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Geomorphological evolution of western Sicily, Italy

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Abstract: This paper proposes a morphoevolutionary model for western Sicily. Sicily is a chain–foredeep–foreland system still being built, with tectonic activity involving uplift which tends to create new relief. To reconstruct the morphoevolutionary model, geological, and geomorphological studies were done on the basis of field survey and aerial photographic interpretation. The collected data show large areas characterized by specific geological, geomorphological, and topographical settings with rocks, landforms, and landscapes progressively older from south to north Sicily. The achieved results display: (1) gradual emersion of new areas due to uplift, its interaction with the Quaternary glacio-eustatic oscillations of the sea level, and the following production of a flight of stair-steps of uplifted marine terraces in southern Sicily, which migrates progressively upward and inwards; in response to the uplift (2) triggering of down-cutting processes that gradually dismantle the oldest terraces; (3) competition between uplift and down-cutting processes, which is responsible for the genesis of river valleys and isolated rounded hills in central Sicily; (4) continuous deepening over time that results in the exhumation of older and more resistant rocks in northern Sicily, where the higher heights of Sicily are realized and the older forms are retained; (5) extensional tectonic event in the northern end of Sicily, that produces the collapse of large blocks drowned in the Tyrrhenian Sea and sealed by coastal-marine deposits during the Calabrian stage; (6) trigger of uplift again in the previously subsiding blocks and its interaction with coastal processes and sea level fluctuations, which produce successions of marine terraces during the Middle–Upper Pleistocene stages.

Keywords: Sicily, geomorphological evolution, Quaternary, uplift, extensional tectonics, down-cutting processes, differential erosion.

Introduction

Sicily is located on the Pelagian promontory of the African plate and is formed by the Iblean foreland, the Gela foredeep, the thick Sicilian orogen, and the thick-skinned Calabrian–Peloritani wedge (Fig. 1).

Previous geological studies have shown that the fold and thrust belt of Sicily was formed in the context of the complex roll-back of the African–Pelagian slab that was associated first with the counter-clockwise rotation of Corsica and Sardinia and the subsequent clockwise rotation of the Calabria–Peloritani–Kabylian units, during the late Neogene (e.g., Rosenbaum et al. 2002; Carminati et al. 2012; Catalano et al. 2013; Vitale & Ciarcia 2013). Various Authors have described the ages of the orogenic construction of the Sicilian chain (e.g., Avellone et al. 2010; Catalano et al. 2013 and references therein) within the framework of the evolution of the Apennine orogen (e.g., Ciarcia et al. 2009; Ascione et al. 2012; Ciarcia & Vitale 2013). From the upper Oligocene, the orogenic construction started with the accretion of the Calabria-Peloritani wedge, and the deposition of flysch (e.g., Numidian flysch) in foreland basins. During the Early–Middle Miocene the deformation of the internal zone occurred, with a first tectonic event characterized by shallow seated thrusting; at the same time, the first wedge-top basins developed. From the Late Miocene, a second tectonic event characterized by deep-seated transpressive deformation occurred, and extension took place in the Tyrrhenian Sea as the shortening and thrusting in the arcuate Apennines–Sicily, east- and southward-directed orogens. The extensional deformation propagates towards the SE associated with the fast retreat and roll-back of the NW-dipping subduction of the Adria–Ionian plate underneath Calabria (Malinverno & Ryan 1986; Doglioni et al. 1999; Pepe et al. 2005; Carminati & Doglioni 2012 and references therein).

According to the plate tectonic setting, the topography and geomorphology of Sicily is the result of constructive (tectonic) and destructive (erosional) forces following the collision between the African and European plates, that produced, among other things, the Sicilian Mountains.

Previous geomorphological studies have been performed since the first half of last century (e.g., Cipolla 1933) and have undergone a boost in recent decades. They deal with the reconstruction of the geomorphology of small areas (e.g., Mauz et al. 1997; Di Maggio et al. 1999) or specific thematic studies (e.g., Ferrarese et al. 2003; Di Maggio et al. 2012, 2014; Madonia et al. 2013; Vattano et al. 2013; De Waele et al. 2016).

Hugonie (1982) carried out studies on a regional scale and proposed a morphoevolutionary model for northern Sicily, emphasizing the role of both structure and climate. Hugonie (1982) imputed to the Plio–Quaternary tectonic phase, the

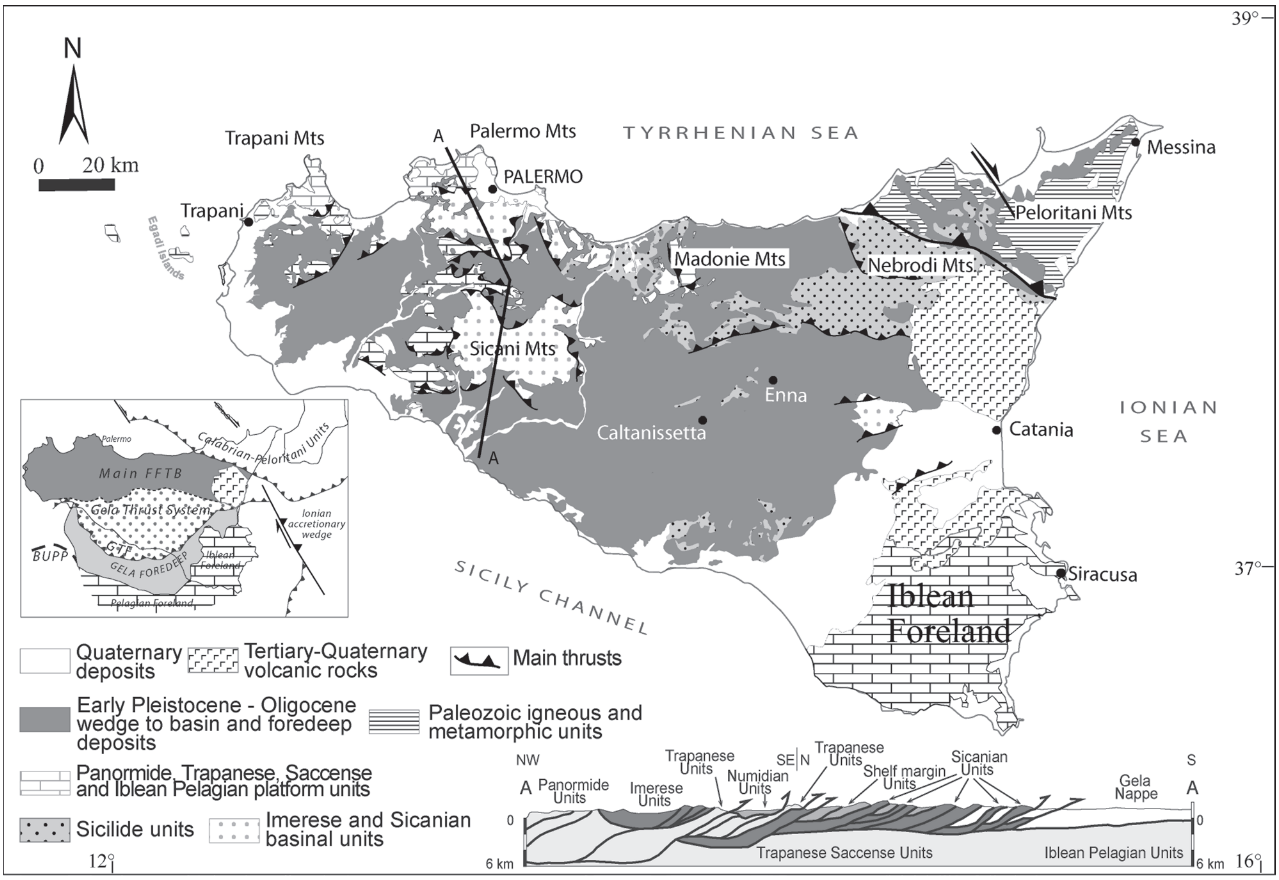

Fig. 1. Geological map of Sicily (data compiled from various Authors — e.g., Catalano et al. 2000, 2013 — modified and simplified). Inset map shows the main elements of the collisional complex of Sicily (FFTB, Fold and Thrust Belt; BUPP, Boundary of Undeformed Iblean–Pelagian carbonate Platform).

genesis of the topographic highs and lows of northern Sicily; to the interaction between uplift and river incision led by differential erosion, the enhancement of the differences in height between the topographic highs and lows, previously produced; to the Quaternary climatic fluctuations, the degradation of tectonic and river slopes.

Based on successions of planation surfaces, erosion glacis on soft rocks and coastal terraces, developing between 1900 m a.s.l. and the present-day sea level, Agnesi et al. (2000) and Di Maggio (2000) proposed polycyclic morphoevolutionary models for north-western Sicily. These models provide for the development of processes of planation/abrasion that migrate to lower altitudes, over time, due to the relative progressive lowering of the base level of erosion produced by a gradual trend to uplift.

This paper is an opportunity for synthesis and analysis of numeous data we collected over the last 25 years, many of which are here published for the first time, supplemented by a wealth of information contained in the geological and geomorphological literature, in order to reconstruct a morphoevolutionary model for the whole of western Sicily. We present here the results of this reconstruction.

Geological background

Western Sicily (Fig. 1) is part of the SE-verging Alpine orogenic belt in the central Mediterranean region and connects north-eastern Sicily, formed by a "European" element (Peloritani units), to the late Cenozoic Maghrebian chain. In this continental subduction collisional complex, several tectonic and stratigraphic elements are differentiated (Fig. 1; Catalano et al. 1996, 2002, 2013 and references therein): 1) A complex consisting of a SE-vergent fold and thrust belt, which is composed of a "Tethyan" element (Sicilidi units) and an African element (Sicilian units); 2) The Sicilidi units are represented by repeated imbricate slice stack deriving from the deformation of Upper Jurassic–Oligocene basin carbonates and sandy mudstones located in the Sicilide facies domain; 3) The Sicilian units are characterized by allochthonous tectonic units deriving from the deformation of Permian–Miocene deep-water carbonates and bedded cherts deposited in the Imerese and Sicanian basins (Basilone et al. 2014, 2016); and Mesozoic–Miocene shelf-to-pelagic carbonates located in the Panormide, Trapanese, Saccense, and Iblean-Pelagian carbonate platform or seamount facies domain; 4) upper

Oligocene–middle Miocene turbiditic deposits (Numidian flysch) cover the Sicilide, Imerese, and Panormide rock successions; lower–upper Miocene deformed foreland marls cover the Sicanian, Trapanese, and Saccense rock successions; Oligocene–Quaternary foreland open shelf carbonates cover the Iblean–Pelagian rock successions; 5) A thick pack consisting of middle Miocene–Pleistocene foreland, wedge-top and foredeep basin deposits (terrigenous, evaporitic, and clastic carbonate rocks), which largely form the Gela Thrust System; 6) A deep-seated and buried foreland, slightly deformed, crops out only in the south-eastern end of Sicily and in the floor of the Sicily Channel.

Fig. 2 shows simplified stratigraphy and original facies domains of the rock bodies of western Sicily.

The tectonic evolution of the western Sicily belt was a progressive accretion of thrust sheets (Catalano et al. 2000) and duplex formation (Catalano et al. 1996), combined with the clockwise rotation of the allochthonous blocks (Oldow et al. 1990; Speranza et al. 2003).

In this context, a Miocene contractional deformation originally produced the progressive detachment of the Sicilidi units and Numidian flysch cover (Puglisi 2014) and their stacking over deep water carbonates (Imerese units), in their turn overthrusting both Sicanian units and shallow water carbonates (Panormide, Trapanese, and Saccense units — Catalano et al. 2013). Deposition of coeval foredeep and wedge-top sediments (Butler et al. 2015; Gasparo Morticelli et al. 2015) accompanied the former event of shallow seated thrusting. Subsequently, during the Pliocene Epoch a deep-seated transpressive event redeformed the innermost tectonic units stacked during the first Miocene event (Avellone et al. 2010); more externally, a contractional event produced the inception of the wedging of the Gela Thrust System overlying the earlier and shallower allochthonous units. These two events also involved the wedge-top basin marly carbonates of the Trubi unit (lower Pliocene; Fig. 2), which are widespread all over Sicily up to the higher altitudes (over 1400 m a.s.l.; Abate et al. 1991). Finally, a Plio–Pleistocene back-arc tectonics originates high-angle extensional faults affecting the northern coastal area of Sicily and southern Tyrrhenian Sea (Pepe et al. 2005; Cuffaro et al. 2011).

Topography

The presence of a main fold-thrust belt influences the relief of Sicily (Figs. 1, 3). An E–W mountain range (Sicilian Apennines) is its topographical expression. The range forms a long and almost

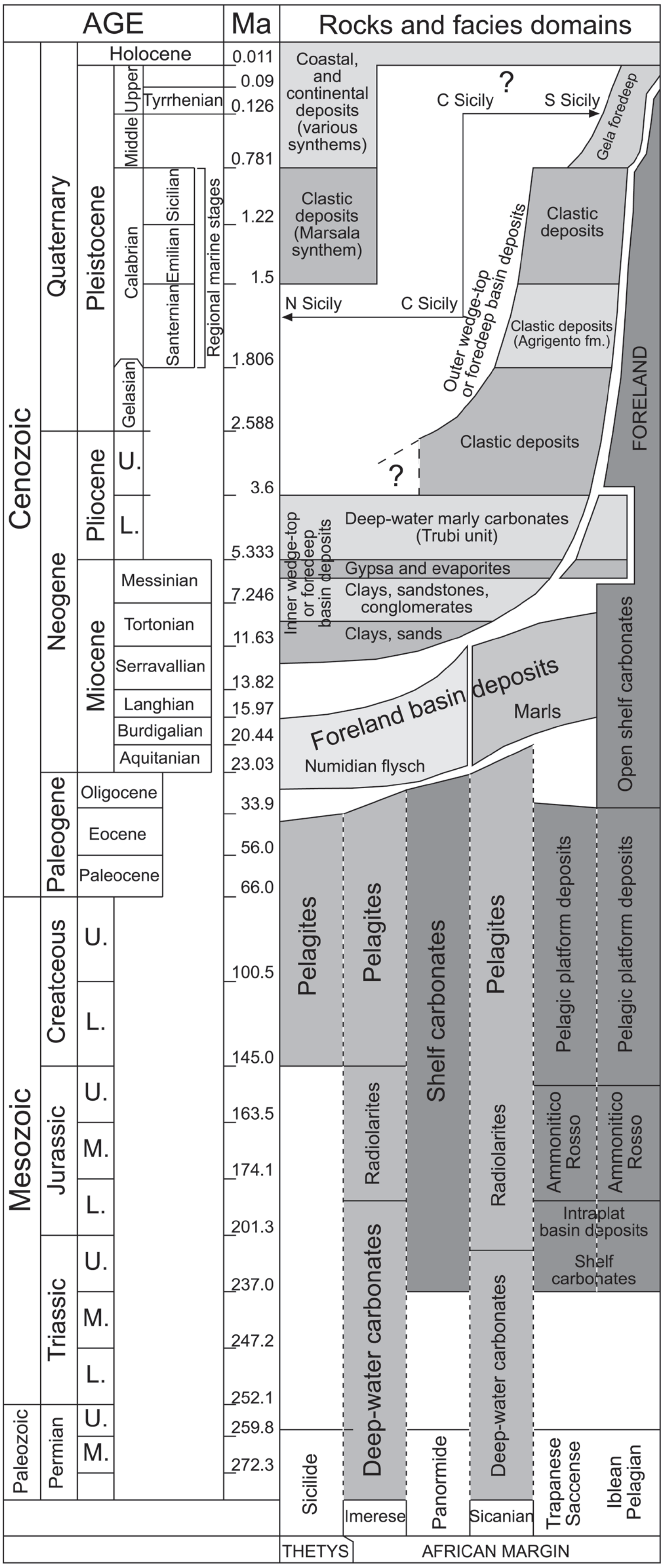

Fig. 2. Schematic stratigraphy and original facies domains of the rock bodies of western Sicily (data compiled from various Authors — e.g., Catalano et al. 2013 — modified and simplified).

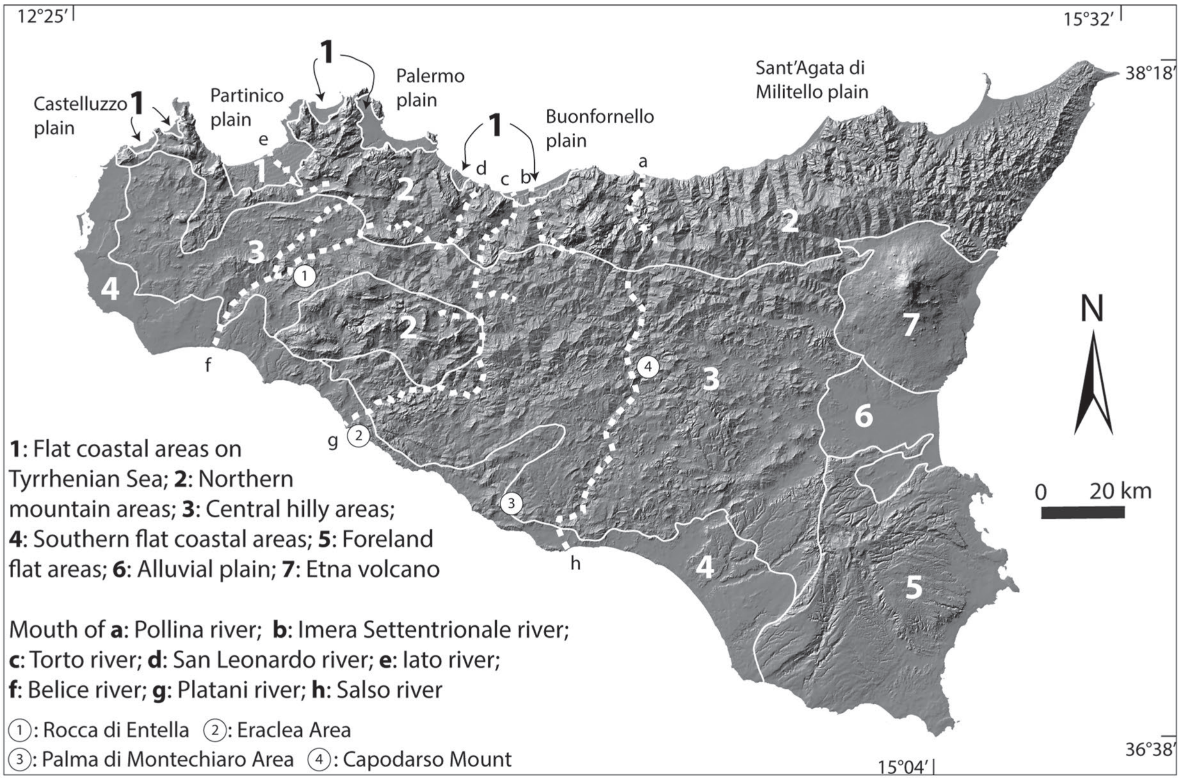

Fig. 3. Shaded relief and main geomorphological units of western Sicily (DTM from Sicilian Regional Environmental Department).

continuous ridge in the northern region of Sicily, from Peloritani and Nebrodi to the Madonie and Palermo Mountains, locally interrupted by N–S narrow and deep transverse valleys of the main rivers draining into the Tyrrhenian Sea (Pollina, Imera Settentrionale, Torto, and San Leonardo rivers). In the north-western and central-western areas, coastal plains and a set of rounded hills and broad valleys, from which a series of isolated reliefs of the Trapani and Sicani Mountains rises up, break the physical continuity of the mountain range. The mountain range and isolated peaks coincide with successions of "hard" and "resistant" rocks hundreds of metres thick (Mesozoic carbonate units), on which the highest relief lies; the deep, narrow or broad valleys and the set of rounded hills are situated on "weak" and easily erodible rocks (calcilutites, marls, and clays of the Mesozoic basin units; Mio–Pliocene cover deposits).

On the northern side of Sicily, the proximity of the mountain range to the Tyrrhenian coast involves the existence of a number of rivers with short and very inclined channels, in which the water flows from S to N. The intense incision processes of these rivers produced deep V-shaped valleys with from medium to strongly inclined slopes, separated by usually sharp ridges. The valley bottoms become wide and flat only near the mouths along the discontinuous coastal plains.

Along the central and southern side of Sicily, the larger distance between the mountain range and the southern coast enables the development of longer and slightly inclined rivers flowing from NNE to SSW (e.g., Belice, Platani, and Salso rivers) on a substrate of weak rocks (Mio–Pliocene foredeep and wedge-top deposits). The lower erosional power of these rivers has produced shallow valleys with gently inclined slopes and flat or rounded bottoms, separated by low hills. V-shaped valleys are only found in the head of the great catchment areas, located along the southern side of the mountain range, and in the lower-order rivers.

In the broad NW–SE coastal strip of the Sicilian Channel, the relief lowers gradually to a landscape of large plains, located in resistant Quaternary clastic rocks and cut by deep canyons with flat bottoms that become wider as they approach the mouth.

Methods

Geological and geomorphological analyses consisting of field mapping, aerial photography interpretation, and comparison with bibliographic data were performed with the aim of defining a morphoevolutionary model of western Sicily.

Geological data were mainly obtained from previous studies (Catalano et al. 2013 and references therein) and field surveys in selected key areas (zones affected by Quaternary deposits and topographic expressions due to tectonics; as in the northern coastal plains).

Geomorphological data regarding the presence of landforms directly or indirectly produced by tectonics, and the relationships between landforms and their geological framework were collected. We searched and examined (Figs. 4, 5) fault scarps/

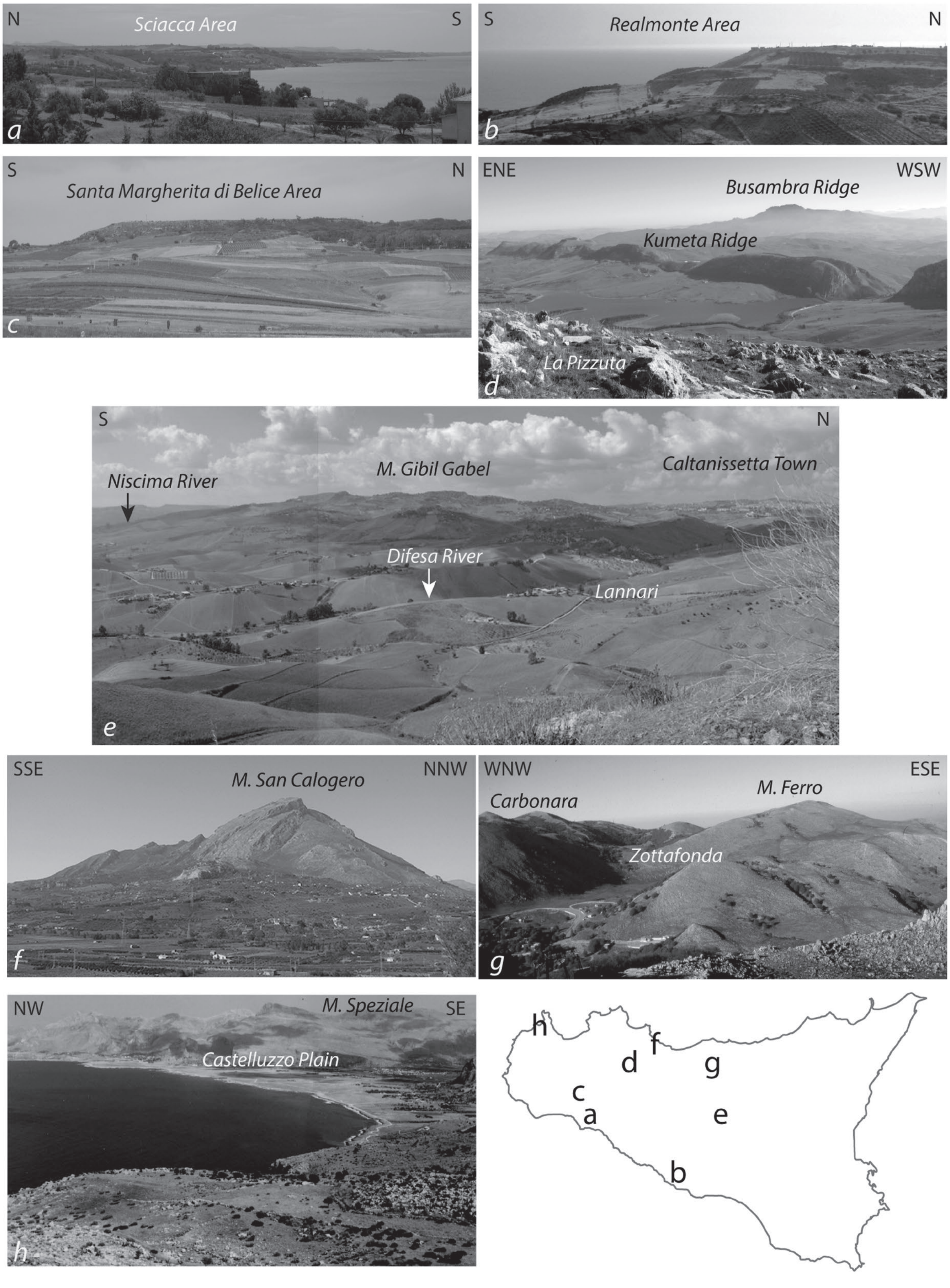

Fig. 4. Landscapes and main landforms of western Sicily. See Fig. 5 for the geological and geomorphological interpretation. **a, b, c** — Flat coastal areas of south western Sicily characterized by marine terraces. **d, e** — Hilly areas of central western Sicily with a rounded relief dissected by river valleys; in (d) a mountain ridge (Kumeta) in "exhumed" carbonate rock produced by differential erosion. **f, g** — Mountain areas of northern western Sicily; in (f) an isolated relief in "exhumed" carbonate rock produced by differential erosion and bounded by inclined structural surfaces (left side) and fault slopes (right side); in (g) a mountain areas with top low-relief surfaces. **h** — Flat coastal areas of the northern end of western Sicily characterized by marine terraces and inward bounded by high abandoned coastal cliffs controlled by normal faults (old fault scarps).

slopes, and topographic highs and lows due to tectonic movements; canyons, V-valleys, and other landforms due to down-cutting processes triggered by tectonic uplift, as well as stair-steps of marine terraces, river terraces, and planation or low-relief surfaces; fault-line scarp/slopes, structurally-controlled complex slopes, and other landforms produced by differential erosion also influenced by high relief; landforms due to deep-seated gravitational slope deformations (DSGSDs), landslides, and generally denudation phenomena following the increased relief.

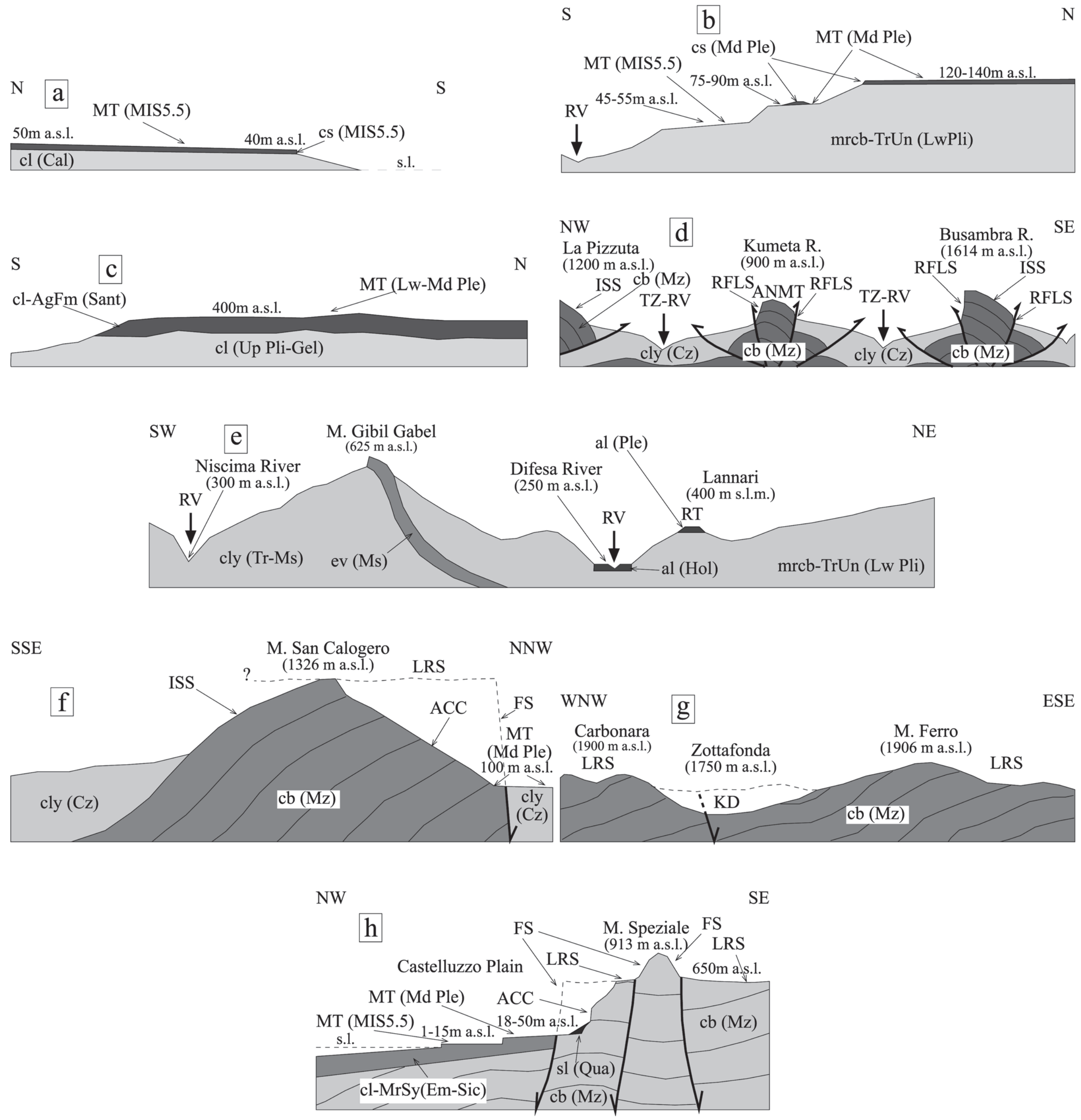

Fig. 5. Geological and geomorphological interpretation of the areas of Fig. 4. **Landforms** (uppercase letters): MT marine terrace; RV river valley; ISS inclined structural surface; TZ-RV triangle zone-type river valley; RFLS resequent fault-line scarp; ANMT anticline mountain; RT river terrace; LRS low-relief surface; ACC abandoned coastal cliff; FS fault scarp; KD karst depression. **Deposits and rocks** (lowercase letters): cs coastal deposit; cl clastic deposit; mrcb marly carbonate rock; cly clayey rock; cb carbonate rock; ev evaporite rock; al alluvial deposit; sl slope deposit. **Stratigraphic units** (after dash): MrSy Marsala synthem; AgFm Agrigento formation; TrUn Trubi unit. **Geochronologic/chronostratighraphic units** (in parenthesis): Qua Quaternary; MIS5.5 Tyrrhenian; Md Ple Middle Pleistocene; Lw-Md Ple Lower–Middle Pleistocene; Em-Sic Emilian–Sicilian; Sant Santernian; Cal Calabrian; Gel Gelasiano; Up Pli upper Pliocene; LwPli lower Pliocene; Ms Messinian; Tr-Ms Tortonian–Messinian; Cz Cenozoic; Mz Mesozoic.

The terms "fault slope" and "fault-line slope" are used to indicate a gentle hillslope with an origin related to the evolution of a fault scarp or a fault-line scarp, and as a result of processes of slope replacement or slope decline; structurally controlled complex slope indicates a hillslope made up of an alternation of hard and weak rocks, on which an alternation of steep and gentle slopes is respectively produced.

In addition, we worked out some geological cross-sections (Fig. 6) to better recognize landforms and generally the relationships between topography and geological features.

Data and results

We present here the data from the morphotectonic studies performed in western Sicily from its southernmost zones.

A stair-step flight of uplifted marine terraces develops from sea level up to about 450 m a.s.l. in the southern areas of western Sicily (Figs. 3, 4a–c, 5a–c, 6a–c). The oldest and highest marine terraces are carved in Calabrian clastic rocks (Agrigento fm.; Figs. 4c, 5c, 6b) of the Santernian regional stage (sensu Ruggieri et al. 1984), that postdate the genesis of the terraces to marine highstand phases of the late Calabrian–Late Pleistocene. In these areas, the better-preserved terraces are in the westernmost southern region (Marsala−Castelvetrano−Sciacca area; Figs. 4a,c, 5a,c), where less orders and very large polycyclic coastal platforms are recognized (Fig. 6b,c); and near the coasts, where only the most recent terraces occur. Towards the south-eastern coast and towards the interior (Realmonte−Palma di Montechiaro area; Figs. 4b, 5b), marine terraces are dissected by river valleys and become fragmented (Fig. 6a); some cycles of river terraces or erosion glacis on soft rocks are present in the valley slopes (Figs. 4e, 5e, 6a). Along the coast of the south-western end, fossils of *Strombus bubonius* and assemblages of "Senegalese fauna" of the Tyrrhenian regional stage (Antonioli et al. 2006 and references therein), contained in coastal deposits lying on wave-cut platforms, allow us to recognize the marine terrace of the Marine Isotope Stage (MIS) 5.5. On the south-eastern coast, the terrace deposits contain insignificant fossils (*Strombus bubonius* is missing), and the terrace of the last interglacial is inferred from altitude and "preservation" (we think that it is the better-preserved, broader, and quite continuous terrace occurring at the lower heights). The inner edge of the MIS 5.5 terrace is from 10 m (SW coast) to 55 m a.s.l. (SE coast). On the south-eastern coast, at lower altitudes we also recognize occasional and smaller marine terraces post-MIS 5.5 with wave-cut platforms developed between 0 and 15 m a.s.l. (e.g., Eraclea area)

In the inland areas of central-western Sicily, the marine terraces disappear and are gradually replaced with a dense network of river valleys (Figs. 3, 4e, 5e, 6a,c–e). River valleys isolate small rounded hills (e.g., Caltanissetta area; Figs. 4e, 5e) in weak rocks (Mio–Pliocene clays and marls of foredeep and wedge-top deposits) or steep structural reliefs (e.g., M. Capodarso; M. Gibil Gabel; Figs. 4e, 5e) in hard rocks (Mio–Pliocene gypsum, calcarenites, and conglomerates intercalated in the foredeep and wedge-top marly/clayey deposits). Along the areas closest to the coastal regions, the structural reliefs are anticline ridges, and syncline depressions (e.g., Siculiana area; Fig. 6a). In the inland areas, they are synclinal ridges (e.g., Ciminna area), and anticline valleys (e.g., upper valley of San Leonardo river; Fig. 6a), both delimited by structurally-controlled complex slopes (Fig. 6e); or isolated mountains bounded by obsequent fault-line scarps and founded on blocks lowered by faults (e.g., Rocca Entella). Successions of river terraces and erosion glacis on soft rocks are also present along the hillslopes (e.g., middle-upper valley of Belice river).

Large structural mountains coincident with tectonic highs and set on Mesozoic carbonate rocks occur in the northern areas of western Sicily and in the Sicani Mountains (Figs. 3, 4d,f–h, 5d,f–h, 6d–g); they are pop-up or anticline-type mountains (e.g., Kumeta and Busambra ridges; Figs. 4d, 5d, 6d). River canyons and narrow V-valleys down-cut these mountains. Broad and deep valleys coincident with tectonic lows and founded on Mio–Pliocene mainly clayey rocks separate the main mountain groups; they are synclinal or triangle zone-type valleys (Figs. 4d, 5d). Along the valley slopes, flights of river terraces or erosion glacis on soft rocks are also present (e.g., valley of Imera Settentrionale river). Mountains and valleys are the result of strong processes of river down-cutting and generally intense denudation, which are selectively performed; the boundaries between mountains and valleys are in fact marked by wide resequent fault-line scarps and slopes or large inclined structural surfaces (e.g., M. San Calogero; Figs. 4d,f, 5d,f, 6d,e). Relicts of hanging planation surfaces, located from a few hundred metres to over 1900 m a.s.l., are present along the slopes and at the top of the mountains. These planation surfaces are not entirely flat or very gently rolling but also include small ridges, hills, and abandoned valleys (low-relief surfaces) due to partial relief reduction (e.g., area of M. Ferro−Carbonara; Figs. 4g, 5g). In the head areas of the river basins that flow into the Tyrrhenian Sea, a number of streams show an inverted drainage produced by river capture processes at the expense of the southern catchments (e.g., upper area of the basins of the Iato and San Leonardo rivers; Fig. 3).

Large and discontinuous topographical depressions occur on the northern side of western Sicily (Tyrrhenian coast). A flat bottom (coastal plain), opened to sea and surrounded by wide scarps hundreds of metres tall to the inland, characterizes these depressions (e.g., Castelluzzo and Conca d'Oro plains; Figs. 3, 4h, 5h, 6f,g). Wedges of Calabrian coastal and neritic clastic deposits from few to tens of metres thick crop out in the coastal plains. These deposits belong to the Marsala synthem (Di Maggio et al. 2008, 2009) and date to the Emilian–Sicilian regional stages (sensu Ruggieri et al. 1984); in addition, they show a very slight dip to the sea and lie on the Meso–Cenozoic rocks with strong angular unconformities. Along the coastal plains, successions of marine terraces develop from 0 m up to 100 m (plain of Castelluzzo; Figs. 4h, 5h), 200 m (plain of

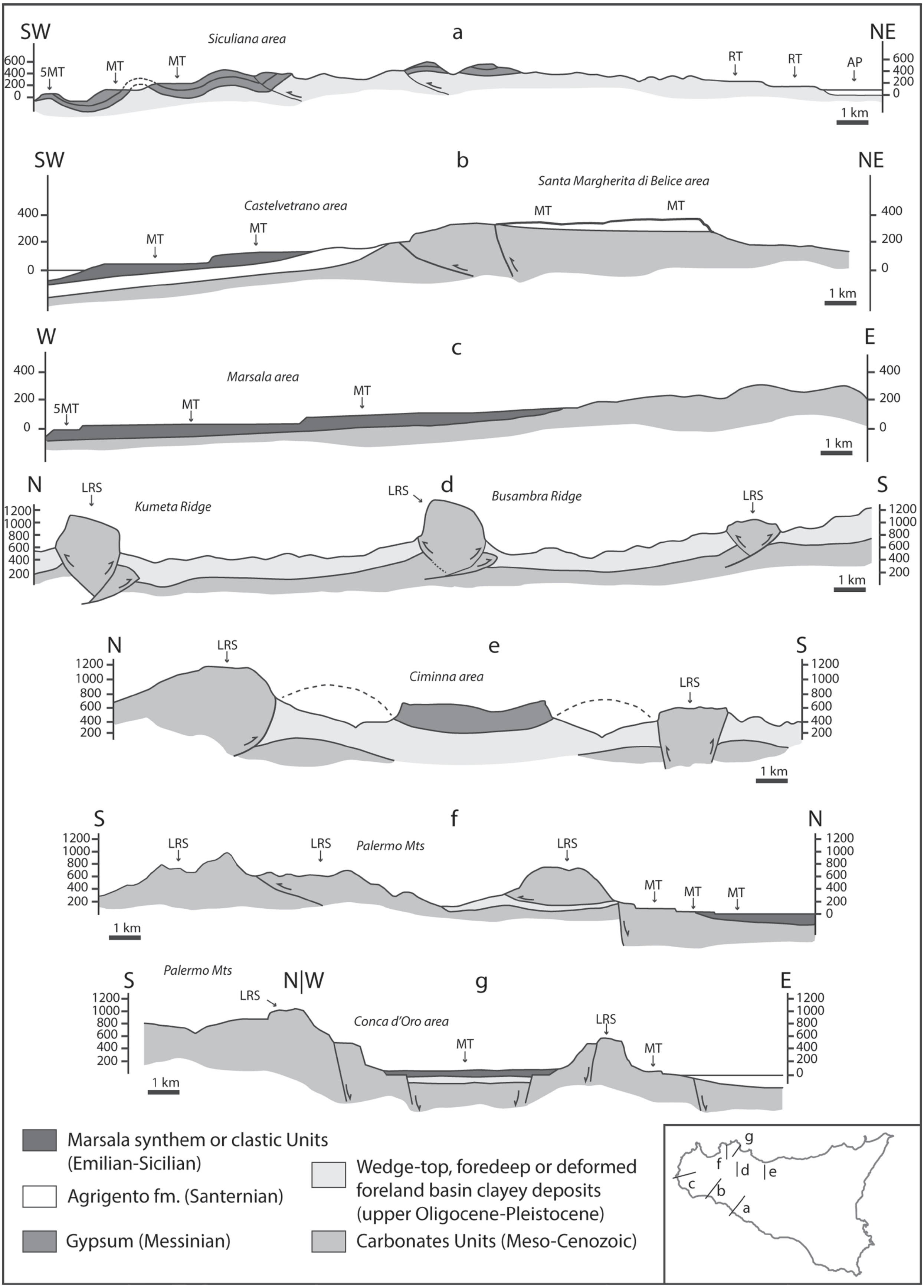

Fig. 6. Geological cross sections: 5MT MIS 5.5 marine terrace; MT marine terrace; RT river terrace; AP present-day alluvial plain; LRS low-relief surface.

Palermo) or 300 m a.s.l. (plains of Partinico, Buonfornello and Sant'Agata di Militello). These terraces are carved on Emilian–Sicilian deposits or pre-Quaternary rocks (Figs. 4h, 5h, 6f,g). The first postdate the age of the terraces to marine highstand phases of the Middle–Upper Pleistocene stages, as supported by palaeontological records (Di Maggio et al. 1999 and references therein; Antonioli et al. 2006 and references therein) and numerous isotopic datings performed on terrace deposits by previous Researchers (Hearty et al. 1986; Bada et al. 1991; Mauz et al. 1997; Antonioli et al. 1999; Scicchitano et al. 2011; Giunta et al. 2012). These terraces are also characterized by few orders and large and well-preserved polycyclic wave-cut surfaces in north-western Sicily (e.g., plains of Castelluzzo and Trapani), and by several orders and narrow and dissected coastal platforms as they proceed eastward (plains of Buonfornello and Sant'Agata di Militello). The inner edge of the MIS 5.5 terraces is from 10 m (Trapani and San Vito lo Capo areas), 15 m (plain of Castelluzzo and Partinico), 20 m (Palermo area), 25 m (plain of Buonfornello) to about 50 m a.s.l. (Sant'Agata di Militello area). Geological and geomorphological analysis further show that the wide and tall scarps surrounding the coastal plains are abandoned coastal cliffs derived from original fault scarps (Figs. 4f,h, 5f,h, 6f,g). Some large tectonically-controlled cliffs are still active, falling in a sheer drop into the sea; whereas broad fault scarps or slopes affect the innermost areas, along the mountain flanks facing the sea, where they cut off and displace the ancient low-relief surfaces (Figs. 4h, 5h, 6g). The presence of great fault scarps and "lowered blocks" at their foot allows the coastal depressions to be interpreted as half-grabens. Finally, a number of forms produced by DSGSD phenomena are present along the mountains of the Tyrrhenian coast and inland characterized by high relief.

Discussion

The collected data from western Sicily show four distinguished regions (Figs. 1, 3), marked by peculiar geological, geomorphological, and topographical settings with rocks, landforms, and landscapes progressively older from south to north. We find flat coastal areas characterized by upper Miocene–Quaternary evaporite/clastic rocks in southern Sicily, where successions of uplifted marine terraces are present; hilly areas characterized by Oligocene–Pliocene clayey, marly and evaporite deposits in central Sicily, where rounded valleys and isolated rolling hills occur; mountain areas characterized by mainly Mesozoic carbonate rocks in northern Sicily, where exhumed structural mountains and deep V-valleys develop; topographically-depressed coastal areas characterized by Quaternary clastic deposits lying with strong unconformity on Meso–Cenozoic rocks on the northern side of Sicily, where stair-step flights of uplifted marine terraces occur along tectonic lows (half-graben) bounded inwards by large tectonically-controlled coastal cliffs.

For the whole of western Sicily, geomorphological survey points out both numerous forms produced by river down-cutting, such as V-valleys and canyons; and a number of forms due to a downward migration of erosion, namely staircases of planation surfaces, erosion glacis on soft rocks, and river or marine terraces. River down-cutting and development of "terraced surfaces" indicate a gradual lowering trend in the general base level of erosion. This trend is typical of areas affected by a widespread uplift trend (Ahnert 1970; Chappell 1974; Iwata 1987; Merritts & Hesterberg 1994; Burbank et al. 1996; Abbott et al. 1997; Whipple & Tucker 1999; Hovius 2000; Jamieson et al. 2004; Ascione et al. 2008; Walker et al. 2011; Gioia et al. 2014).

Along the northern side of western Sicily, geological, and geomorphological analyses underline the occurrence of lowered faulted blocks (half-graben) sealed by the Calabrian deposits of the Marsala synthem; these latter lie on Mesozoic or Cenozoic rocks with strong angular unconformities. The acquired information indicates an extensional tectonic event producing subsidence, block drowning, and deposition of the Marsala synthem, which occurred in northern Sicily during the Calabrian stage. At the same time, a similar tectonic event producing horst-and-graben structures also involved the Tyrrhenian margin of the southern Apennines (Amato & Cinque 1999; Caiazzo et al. 2006).

The overall analysis of data allows the proposition of the morphoevolutionary model described below (Fig. 7).

During the Quaternary period, coastal morphogenesis and tectonic uplift have dominated the more recently surfaced southern areas. After the deposition of the clastic sediments belonging to the Agrigento fm. (after the Santernian regional stage) coastal processes over time produced wave-cut platforms and slightly later deposition of coastal sediments. Owing to uplift movements, the coastal platforms developing during marine highstand phases, in warm climate events, progressively emerged and migrated to higher altitudes, producing the present-day stair-step flight of marine terraces. Given the altitude of the inner edge of the MIS 5.5 marine terrace, the average rate of post-Tyrrhenian uplift is between 0.032 (SW coast) and 0.4 m/ky (SE coast). Unlike our interpretations, Antonioli et al. (2006) suppose that the Tyrrhenian terrace is drowned beneath the Sicilian Channel, suggesting a post-Tyrrhenian tectonic subsidence in southern Sicily linked to the development of the Quaternary Gela foredeep. However, as previously discussed, all our data from south to north Sicily show a geomorphological evolution characterized by prevailing vertical erosion and downward migration of the general base level of erosion, indicating a tectonic uplift trend. As demonstrated by the facies and distribution of the Neogene to Santernian marine units present here, this area of "old" foredeep/wedge-top basins was submerged during the construction of the accretionary wedge. After the end of the accretion, and the south-westward constant migration of the Gela Thrust System and its foredeep (the present-day Gela Foredeep is further south-west of the southern coasts of Sicily), it is fair to assume that the elastic rebound of the Iblean-Pelagian

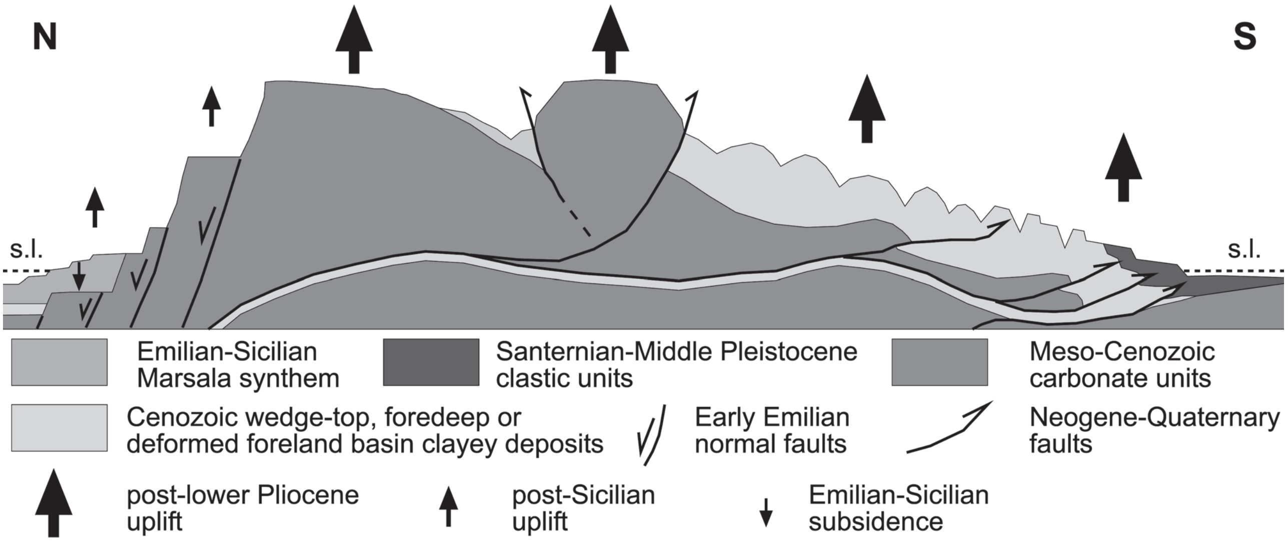

Fig. 7. Morphoevolutionary model of western Sicily. See text for discussion.

slab involves uplift (Doglioni 1991), and processes of gradual land emersion. On the other hand, if the low rates of uplift (0.032 m/ky) have ensured that the sea returns to the same level several times, creating well developed polycyclic platforms, and that the slow emersion of the latter produces the present-day existence of broad and well preserved flat surfaces in the south-western coastal areas, the higher uplift rates we achieve in the south-eastern coastal areas (0.4 m/ky) better explain the numerous orders of marine terraces present here, consisting of smaller wave-cut platforms strongly dissected by river valleys (Chappell 1983; Schumann et al. 2012 and references therein).

The geomorphological setting of central-, and north-western Sicily is the result of the interaction between the tectonic uplift acting to elevate the relief and the following processes of river incision and denudation in general, which tend to lower it, removing great volumes of rock (e.g., Summerfield 1991; Kooi & Beaumont 1996; Burbank & Anderson 2012). These regions represent areas that became dry land long ago, and where erosion has already removed younger upper clastic deposits, destroyed ancient marine terraces, and progressively exhumed older underlying rock.

In central-western Sicily, river incision and denudation processes over time dismantled more resistant Quaternary cover rocks and unearthed easily erodible Neogene rocks below. Isolated, rounded hills originated on the latter. Anticlinal ridges and synclinal valleys developed where the progressive down-cutting has resulted in the exhumation of deeper folded layers of hard rock (middle–upper Miocene evaporite limestones and gypsum, and conglomeratic and sandstone benches). In the innermost areas, where a major incision partially brought to light masses of weak rock again (Oligocene–middle Miocene clayey component deposits) relief inversion processes (Summerfield 1991; Pain & Ollier 1995) produced synclinal ridges and anticlinal valleys, or topographic highs and lows located on previously lowered and uplifted, faulted blocks, respectively. Rounded hills were formed again, where erosion totally removed the Miocene layers of hard rocks. Therefore, data analysis shows that the strong denudation involves novel and continuously changing landforms, although relief modelling affects these areas for a long time.

In north-western Sicily and the Sicani Mountains, the ever deeper progress of the erosion led to the exhumation of the oldest rock successions in Sicily (Mesozoic–lower Oligocene carbonates). The result is a geomorphological setting characterized by large landforms due to differential erosion. Generally, the down-cutting processes considerably slowed down along the resistant carbonate rocks, located on structural highs, producing an elevated and large mountain relief (pop-up or anticline-type mountains); whereas they acted with greater strength and depth along the easily erodible rocks (upper Oligocene–Miocene clays and marls) still preserved in structural lows, creating deep and wide river valleys (synclinal or triangle zone-type valleys). The cause which led to a general matching between topography and tectonic structure is the geological setting marked by weak rocks above hard rocks (Agnesi et al. 2000; Di Maggio 2000); unlike central-western Sicily, where the occurrence of weak rocks beneath hard rocks permitted the development of relief inversion processes. However, the large distribution of resistant carbonate rocks in north-western Sicily is responsible for the preservation of the oldest landforms of Sicily, such as the not fully developed planation surfaces with their hanging, small ridges and hills, and abandoned valleys. Within the geomorphological literature, a similar landform set is known as palaeolandscape (Widdowson 1997 and references therein), gentle erosional landscape (Amato & Cinque 1999) or relict landscape (Clark et al. 2006). Though the best potential for their preservation exists in the cratonic cores and in the tectonically stable interiors of continents, planation surfaces and low-relief surfaces may also be identified within several orogenic belts (e.g., Winkler-Hermaden 1957; Adams 1985; Iwata 1987; Kennan et al. 1997; Amato & Cinque 1999; Frisch et al. 2000; Clark et al. 2006; Legrain et al. 2014). In agreement with the interpretation of Amato & Cinque (1999) for the Campano–Lucano Apennines, the relicts of the planation surfaces and their connected landforms of western Sicily belong to uncompleted erosion cycles that had a duration of some hundred thousand years and that occurred during the construction of the chain, when the relief was located at a lower elevation, but higher and far from the base-level (S coast), though the topographical surface was gently graded. The subsequent erosion then cut down the surrounding areas on weak rock, leaving low-relief surfaces on resistant rock. In addition, these relicts remained until the present-day because the Sicilian Apennines are a very recent belt, lately surfaced, and the erosion has not had enough time to lead to intersection of river valleys and to reach the innermost areas.

In the northern end of western Sicily and after the construction of an elevated relief, the important extensional tectonic event that occurred during the Calabrian stage (about 1.5 Ma — Hugonie 1982) produced normal faults representing the peripheral effect of the back-arc extension of the Tyrrhenian Sea (Amato & Cinque 1999; Nigro & Renda 2005; Pepe et al. 2005; Caiazzo et al. 2006; Di Stefano et al. 2007; Cuffaro et al. 2011; Carminati & Doglioni 2012). These faults resulted in the displacement of the previous low-relief surfaces and the dismantling, collapse, and lowering of the northernmost margin of the Sicilian mountain belt under the Tyrrhenian Sea. Furthermore, the extensional event produced the large fault scarps hundreds of metres tall, some of which were changed into sea cliffs, and allowed the deposition of the Marsala synthem along the drowned faulted-blocks that were affected by subsidence during the Emilian-Sicilian regional stages. As a result of a subsequent uplift event (during or shortly after the Sicilian stage) these blocks gradually emerged starting during the Middle Pleistocene stage, as indicated by the present-day stair-step flights of uplifted marine terraces of the Middle-Upper Pleistocene stages, which are located in the northern coastal plains up to about 100-300 m a.s.l. Based on the altitude of the inner edge of the MIS 5.5 and in agreement with the researchers who studied these coastal areas (Mauz et al. 1997; Antonioli et al. 1999, 2006; Di Maggio et al. 1999; Scicchitano et al. 2011; Giunta et al. 2012; ; Sulli et al. 2013; Basilone & Di Maggio 2016) the average rate of the post-Tyrrhenian uplift is between about 0.032 – 0.1 (NW coast) and 0.36 m/ky (NE coast). Generally, a few, large polycyclic coastal platforms overlooking the MIS 5.5 marine terrace developed where the uplift rate is less than 0.1 m/ky (e.g., Trapani and San Vito lo Capo areas); while successions of several orders of marine terraces consisting of smaller coastal platforms occurred where the uplift rate is higher than 0.1–0.15 m/ky (e.g., plain of Buonfornello; Sant'Agata di Militello area).

On the northern side of Sicily, the post-Sicilian uplift causes of the previously subsiding blocks might be found in the continuous rise of the footwall of the extensional faults, which would "passively" involve and drag up the lowered hanging wall laid on it.

More generally, the crustal shortening, thickening and consequent isostatic compensation affecting all zones of collision can explain the low rates of widespread uplift (maximum value 0.4 m/ky) recorded in western Sicily from south to north (Babault & Van Den Driessche 2013; Schoenbohm 2013 and references therein).

The effects of the tectonic processes affecting the whole of western Sicily (gradual Quaternary uplift from south to north; sudden Emilian block-faulting to its northern side) consist of a strong asymmetry in its topographic profile, with a northern slope much shorter and steeper than the southern slope. Accordingly, the steeper northern rivers with a higher erosion power are characterized by regressive erosion and over time have enlarged their catchment areas at the expense of the southern river basins, through capture phenomena (see inverted drainage phenomena in the head areas on the northern river basins). Following these processes, the regional watershed is currently located further south than the line connecting the highest mountain peaks of Sicily.

Furthermore, the river down-cutting, uplift movements, and extensional tectonics result in a high relief that is a major cause of the development of the surface landslides and DSGSD phenomena affecting the mountain areas of northern Sicily (Di Maggio et al. 2014 and references therein; Agnesi et al. 2015).

Finally, as regards the timing of the geomorphological evolution of Sicily it is necessary to specify the following constraints: (1) the deep-water marly carbonates of the Trubi unit testify that the studied fold and thrust belt was still largely submerged by the sea up to the lower Pliocene (3.6 Ma); (2) the marine clastic deposits of the Agrigento fm. indicate that the emersion of the southern areas of western Sicily began after the post-Santernian (1.5 Ma ago); (3) the shallow-water clastic deposits of the Marsala synthem and their relationships with the substratum show that the areas of the northern side were above the surface in the pre-Emilian (before 1.5 Ma), submerged during the Emilian–Sicilian interval (1.5–0.8 Ma ago), and again emerged from the Sicilian regional stage (after 0.8 Ma ago). Consequently, the emersion of the older areas of central and northern Sicily and the beginning of the first relief modelling processes occurred between 3.6–1.5 Ma ago.

Conclusion

The reconstruction of the geomorphological evolution of western Sicily highlights the following:

- The occurrence of a very recent mountain belt, which started its geomorphological evolution less than 3.6 Ma ago and only recently rose above sea level.
- The creation of new relief in the southern areas affected by uplift, the causes of which are to be found in the elastic rebound of the Iblean-Pelagian slab following the south-westward constant migration of the accretionary wedge and its foredeep.

- The interaction between uplift, coastal processes, and sea level changes in southern areas, responsible for the production of a staircase of marine terraces.
- The upward and inwards gradual migration of the created relief, with the south-westward progressive shift of the shoreline, owing to uplift produced by isostatic compensation following the crustal shortening and thickening.
- The interaction between uplift and river down-cutting in central and northern areas, responsible for the dismantling of the easily erodible younger rocks (Quaternary clastic deposits and Neogene clays) and older landforms (e.g., marine terraces), exhumation of the underlying resistant older rocks (Messinian gypsum and Mesozoic carbonates), and genesis of river valleys and isolated hills/mountains.
- The gradual increase of relief from south to north, responsible for the development of differential erosion, DSGSDs, surface landslides, and a strong denudation generally.
- The occurrence of a constantly changing relief on easily erodible rocks in central areas, in which novel, and continually reworked landforms develop.
- The production of an elevated relief, built on resistant rocks to the north, on which the oldest landforms (low-relief surfaces) are better preserved.
- The disruption of relief on the northern side of Sicily occurring about 1.5 Ma ago, the causes of which are to be found in the extensional tectonics linked to the opening of the back-arc basin of the Tyrrhenian Sea.
- The formation of shallow-water basins, affected by subsidence between 1.5–0.8 Ma ago, and developed on the lowering faulted blocks flooded from the sea along the areas of the northern side.
- The triggering of uplift again in the previously subsiding blocks occurring from about 0.8 Ma, the interaction of which with coastal processes and sea level fluctuations produces the succession of marine terraces along the areas of the northern side.

Finally, it should be noted that the morphoevolutionary model presented here fits well with the geological and geomorphological settings, and the topography of western Sicily, characterized by outcroppings of progressively older rocks and landforms from south to north, and their sudden "rejuvenation" in the areas of the northern side, and by a gradually increasing relief from south to north, and its sudden falling in the areas of the northern side.

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