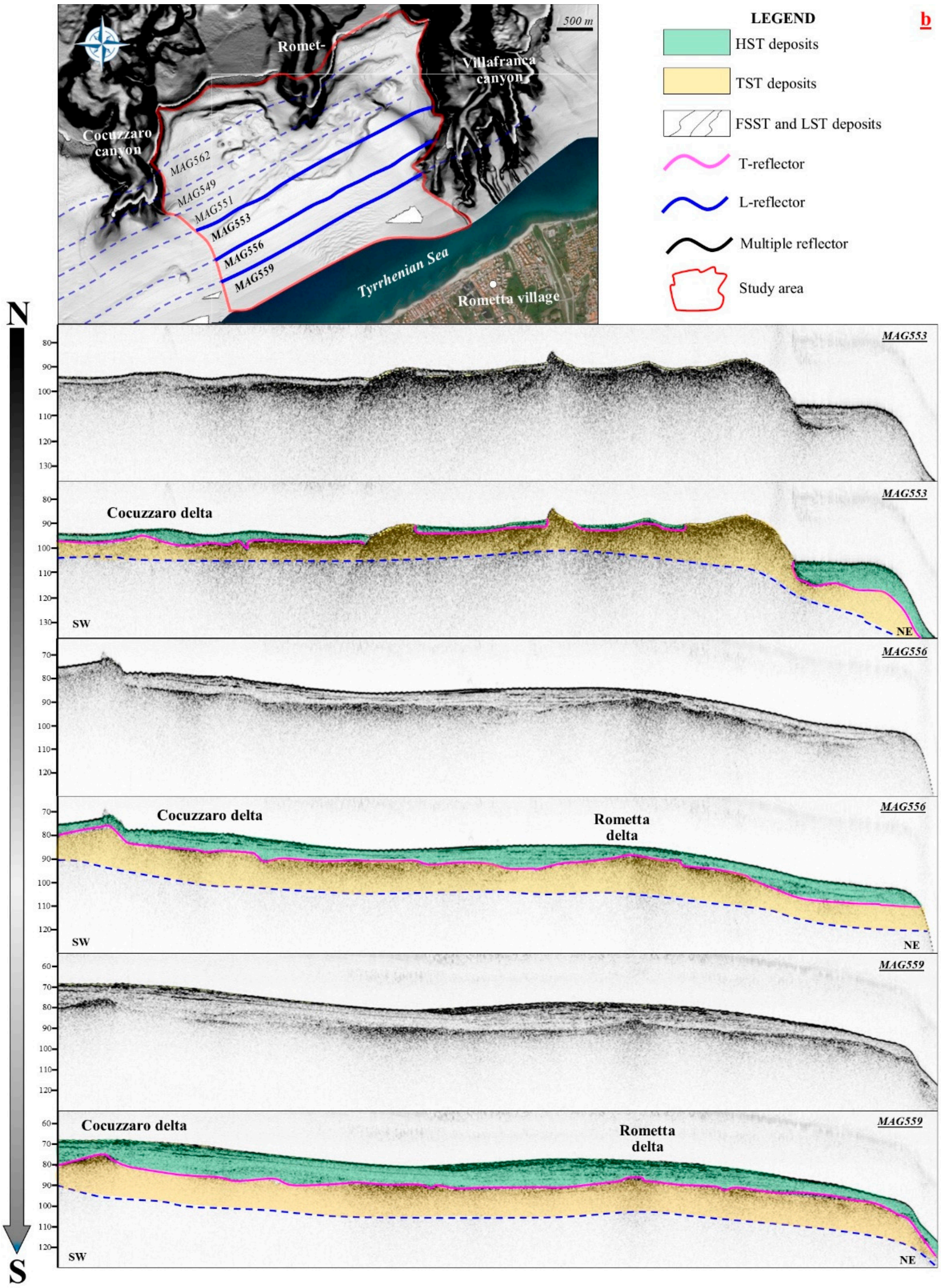
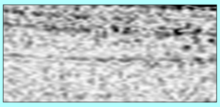
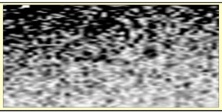
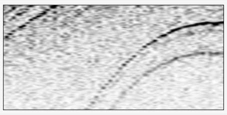


Figure 3. (**a**) Location and interpretation of three CHIRP seismic profiles (MAG562, MAG549 and MAG551,) analyzed for the seismic-stratigraphic reconstruction of the northern portion of the study area. (**b**) Location and interpretation of the CHIRP seismic profiles (MAG553, MAG556 and MAG559) analyzed for the seismic-stratigraphic reconstruction of the southern portion of the study area. The acronym MAG is equivalent to "Marine Geohazards along the Italian Coasts project".

Table 1. Facies analysis and stratigraphic position of the depositional units interpreted in this study.

	Seismic Facies	Acoustic Features	Interpretation
Highstand System Tract		Sequence of high amplitude reflectors with good lateral continuity and sub-horizontal trend	Deposits of the river deltas lying along the north-eastern Sicily coastline
T-reflector		*Moderate amplitude reflection and good lateral continuity*	*Maximum Flooding Surface*
Transgressive System Tract		Sequence of chaotic high amplitude reflectors	Transgressive deposits
L-reflector		*High amplitude reflection and excellent lateral continuity*	*Subaerial erosional surface*
Lowstand and Falling Stage System Tract		Moderate-low amplitude reflection with setting from sub-vertical to sub-horizontal and slightly wavy	Foreset of the prograding clinoforms of the northeastern Sicilian continental margin

Upwards, the TST deposits are bounded by a second main reflector (named here T-reflector), characterized by an excellent lateral continuity. It is interpreted as corresponding to the Maximum Flooding Surface (MFS). In the central and southern portions of the study area, the T-reflector is covered by a blanket of more recent sediments (MAG556 and MAG559 seismic profile; Figure 3). In particular, especially in the southern portions, it is evident that the T-reflector bounds the Highstand System Tract (HST) deposits characterized by downlap terminations on the T-surface. HST represents the deposits of the river deltas that lie along the northeastern Sicilian coastline and are their distal fine-grained equivalent. In the northern area, where the HST is not present, the T-reflector coincides with the seafloor. The thickness of HST deposits increases considerably near the coastline. Here, in fact, the coalescing Cocuzzaro and the Rometta deltas have their maximum thickness (about 25 m; MAG556 and MAG559; Figure 3b). Towards the north, the delta deposits gradually thin until they reach the limit of the resolution. Finally, the seismic-stratigraphic analysis shows the depositional character of the Cocuzzaro canyon (MAG562 and MAG549 seismic profiles; Figure 3a), while the Rometta canyon markedly shows an erosional character with the lowstand succession outcropping in the canyon bottom.

5. Morpho-Bathymetric Analysis

5.1. Western Sector

The westerm sector (about 7 km^2) lies between the eastern portion of the Cocuzzaro canyon and the Rometta canyon (Figure 4a). The offshore portion of the Cocuzzaro delta covers a large part of this sector up to a depth of about −50 m. In the northernmost and deeper portions of the study area, Figure 4a shows the development of some geomorphic elements lying on a plateau characterized by an irregular trend along the −120 m contour and that marks the last Holocene lowstand of sea level. As also seen with the seismic-stratigraphic analysis, these elements are interpreted as progradational bodies connected with the last Holocene cycle of lowstand constituting the basis of the paleo-cliff 1. The N-S bathymetric profile 1 (P1; Figures 4a and 5a) crosses the central area of this sector located between the Cocuzzaro and Rometta canyons. At a depth of 117 m, the slight convexity of the seabed contours is interpreted as a paleo-beach wedge (Figures 4a and 5a). This paleo-beach area is located at the base of paleo-cliff 1 elongated in ENE-WSW direction for about 1 km with an arcuate trend. With a gradient of 12°, the paleo-cliff 1 reaches a depth of 94 m and is interpreted as step 1 of the lowstand succession on which the transgressive wedge develops.

At a depth of 91 m, the irregular morphology of the seabed corresponds with the development of a transgressive relict body with a sub-circular shape, being part of a paleo-coastal barrier (named here paleo-coastal barrier A). Its asymmetric morphology shows a gradient of 8° in the norther side and a gradient of 2° in the southern side (Figure 5a). The MAG562 seismic profile (Figure 5b) shows that coastal barrier A corresponds to an area with a very reflective acoustic facies. Southwards, at the rear of the paleo-coastal barrier A, a morphological depression is present on the seafloor with a slight concavity of the contours (Figure 4a). At a depth of 89 m a symmetric (both sides with a gradient of about 6–7°) transgressive relict body (named paleo-coastal barrier B) is detected. It shows a thickness of about 5 m and is flanked landwards by a further depression. The different depth of the two paleo-coastal barriers suggests that they are not contemporary and mark two short steps of rising sea levels. The subcircular shape and the scarce areal extension of these paleo-coastal barriers suggests a poor state of preservation due to the action of tidal currents and oceanic waves.

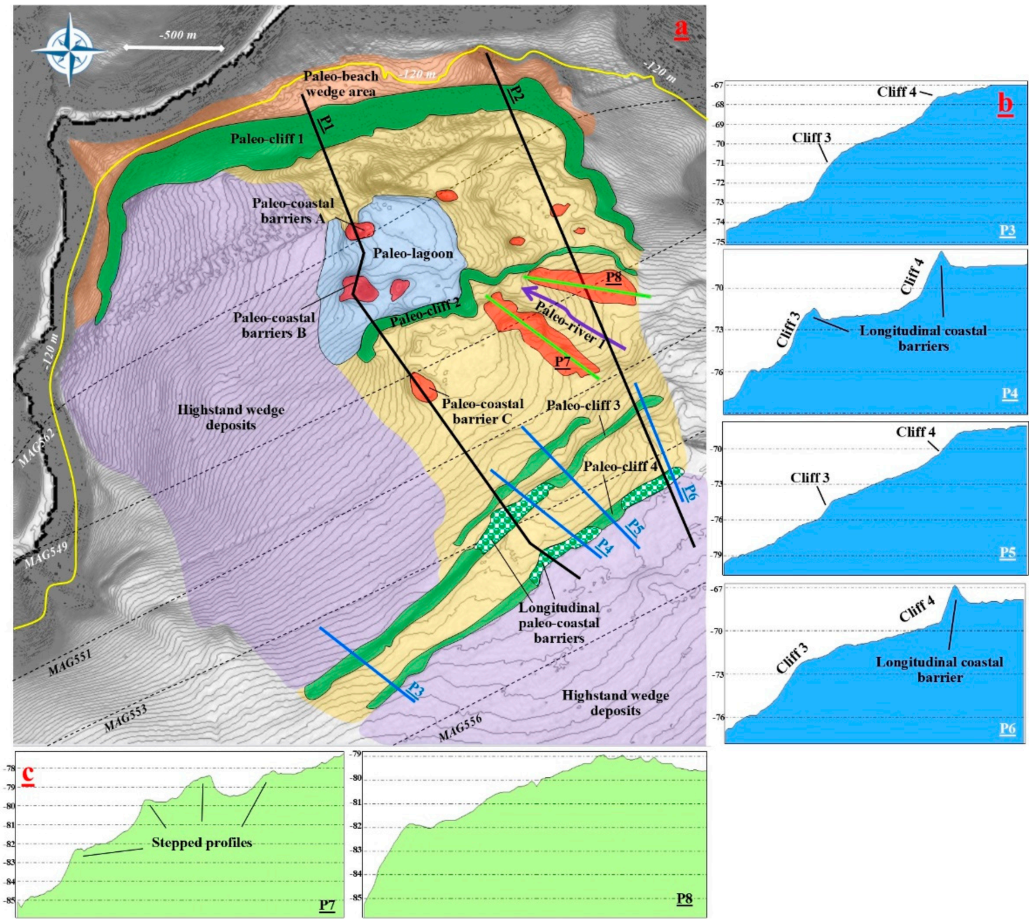


Figure 4. (**a**) Mapping of the main geomorphic elements outcropping on the seabed of the western sector of the study area, with particular focus on the relict Transgressive System Tract deposits. (**b**) The P3, P4, P5 and P6 bathymetric profiles, about orthogonal to paleo-cliffs 3 and 4. (**c**) The P7 and P8 bathymetric profiles about longitudinal to the paleo-river 1 delta.

Southwards, at a depth of 84 m, the P7 (Figure 4c) shows another cliff (named here paleo-cliff 2) with a gradient of about 12°. The MAG533 seismic profile shows that the paleo-cliff 2 has a very reflective facies (Figure 5c). It is interpreted as step 2 of the lowstand succession. Southward, at a depth of 80 m (Figures 4a and 5a), a third geomorphic element—interpreted as a relict of the paleo-coastal barrier C—with a sub-elliptical shape is present. From a depth of about 79 m to 72 m, the seabed is relatively smooth and here it is interpreted as a transgressive sand sheet (Figure 5c), likely connected to the high energy of waves or to a rapid rise in sea level that did not allow the same preservation as seen in the deeper coastal barriers.

The transgressive sand sheet terminates at a depth of 72 m against the step, with a gradient of about 7°, and NW-SE straight trend (Figure 4a). The lower is interpreted as a well-preserved longitudinal coastal barrier developed on the paleo-cliff 3. Only 200 m southwards, at a depth of 68 m, a further slight morphological (gradient of about 4°) variation on the seafloor dip corresponds to a gentle cliff (named here paleo-cliff 4) partially draped by the Rometta delta. The paleo-cliff 4, well-imaged also on the MAG553 seismic profile (Figure 5e), is interpreted as a further step of the lowstand succession covered by the highstand wedge deposits, belonging to the delta deposits of the Rometta River.

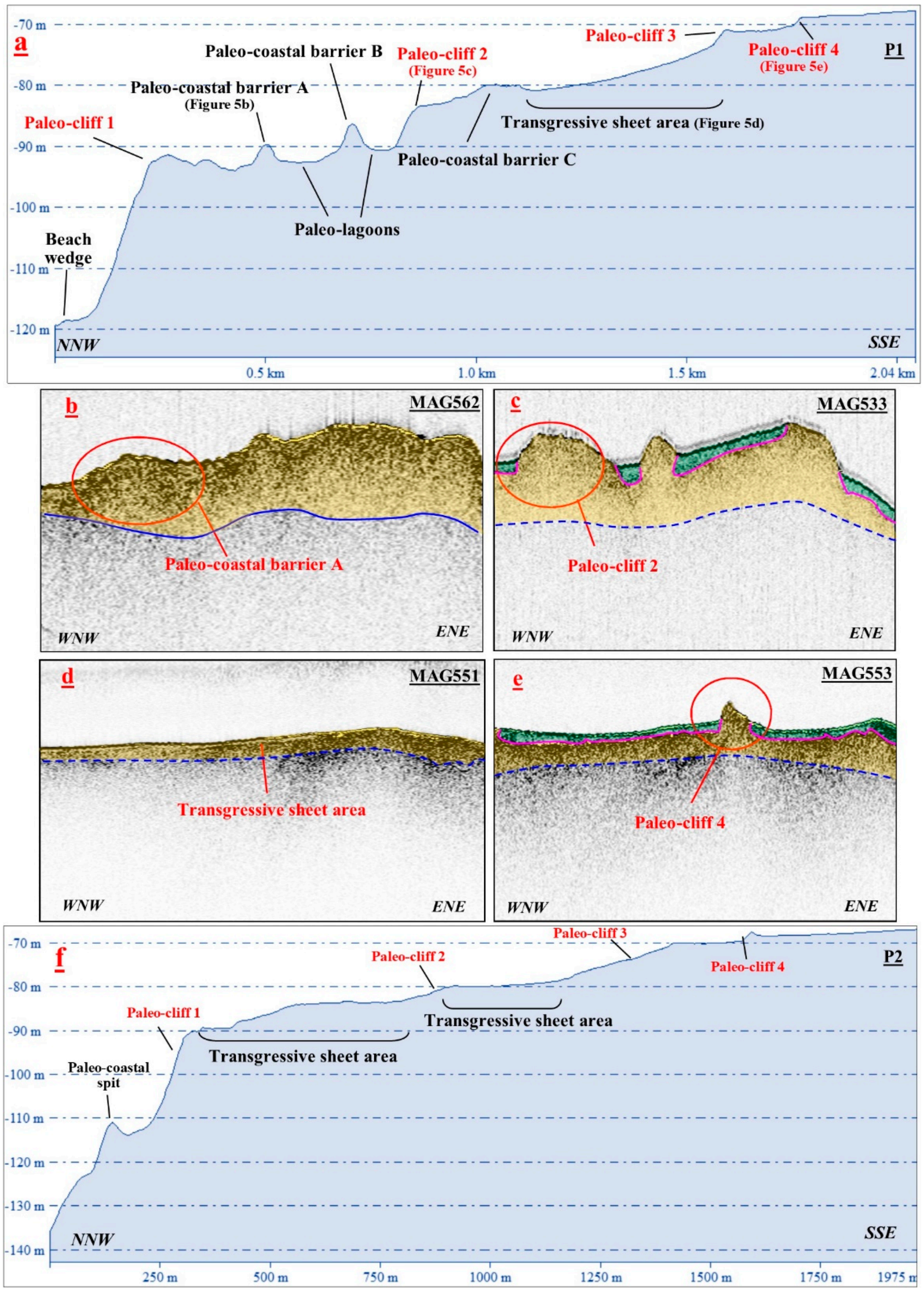


Figure 5. (**a**) The P1 bathymetric profiles arranged in NW-SE direction and location of the main TST geomorphic elements. (**b**) Detail of the profile MAG562. (**c**) Detail of the profile MAG533. (**d**) Detail of the profile MAG551. (**e**) Detail of the profile MAG553. (**f**) The P2 bathymetric profiles arranged in NW-SE direction and location of the main TST geomorphic elements.

The bathymetric profile 2 (P2; Figure 5f), located 500 m northeastwards of the P1, shows many of the geomorphological features described previously. At a depth of about 100 m, the continuation of the paleo-cliff 1 (gradient of 11°) is present, representing step 1 of the lowstand succession. At its base (at a depth of 112 m), a marked convexity of the contours marks a narrow and elongated body with a relief of about 5 m elongated in a NW-SE direction (Figures 4a and 5f). The latter is interpreted as a TST coastal spit. Above the paleo-cliff 1, at a depth of 90 m, another transgressive body is present, that is interpreted as a transgressive sand sheet. Southwards, it ends against another morphological high located at 82 m, which represents the continuation of the paleo-cliff 2 in this area. Above, the contour trend shows some small bathymetric variations: from 79 m to 75 m in depth another transgressive sheet is evident (Figure 5d). Southwards, at a depth of 72 m, the lateral continuation of the longitudinal coastal barrier on the plaeo-cliff 3 is present and at a depth of 68 m, the continuation of the paleo-cliff 4 develops.

In the central-eastern portion of this sector, an area with a pronounced seaward concavity of the contours highlights the path of a paleo-river (paleo-river 1; Figure 4a), which extends for about 500 m in a NW-SE direction between the paleo-cliff 2 and the paleo-cliff 3. Profile 7 (P7; Figure 4c) shows the western side of the delta associated with the river and highlights the preservation of at least four small steps, most likely associated with four short and progressive moments of rising sea levels. Profile 8 (P8; Figure 4c), instead, shows the morphological features of the eastern portion of the paleo-river 1 delta, with a more homogeneous bathymetric profile. The different geomorphological settings of the paleoriver 1 sides could be due to local variations in transgressive reworking during the sea-level rise.

The bathymetric profiles P3, P4, P5 and P6, oriented approximately NW-SE, show a lateral morphological variability of paleo-cliffs 3 and 4 (Figure 4b), recording an important step in the variation in the sea level rise. Specifically, the profiles P3 and P5 display the portions of the two cliffs characterized by moderate gradients (about 3°); conversely, the P4 and P6 profiles show high gradients (about 8°), very likely associated with the good preservation of paleo-longitudinal coastal barriers that were placed on the two cliffs during the transgressive phase.

The morphological characterization of the transgressive depositional wedge shows that the geomorphic elements can vary in response to the continuous or sudden changes in the rate of sea level rise, probably depending on the palaeotopography or exposure to the action of waves.

5.2. Eastern Sector

The eastern sector includes the area between the Rometta canyon head and the western portion of the Villafranca canyon (Figure 6a).

The northern part is dominated by the Rometta canyon head with a gradient of 14° at a depth of 85 m. This break of slope represents the limit of a first morphological body characterized by a slight convexity in the contours and is interpreted as a TST body. The transparent high-reflectivity seismic facies is indicative of coarse-grained facies and highlights that it is likely formed by reworked deposits. In the central portion a sector is characterized by a low gradient (from 79 m to 68 m of depth). Here, the contours, with an arcuate trend for about 1 km, suggest the presence of relatively well-preserved beach bodies, which are about 1.5 m high and with a gradient of about 1°, interpreted as cuspate beaches (Figure 6a). Profiles 9 and 10 (P9 and P10; Figure 6b,c) show the geometry of the cuspate beaches and their distribution on two different bathymetric levels. The first level, between −82 m and −72 m, is characterized by the presence of at least three paleo-cuspate beaches continuously aligned for about 1.3 km (Figure 6c). In particular, P9 (Figure 6c) shows the heterogeneous development of these beaches, which tend to deepen towards the east maintaining a poor degree of preservation, with the presence of slight morphologies and rounded peaks of the reliefs.

P10 (Figure 6c) shows the morphological features of the shallowest second level of paleo-cuspate beaches (between −70 m and 62 m), extending for about 1.4 km. Here, in fact, the paleo-beaches tend to deepen towards the east, at the same time but maintaining an excellent degree of preservation (steep morphologies and gradients up to 8°). Furthermore, the MAG551 and MAG553 seismic profiles (see the inset in Figure 6b,c) show the acoustic facies of these paleo-cuspate beaches, characterized by a high amplitude of the reflectors and a poor penetration of the acoustic signal, interpreted as being due to the presence of coarse-grained sediments.

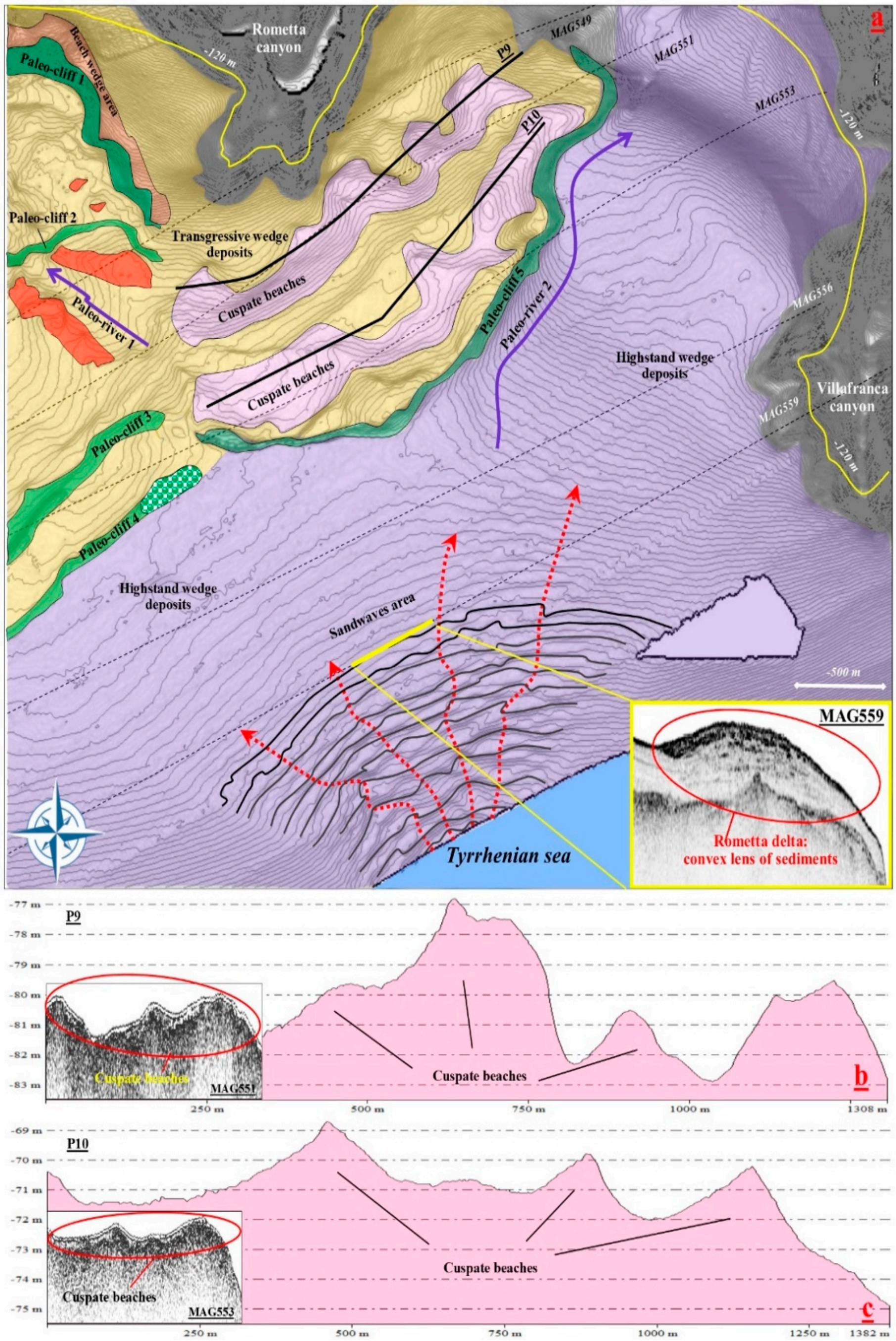


Figure 6. (**a**) Mapping of the main geomorphic elements outcropping on the seabed of the eastern sector of the study area, with particular focus on the relict Transgressive System Tract deposits. (**b**) The P9 bathymetric profile about, longitudinal to the first level of the cuspate beaches. (**c**) The P10 bathymetric profile about, longitudinal to the second level of the cuspate beaches.

Southwards, at a depth of 68 m, another paleo-cliff (5) shows an arcuate trend for about 2 km. It displays portions dominated by geomorphic elements attributable to longitudinal coastal paleo-barriers that alternate with flatter areas (gradients < 2°) due to the pellicular coverage of the nearby HST deposits.

Above paleo-cliff 5, the highstand wedge deposits of the Rometta delta are present (Figure 6a). At a depth of about 70 m, the contours show the presence of an extensive, meander-shape and slight engraved depression, oriented NE-SW, which is interpreted as the relict path of another paleo river (paleo-river 2; Figure 6a). Furthermore, the sediments carried by this river probably contributed to the development of the longitudinal barriers on the paleo-cliff 5.

In the inner shelf, to the west of the Villafranca Canyon, an area with seaward convex bathymetric contours is present (Figure 6a). It is interpreted as the Rometta submerged delta.

Sandwaves occur over the entire surface of the Rometta delta offshore continuation (Figure 6a). The sandwaves extend to deeper water eastwards, showing that the delta is asymmetric. The delta asymmetry is confirmed by the MAG559 seismic profile (see the inset in Figure 6a), showing that its upward convex lens of sediments with strong and discontinuous reflection thin eastwards, approaching the head of the Villafranca Canyon.

6. Discussion

In the study area the highstand wedge is limited to the inner shelf going no deeper than 85 m, at times leaving the past coastal system outcropping uncovered at the seafloor of the outer relict shelf. As the relict shelf areas are located in correspondence with smaller rivers, it is evident that it is the amount of sediment input from the rivers that controls the seaward extent of the inner shelf highstand wedge and the presence of a relict outer shelf. The Cocuzzaro and Rometta delta deposits widely develop on the offshore portions of the inner continental shelf and make up most of the prograding highstand sediment wedge. On the whole, thanks to the great accommodation space, the study area allows the maximum areal development of the delta deposits, in particular of the Cocuzzaro and Rometta rivers.

The study area is characterized by numerous geomorphological elements, belonging to at least four different phases of the last transgressive cycle.

The Lowstand System Tract (LST) is bounded at the top by a widespread erosional surface (L-reflector) and represents the base of the units deposited during the last sea level rise. The evolution of the Transgressive and Highstand System Tracts (TST and HST) is strongly influenced by the geometry of the L-erosional surface that determines the accommodation space for the sediment that accumulated during the successive rise of the sea level.

The TST deposits, bounded at the top by the maximum flooding surface, consist of geomorphic elements that represent the past landscape. These elements include coastal barrier-lagoon systems formed at different locations and a bathymetry on the shelf that, therefore, track the variations in coastline position during the last sea level rise [6,7]. Past coastal systems are mainly developed in the 70–110 m bathymetric range. The last sea level rise did not occur continuously but proceeded in steps, with tracts of rapid rising punctuated by periods of relatively slower rates of rise. One of the tracts with a relatively lower rate of seafloor rise occurred when the sea level rose from about 90 to 70 m below its present position. This corresponds with the depth where, in the northeastern Sicilian relict outer shelf, the coastal systems are best developed. Therefore, the transgressive geomorphic elements in the study area could have formed during an interval of a relatively reduced rate of sea level rise.

6.1. Last Transgressive Stage Reconstruction

A reconstruction of the geomorphological evolution of past coastal systems during the last transgressive stage is provided. Specifically, we simulated sea level rise in four steps

(−120 m, −100 m, −80 m and −70 m), roughly corresponding to the level of four paleo-cliffs mapped through the multibeam dataset.

Furthermore, each step was compared with the relative eustatic variations [29] highlighting the good correspondence between the development of the TST geomorphic elements and the short-standing phases of the sea level.

6.1.1. Sea Level −120 m

At this time, paleo-cliff 1 represents step 1 of the lowstand succession on which the TST deposits develop (Figure 7).

On the basis of the large lateral extension, paleo-cliff 1 is interpreted as a regional feature, connected with the last drop in sea level and responsible for this terrace development. It is likely that the arcuate development towards the south-east of the paleo-cliff 1 represents the crowning of the Rometta canyon, today developed predominantly deeper. The wavy nature of the contours tends to support the formation of the beach wedge and of the spit around the base of the paleo-cliff 1 (in the central portion), while the overlying regressive beach bodies are probably subject to sub-aerial erosional activity.

Furthermore, the bathymetric morphology, at a depth ranging from 85–70 m, suggests that a fluvial incision (paleo-river 1) affected the shelf sector when the sea level was at −120 m.

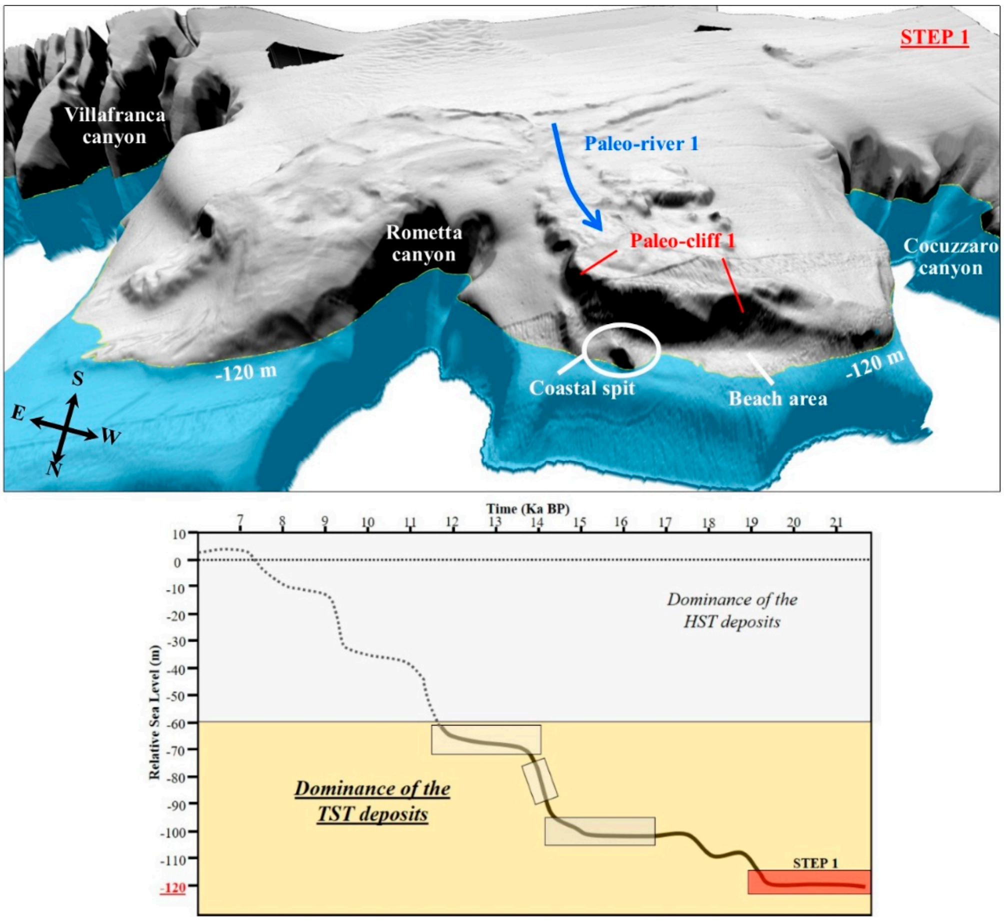


Figure 7. On the basis of a 3D bathymetric map, the reconstruction of the geomorphological evolution of past coastal systems of the area between the Cocuzzaro and Rometta canyons, simulating a sea level of −120 m.

6.1.2. Sea Level −100 m

When the sea level reached −100 m the paleo-cliff 1 was completely submerged (Figure 8). The rise of the sea level causes a different development of the fluvial incisions.

In connection with the mouth, the paleo-river 1 flows into a lagoon system developed as shown by the remnants of a past single longitudinal coastal barrier.

Furthermore, with the gradual and progressive rise of the sea level, the several geomorphic elements tend to extend mainly in proximity with the Rometta canyon head, where they show a greater areal development.

Simultaneously, the western sector is totally submerged and today totally covered by HST deposits, while in the eastern part of the study area, the rivers do not change their trend and the wave action tends to develop only small beach bodies (beach area).

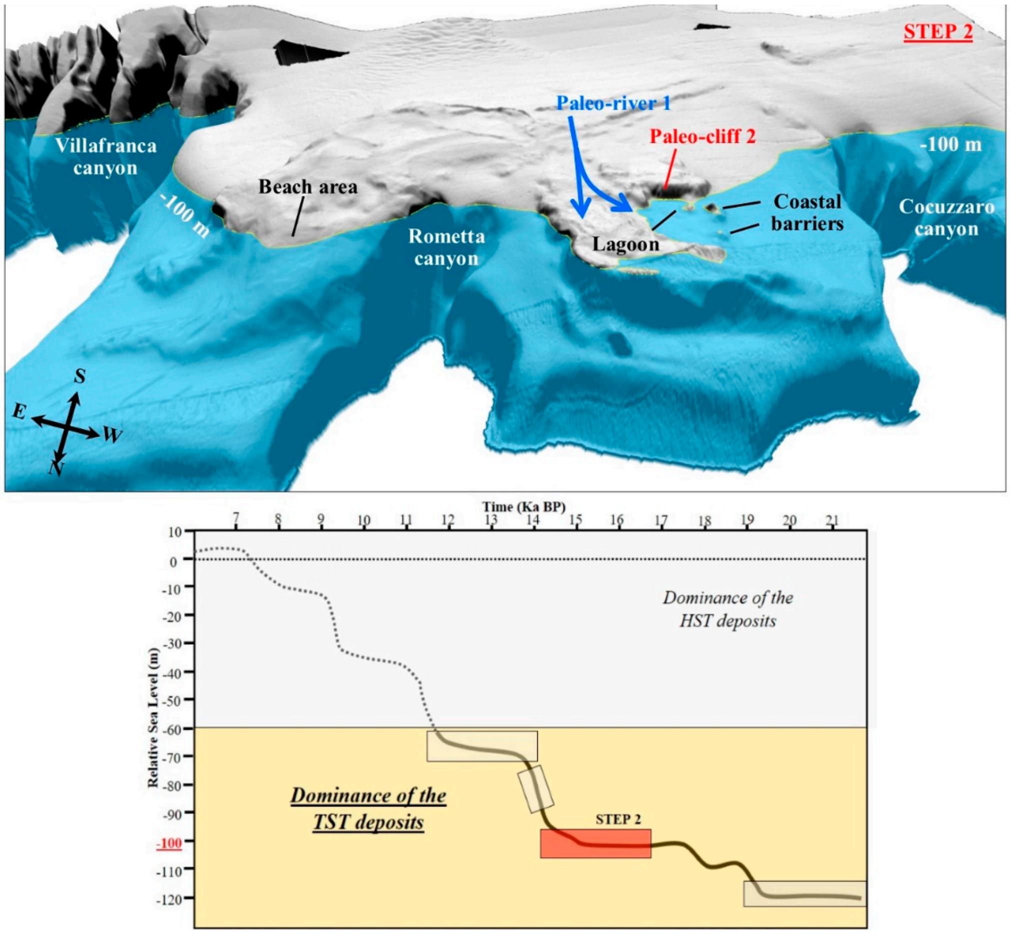


Figure 8. On the basis of a 3D bathymetric map, the reconstruction of the geomorphological evolution of past coastal systems of the area between the Cocuzzaro and Rometta canyons, simulating a sea level of −100 m.

6.1.3. Sea Level −80 m

Gradually, also in the southeastern portion, the TST deposits increase its areal extension, characterized by reworked beaches and likely connected to the intense action of the oceanic waves (Figure 9). The paleo-river 1 retreats its course in the inner shelf and, therefore, in the central portion the marked development of transgressive beaches starts (named here first level of the cuspate beaches). In the western part most of the geomorphic elements are submerged. The paleo-cliff 3 is formed in an intermediate step of rising sea level (about −75 m), marked by the formation of a widespread longitudinal coastal barrier.

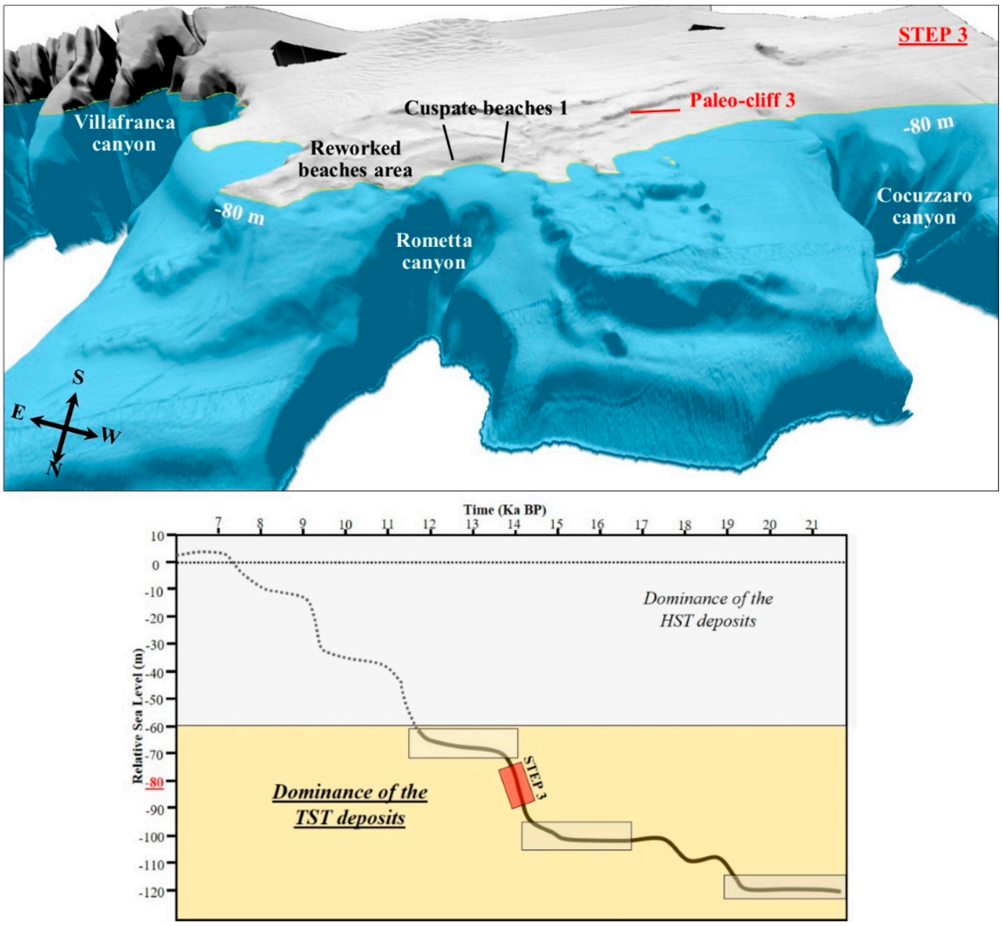


Figure 9. On the basis of a 3D bathymetric map, the reconstruction of the geomorphological evolution of past coastal systems of the area between the Cocuzzaro and Rometta canyons, simulating a sea level of −80 m.

6.1.4. Sea Level −70 m

The contour at −70 m well marks the last transgressive geomorphic elements outcropping on the seabed (Figure 10). In fact, at this stage, the development of a second level of cuspate beaches and, northwards, of a longitudinal coastal barrier on the paleo-cliff 4 occurs. The latter represents the depositional expression by the paleo-river 3, which flows in a north-east direction, parallel to the paleo-cliff 4, and discharges its sediments near the head of the Villafranca canyon.

Above the −70 m bathymetric and up to the Sicilian coastline, all the transgressive geomorphic elements are covered and well-preserved by the current deltas of the Rometta and Cocuzzaro rivers (HST deposits).

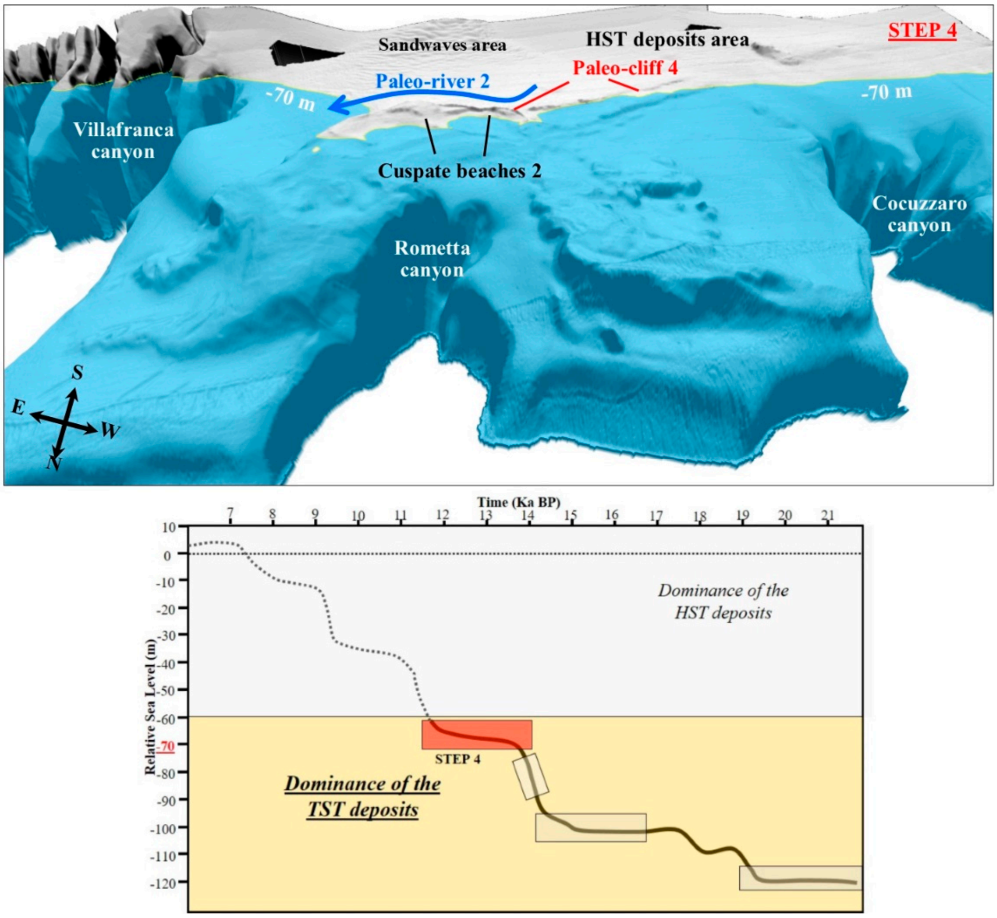


Figure 10. On the basis of a 3D bathymetric map, the reconstruction of the geomorphological evolution of past coastal systems of the area between the Cocuzzaro and Rometta canyons, simulating a sea level of −70 m.

7. Conclusions

Through multibeam bathymetric data and high-resolution CHIRP seismic profiles, a characterization of the geomorphological and stratigraphic setting of the north-eastern Sicilian continental shelf, between the offshore areas of the Cocuzzaro River and Saponara River, is provided. The main result of this study is the mapping of the geomorphic relicts formed during at least four steps of sea level rise of the last eustatic cycle. Each step corresponds to the development of a continuous lateral terraced portion on which different types of transgressive bodies (coastal barrier-lagoon systems, transgressive sheet areas, cuspate beaches) lie, characterized by a variable state of preservation. In general, the western sector shows a greater variability of TST deposits, sometimes interrupted by areas where a large development of transgressive sheet areas is observed, due to an increase in the speed of sea level rise. Instead, the eastern sector shows a poorer overall preservation of TST deposits (two levels of cuspate beaches) and a lower accommodation space, due to the greater development landwards of the Rometta canyon head.

Other important results are synthetized as follows:

- The lowstand and the falling stage succession corresponds with the foreset of prograding clinoforms of the continental margin. The clinoforms are cut by the erosional surface formed during the last lowstand emersion.
- The L-erosional surface determines the accommodation space for the sediment accumulation during the subsequent rise of the sea level.
- The transgressive deposits are preferentially preserved in the 70–100 m bathymetric range, bounded at the top by the maximum flooding surface and consisting of the

relict geomorphic elements that represent past landscapes. These elements track the variations in the coastline position during the last sea-level rise and they have also been reconstructed with the support of 3D bathymetric maps. One of the tracts with a relatively lower rate of rise of seafloor occurred when the sea level rose from about 90 to 70 m below its present-day position. This corresponds with the depth where, in the northeastern Sicilian relict outer shelf, the coastal systems are best developed. Therefore, the transgressive geomorphic elements could have formed during an interval of a relatively reduced rate of sea level rise.

- The highstand wedge consists of the Cocuzzaro and Rometta delta deposits that widely develop on the offshore portions of the inner continental shelf. The bathymetric data image of the deltas starts from a distance of 600 m from the coastline at an average depth of 40 m. The highstand wedge does not reach depths of more than 85 m, leaving the past coastal system cropping out at the seafloor of the outer relict shelf uncovered.

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