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Transtensional/extensional fault activity from the Mesozoic rifting to Tertiary chain building in Northern Sicily (Central Mediterranean)

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Abstract: Extensional structures of different ages characterize the Sicilian fold-and-thrust belt. Normal faults ranging in geometry from stepped to listric and formed in different geodynamic settings significantly controlled the pattern of syntectonic deposits. Since Mesozoic times Sicily has experienced deformation related to the opening of the Tethys Ocean. Between the Upper Triassic and the Cretaceous normal, strike- and oblique-slip faults, developed in northern Sicily, in the framework of a transtensional deformation regime induced by the oblique rifting of the African and European continental passive margins. Since Tertiary times a reversal in the general relative plate motion induced convergence, followed by collision of the European and African margins. Neogene compressional deformations were locally associated to extensional structures related to the orogenic wedge taper and to the Pliocene-Pleistocene Tyrrhenian Basin evolution. The persistent activity of extensional structures at different times and within different tectonic pictures is magnificently preserved in the following Triassic-to-Recent stratigraphic record: (i) carbonates were deposited on the Jurassic passive margin, formed by neritic platforms and intervening pelagic basins; (ii) the Cretaceous extension in the Africa plate boundary followed Late Triassic-Early Jurassic transtension due to Neotethys stretching; (iii) clastic deposition occurred during Neogene chain building ahead of the advancing thrust front (foredeep deposition) and in the inner sectors of the orogenic wedge (perched deposition in extensional setting); (iv) the perched-basin deposition at the rear of the wedge was probably related to the extensional collapse of the taper during the Late Miocene and (v) the attenuation of previously thickened lithosphere corresponds to the onset of the Tyrrhenian stretching.

Key words: Mesozoic–Tertiary, Sicilian Maghrebian Chain, modes of extension, basin formation, normal faults.

Introduction and objectives

Tectonic inversion, that is the switch from extensional to contractional deformation regimes or *vice versa*, is an important process in the evolution of collision mountain belts (e.g. Williams et al. 1989). The early rift-basin history of many orogenic systems is clearly preserved within their stratigraphic record (e.g. the Alps: Gillcrist et al. 1987; Butler 1989) and, in turn, mountain belts may be subject of late/or post orogenic collapse (e.g. the Western Cordillera in North America — Constenius 1996). The effects of extensional deformations recognized within orogenic systems generally subdivided into pre- or post-thrusting events, the successive modifications of pre-thrusting extensional structures during orogenic events and their eventual reactivation during the onset of late or post-orogenic extension (Tavarnelli 1996) are not well documented. The goal of this paper is to underline that the Sicilian Maghrebian Chain is characterized by a long history of extension, starting with the formation of a passive margin and active through the evolution of the fold-and-thrust belt up to its collapse and to the consequent post-orogenic deformations.

In fact, carbonate platforms, belonging to the African passive margin and characterizing the Sicilian Maghrebian Chain, developed during Mesozoic times under the crustal attenuation regime which led to the opening of the Tethys Ocean (Dercourt et al. 1986). From the Oligocene onwards, as a consequence of the convergence of the African and European plates, these platforms suffered contractional deformations and were affected by folding and thrusting during the construction of the Apenninic-Maghrebian Chain. Syn-orogenic extensional strains, intense at shallow crustal levels, induced the formation of basins in several domains of the evolving chain–foredeep–foreland system, namely in the foreland, in the foredeep and in the back of the chain (Oldow et al. 1993; Keller et al. 1994; Tricart et al. 1994).

At shallow crustal levels of the Sicilian Maghrebian Chain extensional tectonics mainly gave rise to syn-sedimentary normal faults recognized within the Mesozoic–early Tertiary pre-orogenic successions and the upper Tertiary syn-orogenic and post-orogenic successions. Syn-sedimentary normal faults are also overprinted by Neogene thrust-related deformations.

The evidence of transtensional structures of different ages and the stratigraphic record of Mesozoic extension has been described by many authors (Truillet 1966, 1970; Wendt 1965, 1971; Bernoulli & Jenkins 1974; Catalano & D'Argenio 1982; Bouillin et al. 1992; Martire et al. 2000), and related to the opening of the Neotethys Ocean. A younger episode of extensional tectonics, connected to the evolution of the orogenic

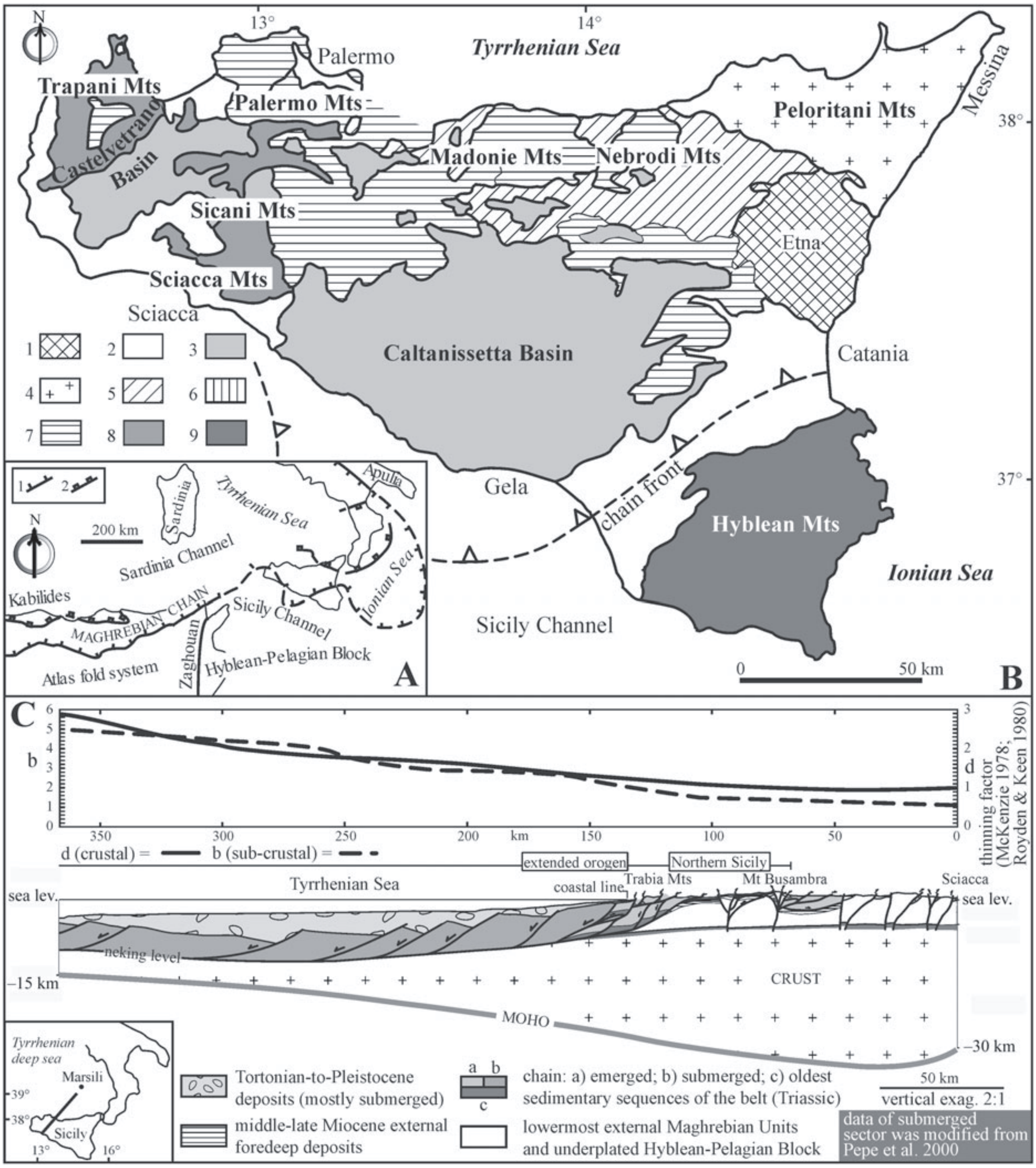

Fig. 1. **A** — Tectonic sketch of the Central Mediterranean. 1 — Front of the Apenninic-Maghrebian Chain (in the Ionian Sea: front of the "Calabrian Ridge"); 2 — front of the Kabilides units and Calabrian Arc borders. **B** — Tectonic sketch of Sicily. 1 — Etna volcano; 2 — Upper Pliocene-Pleistocene deposits (foredeep in Southern Sicily); 3 — deformed Miocene-Upper Pliocene foredeep (Gela Nappe *p.p.* in the Caltanissetta Basin); 4 — Peloritani units and related Oligocene-Miocene syn-tectonic deposits; 5 — Sicilidi Units and related Oligocene-Miocene syn-tectonic deposits; 6 — carbonates of the Panormide Units and related Oligocene-Miocene syn-tectonic deposits; 7 — pelagic carbonates Imerese-Sicani Units and related Oligocene-Miocene syn-tectonic deposits; 8 — units derived from the Western sector of the Hyblean-Pelagian Block of Sicily (compressional deformation inside) and related Oligocene-Miocene syn-tectonic deposits; 9 — South-eastern sector of the Hyblean-Pelagian Block of Sicily (foreland, extensional deformation inside). **C** — Schematic crustal section across the Sicily belt, showing the structural style of the extended orogen. Cross-section only shows the main Pliocene-Pleistocene strike-slip structures. The crustal and sub-crustal thinning factors (McKenzie 1978; Royden & Keen 1980) have been calculated; for their computation we assumed an initial crustal thickness ranging from 30 km in the foreland areas to 35 km in the inner sector of the chain (Pepe et al. 2000). The lithospheric initial thickness ranges from 100 km in the external areas to about 200 km in the chain roots. In the strong subsiding sectors of the analysed transect the δ factor is about 3, the β factor is equal to 5, whereas the necking level is located at about 10 km (Pepe et al. 2000). The water depth and thickness of the submerged late Tortonian–Pleistocene basin fill deposits related to the stretching factors fit the theoretical values proposed by McKenzie (1978).

wedge taper (Kezirian et al. 1994; Giunta et al. 2000) and to large-scale rotations (Oldow et al. 1990), has affected this chain since Miocene times.

In this paper we analyse the extensional tectonics along the Sicilian Maghrebian Chain, from pre-orogenic to orogenic processes by using several examples and we propose an attempt to extrapolate the role of these tectonics in the formation of Mesozoic-Tertiary basins for the Western Mediterranean orogens. The Mesozoic transtensional/extensional tectonics was produced during the rifting processes leading to the opening and evolution of the Neotethys Ocean. The activity of transcurrent/normal faults induced basin formation and controlled facies and thickness distribution of the rift-basin deposits. The Tertiary syn-collisional extensional tectonics controlled the basin formation in the orogenic wedge. Normal faults developed ahead of the advancing thrust front determined the accommodation space for foredeep sedimentation.

Structural setting of Sicily

Sicily, located between the Apennines and North-Africa, is the easternmost sector of the Maghrebian fold-thrust belt, formed during the Neogene (Fig. 1A). In the mainland, a southward-tapering orogenic wedge is exposed and the thrust front forms an arcuate salient in Southern Sicily and in the Sicily Channel and Ionian Sea (Fig. 1A).

The Sicilian Maghrebian Chain, corresponding to a thrust belt–foredeep–foreland system (Ogniben 1960; Broquet et al. 1966; Grandjacquet & Mascle 1978; Catalano & D'Argenio 1978, 1982), extends with a dominant W–E trend from the Trapani Mts to the Peloritani Mts (Fig. 1B) and it is formed by a stack of imbricate foreland-verging folds and related thrust sheets (Grandjacquet & Mascle 1978; Bianchi et al. 1987; Roure et al. 1990; Catalano et al. 2000). The north-eastern corner of Sicily (Peloritani Mts), composed of sedimentary and crystalline terrains, is a belt of controversial origin, interpreted as a microplate interposed between the African and European margins during the Mesozoic–early Tertiary times (Amodio Morelli et al. 1979), or as a segment of the European margin (Bouillin 1986; Bouillin et al. 1992).

The tectonic units were piled along shallow thrusts and were transported southwards during the construction of the Neogene Apenninic-Maghrebian fold-thrust system (Ogniben 1960; Broquet et al. 1966; Scandone et al. 1974; Catalano et al. 1979; Catalano & D'Argenio 1982).

The syn-tectonic deposits lying on the stacked chain units are progressively younger toward the foreland, and were affected by contractional deformations acquired during the southward migration of the thrust front (Caire et al. 1960; Broquet et al. 1984; Roure et al. 1990; Nigro & Renda 2000). These deposits are widespread in central Sicily, in the Nebrodi Mts and in the southern slopes of the Madonie Mts (Fig. 1).

The south-eastern portion of the island is occupied by the Hyblean Foreland representing the emergent sector of the Pelagian Block (Winnock 1981) which extends from Tunisia through to the Sicily Channel.

Compressional tectonics linked to the chain building mainly developed through crustal block rotations and oblique-slip thrusting (see Ben-Avraham & Grasso 1990, 1991; Oldow et al. 1990; Reuther et al. 1993; Lickorish et al. 1999; Nigro & Renda 2001a for field and paleomagnetic evidence).

Starting from the Northern Sicily coast, a process of crustal attenuation and subsidence has affected the chain since Late Tortonian times (Kezirian et al. 1994; Giunta et al. 2000; Fig. 1C). Repeated failure of the orogenic wedge also occurred during the Pliocene–Pleistocene times (Nigro & Renda 2001b).

The stratigraphic successions of Sicily indicate a deposition onto differently subsiding and fault-controlled blocks (Scandone et al. 1974; Biju-Duval et al. 1977; Catalano & D'Argenio 1978, 1982), displaying a facies distribution with carbonate platforms and intervening pelagic basin during Mesozoic–early Tertiary times (Fig. 2).

Palinspastic restorations of the Sicilian Maghrebian Chain (Catalano & D'Argenio 1978, 1982; Catalano et al. 1979; Dercourt et al. 1986; Casero & Roure 1994) indicate a physiographically sinuous continental shelf margin, represented by

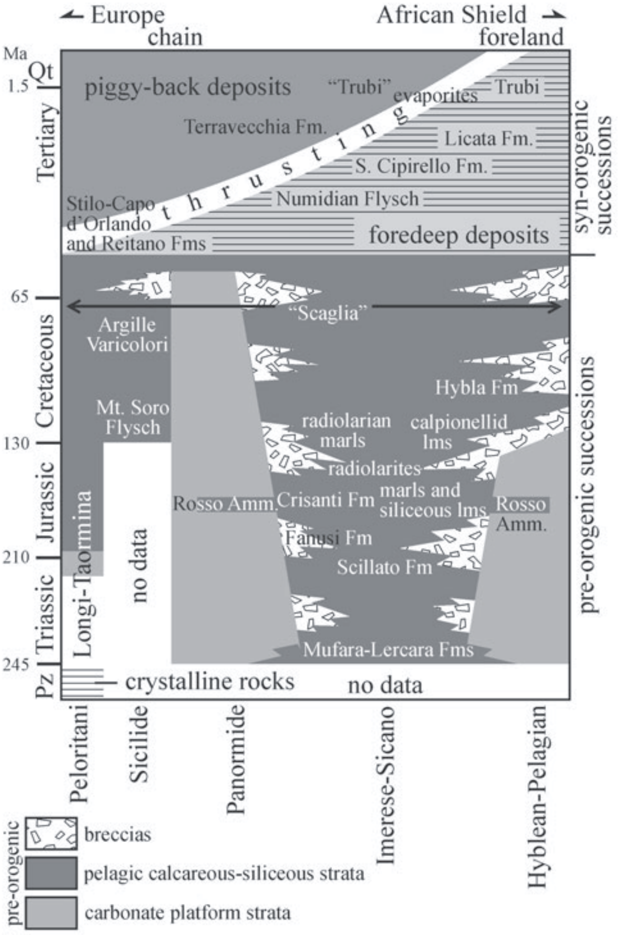

Fig. 2. Stratigraphic sketch of Sicily. Carbonate sedimentation represents the pre-orogenic strata. Mesozoic-lower Tertiary platforms are known as Peloritani (partly), Panormide and Hyblean-Pelagian, while the intervening pelagic basins are known as Sicilide and Imerese-Sicano. The Sicilide Basin was characterized by turbiditic deposition. Clastic deposits represent the Tertiary syn-tectonic strata filling the basins located inner and outer with respect to the thrust front.

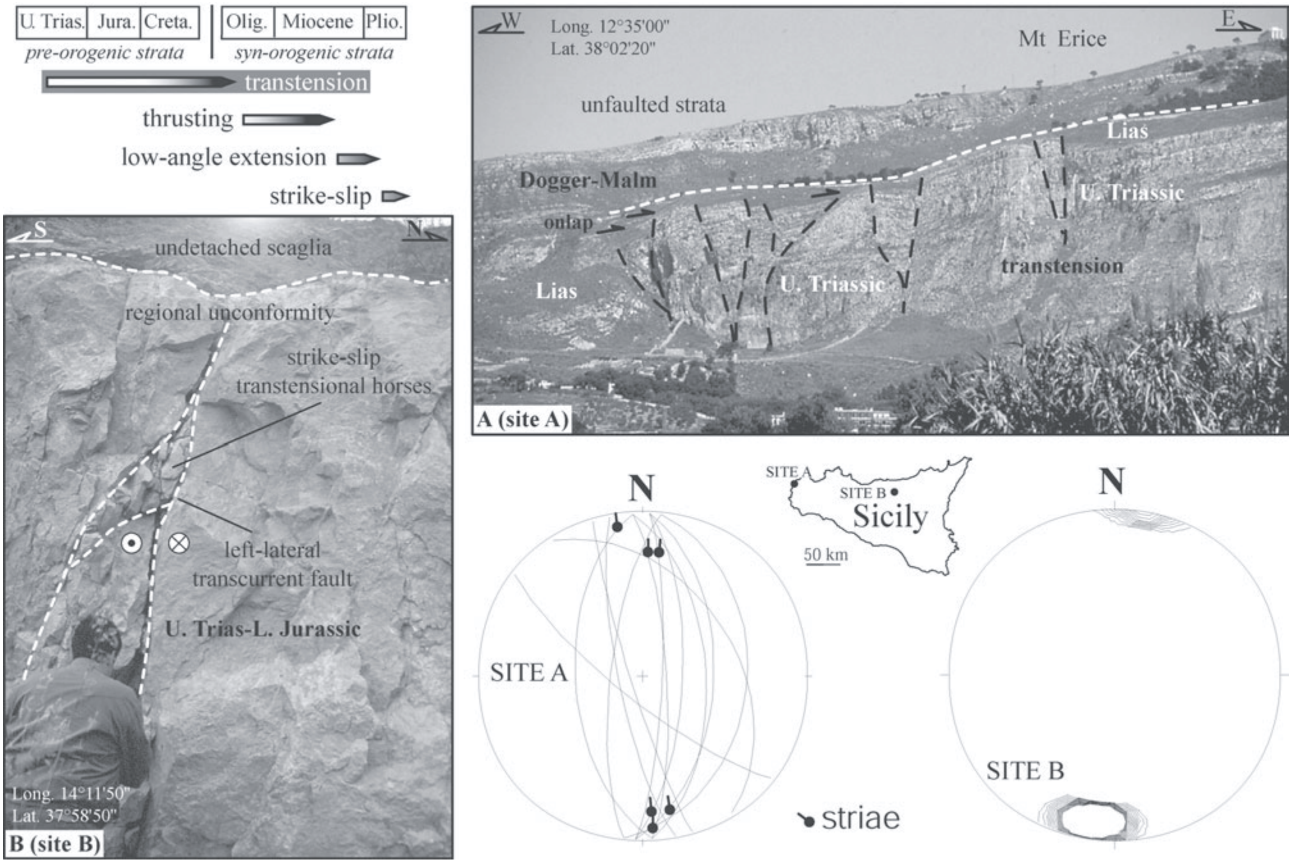

Fig. 3. Mesozoic strike-slip deformations in Western Sicily (faults are plotted in the stereonets). **A** — Negative flowers affecting the Upper Triassic carbonate platform strata and the Lower Liassic pelagic strata (left side of photo) in the Trapani Mts (site A). The Liassic deposits overlay the platform during faulting. The Dogger-Malm unfaulted strata post-date deformation in the site. **B** — Transcurrent fault displacing carbonate platform strata in the Eastern Madonie Mts (site B). Erosion occurred before the Upper Cretaceous unconformable deposition of the pelagic deposits. See text for further explanations.

salients and recesses (Scandone et al. 1974; Catalano & D'Argenio 1982).

Structural pattern of the extensional structures within the Sicilian strata

Various scale normal faults, recognized in Sicily and produced by extension of the crust, are here ascribed to four main stages.

We focused mostly on the north-western part of the island featuring many tectonic units (sites A to F; Figs. 3–10).

Mesozoic extension

Late Triassic–Early Jurassic

Normal/transcurrent fault systems displace the Upper Triassic-Lower Jurassic strata of the Western-Northern Sicily carbonate platforms, showing a mostly N–S or E–W orientation (Trapani and Eastern Madonie Mts; sites A and B in Fig. 3, respectively). Locally preserved slickensides, with pitch indicating a gently-dipping slip vector, allowed us to recognize lateral displacements for strike-slip deformation mechanism. Slickensides and calcite fibres show left-lateral and, to a smaller extent, right-lateral displacements.

Dip-slip faults (dipping 30° to 60°) are also present, with not always well preserved kinematic indicators and locally showing extensional displacements.

Transcurrent faults are characterized by damage zones in which strike-slip horses developed (Fig. 3B), with associated joints and spaced cleavage.

Facies and thickness distribution of the Lower Jurassic-Lower Cretaceous pelagic deposits and the stratal relationships with their substrate (Wendt 1965; Mascle 1979; Trimaille 1982) suggest tilting of faulted blocks along the carbonate platform-basin boundaries. In several sites (Fig. 3A) Middle Jurassic pelagic strata onlap and lie on the carbonate platform faulted strata. The lithofacies of the pelagic strata involved in the strike-slip faulting range from hemipelagic (Fig. 3A) to condensed (Figs. 4A, 5E).

Carbonate or dolomitic breccias, ranging in thickness from a few centimeters up to several hundred of meters (Trapani and Palermo Mts, respectively), are present within the pelagic strata near the transcurrent fault strands.

The faults with lateral displacements locally exhibit opposite dips forming flower structures (Fig. 3A) with widespread block tilting.

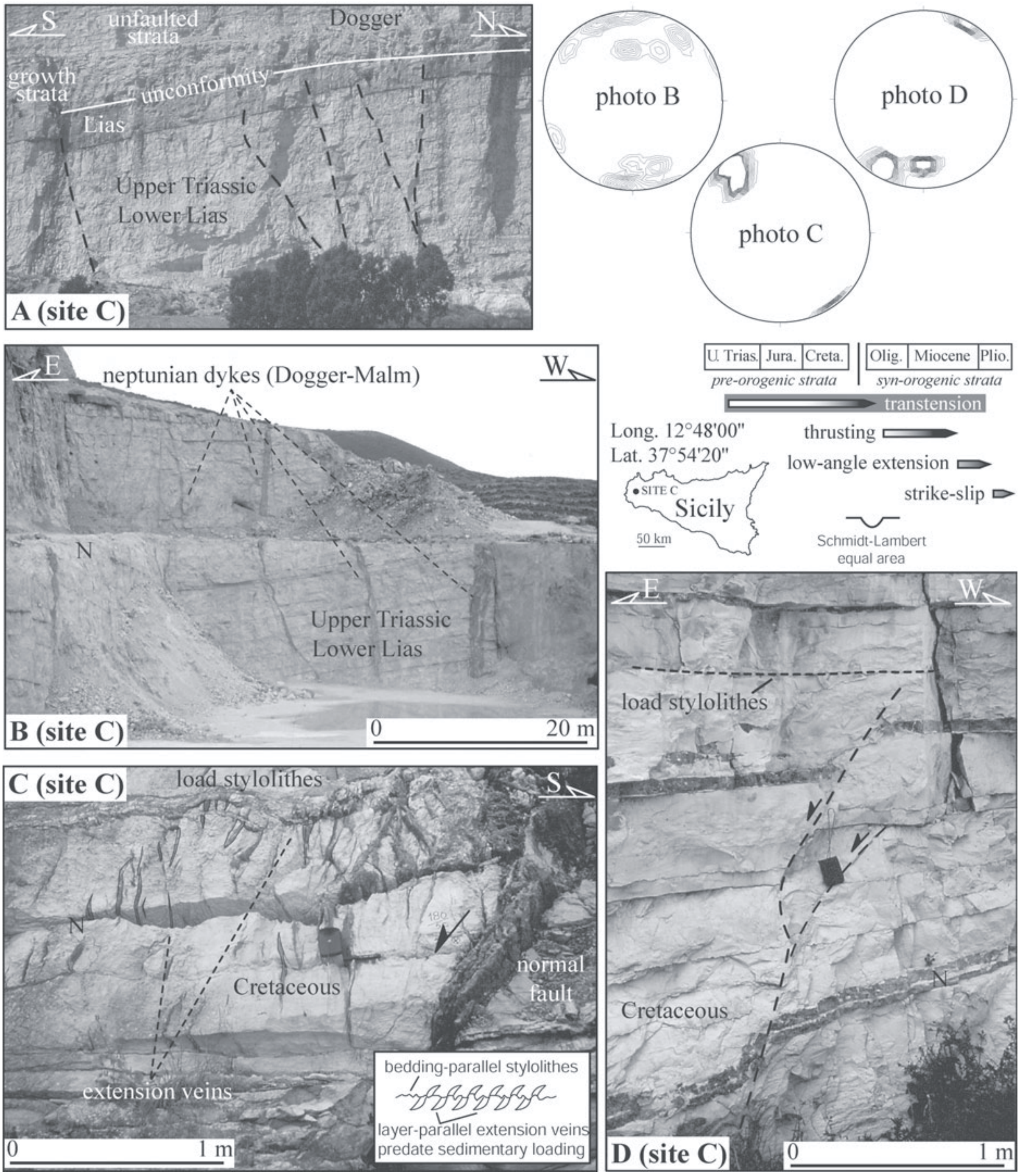

Fig. 4. Examples of Jurassic and Cretaceous tectonics (faults are plotted in the stereonets). **A** — Extensional-transtensional faults affecting the Upper Triassic-Lower Liassic carbonate platform-condensed pelagic deposits in the Southern Trapani Mts (site C). Normal fault activity reveals the wedge geometry of the Dogger growth deep-water strata overlying the carbonate platform. **B** — Extensional tectonics during the Dogger–Malm is represented by extensional fractures filled by pelagic deposit of this age. **C** — Extensional tectonics occurred during the Cretaceous. Widespread small-scale structures, corresponding to sub-vertical extension veins truncated by bedding-parallel stylolites, indicate extensional deformation. **D** — Syn-sedimentary normal fault affecting the Cretaceous pelagic strata are characterized by upwards decreasing of displacement and are truncated by load stylolites.

Fault breccias are also present with thickness decreasing eastwards from a few meters (Trapani Mts) to many tens of meters (Palermo Mts), where tilted blocks of carbonate platform strata are affected by paleokarst structures (Ferla & Bommarito 1988).

The present-day orientation of these faults is mostly N–S in site A (Trapani Mts). Instead, in site B (Eastern Madonie Mts) the orientation of the faults affecting the carbonate platform deposits is on average W–E and Upper Cretaceous basin deposits lie over the fault zones (Fig. 3B).

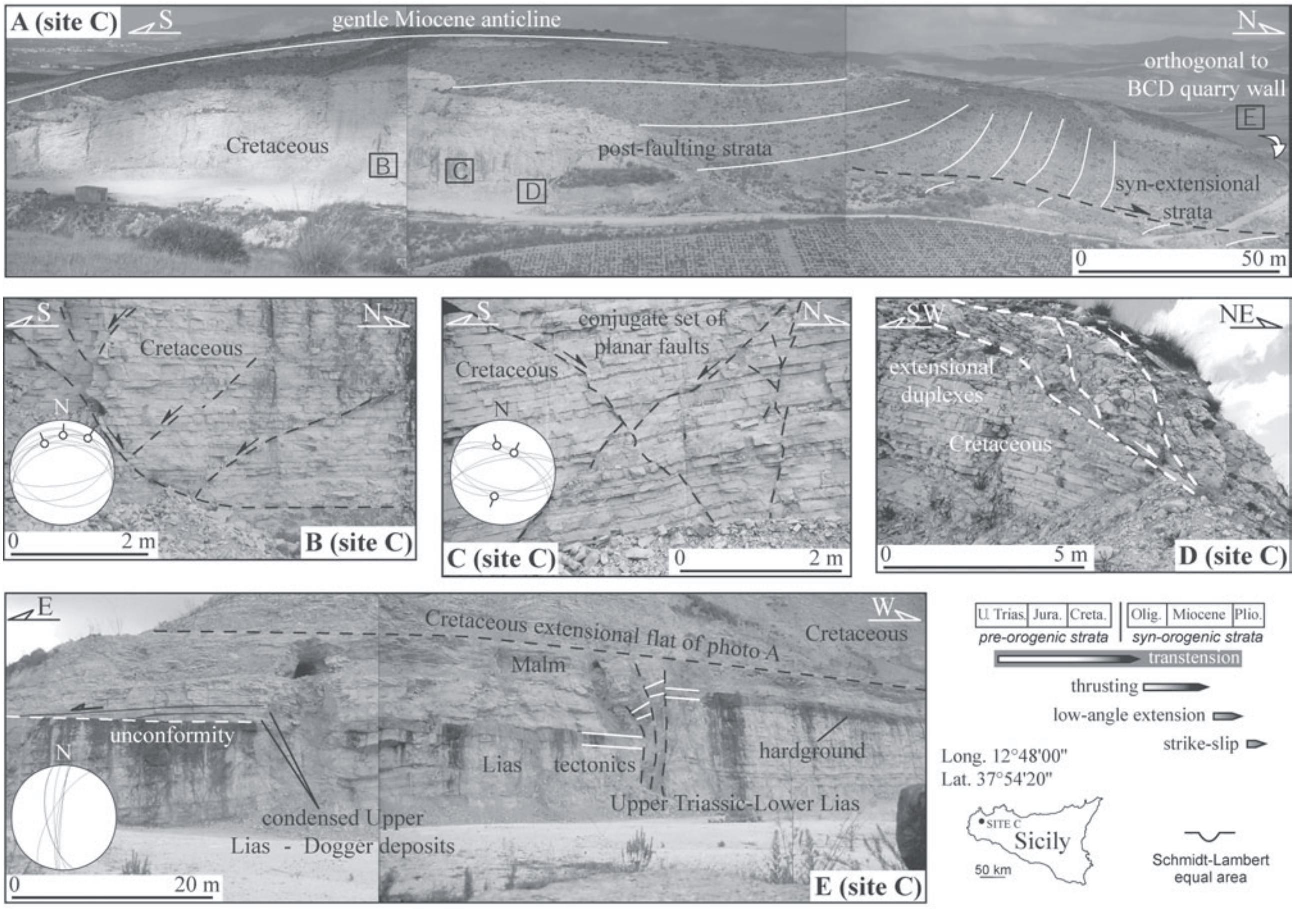

Fig. 5. Example of Cretaceous extensional tectonics in the Southern Trapani Mts (site C). **(A)** 100 m-in-scale listric normal fault affecting the basin-plain deposits. Listric normal faults fade out upsection within the Cretaceous strata, exhibit various relationships with bedding, and are characterized by stepped geometry defined by alternating, wide (up to 100 m) sub-horizontal flats connected by low-angle extensional ramps. The Upper Cretaceous strata post-date faulting. Associated mesoscopic structures are abundant, and mainly consist of fault fans, in which antithetic normal faults are widely associated with the synthetic master faults. Syn-sedimentary meso-scale structures are recorded in the footwall. These are represented by extensional fans, with master and antithetic fault sets **(B)**, conjugate set of planar faults **(C)** and extensional duplexes **(D)**. These sets were probably generated prior to bed tilting during Miocene deformation, because their obtuse bisectors are normal to the bedding in both hinge regions and limbs of the compression-induced gentle anticlines. The Cretaceous extensional tectonics followed the Early Jurassic transtension. In photo **E** (orthogonal to photo A) the flat of the Cretaceous listric normal fault cuts a transtensional fault sheaf. The Early Jurassic tectonics induced rapid drowning of the Lower Lias carbonate platform, as shown by the thin condensed horizons over the neritic carbonates. Faults are plotted in the stereonets. See text for further explanations.

The Lias-Dogger pelagic (locally condensed) beds overlying the Triassic carbonate platform strata (Fig. 4A) define a typical wedge growth pattern. These strata are mildly folded and unconformably covered by the Middle Jurassic deep-water deposits. These elements, in combination with observed block-tilting phenomena, may result from the development of roll-over structures during deformation.

Extensional fracture systems, locally filled by Dogger-Malm deposits (Fig. 4B), are present in the hanging-walls of the faulted blocks, with spectacular examples in the hinge regions of roll-over anticlines (Southern Trapani Mts).

Late Jurassic–Cretaceous

In Western Sicily (Trapani Mts), Cretaceous extensional tectonics are mainly represented by various scale normal faults, mainly with a trend at low angles to a mean W–E direction, that is normally to the Middle Jurassic transtensional faults (see stereonets of Figs. 4 and 5).

Bedding-parallel stylolites and bedding-normal en-échelon calcite veins (Fig. 4C), the most representative syn-sedimentary extensional structures, show evidence of a simultaneous development during the same deformation.

Syn-sedimentary normal faults, characterized by an upward decrease of displacement along their surfaces, pre-date the diagenetic stylolites (Fig. 4D). Soft-sediment deformation is also suggested by fault tips accommodated downwards by folding (Fig. 4D).

Examples of syn-sedimentary Cretaceous extensional structures are also shown in Fig. 5. Cretaceous normal faults have locally experienced deflection or folding as a consequence of the superimposed Neogene contraction (see Fig. 5A).

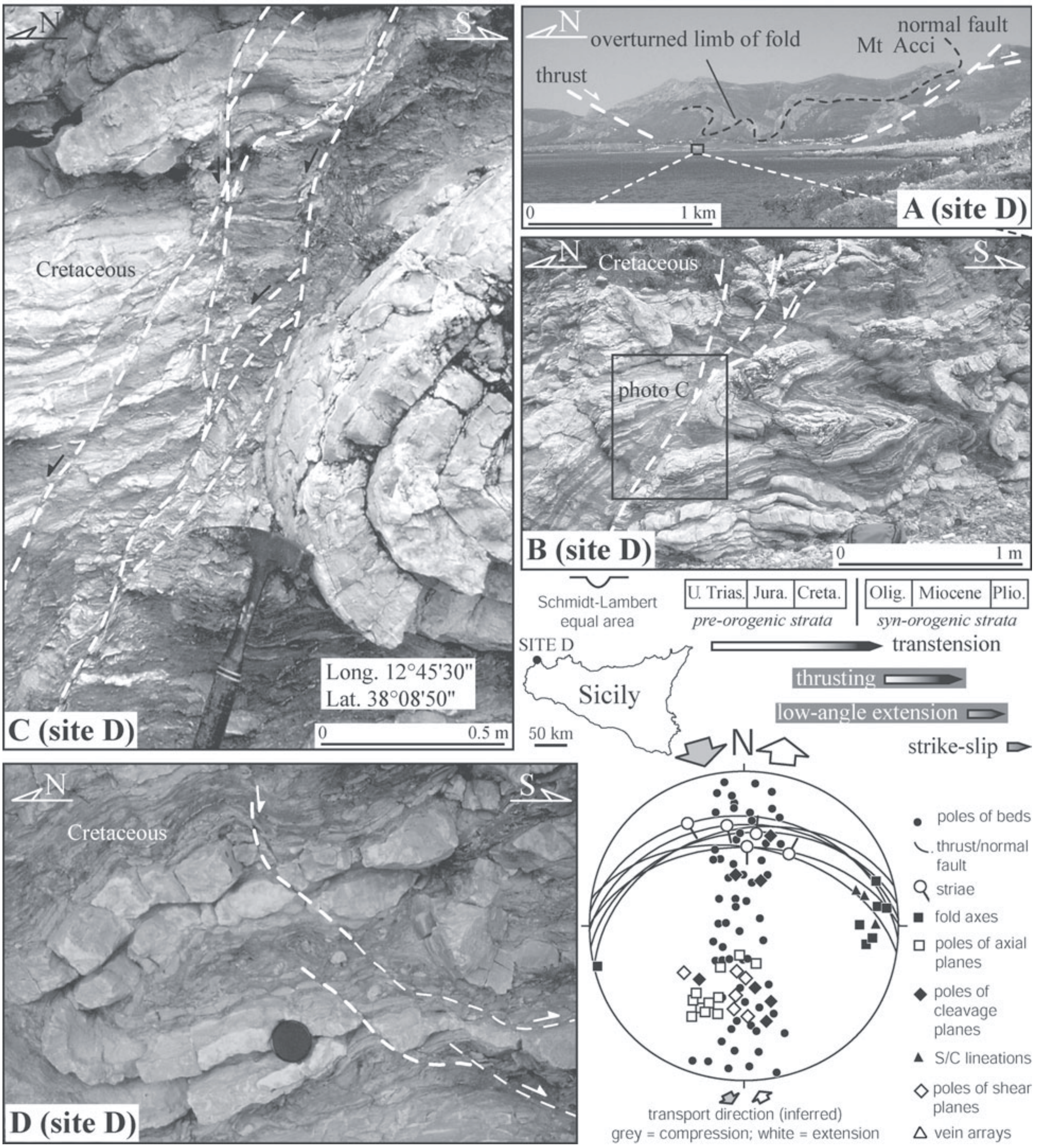

Fig. 6. Miocene extension during folding and thrusting in the Trapani Mts, followed by Late Miocene (?)-Pliocene extension (site D). Compressional structures are represented by south-verging folds and reverse faults, subsequently northwards tilted due to the activity of a north-dipping listric normal fault. 1 kilometer-in-scale contractional structure is represented by a ramp-anticline in which the forelimb is overturned (**A**). The thrusting provided the geometric superposition of the slope/basinal deposits over the Western extent of the carbonate platform. Metric-in-scale structures indicate extension during folding/thrusting (as in photo **D**) and after compression (photos **B** and **C**). Post-folding extension is represented by innerward-dipping normal faults, which cut folds and cleavage (photos **B** and **C**). Locally, previous shear zones have been re-utilized and negatively inverted. Intra-folding extension (photo **D**) is already represented by foreland-dipping normal small faults, generally located in the hinges of the drag folds. These faults may represent the effect of the activation of synthetic structures during thrusting coupled by shearing. See text for further explanations.

In Fig. 5E a Cretaceous normal fault parallel to bedding defines an extensional flat truncating older faults which affect the carbonate platform and the Jurassic condensed strata.

Several vertical faults with oblique-slip kinematics offset beds or slump horizons at the outcrop-scale, act as transfer zones from one decollement horizon to another, accommodating both flexural shear and producing significant variations in bed thickness.

Neogene extension

Oligocene-Miocene interplay between compression and extension

Since Oligocene times, the Sicilian passive margin has experienced contraction and was affected by thin-skinned, piggy-back thrusting (terminology after Butler 1987) that produced significant displacements towards the southern foreland (Broquet et al. 1966, 1984; Catalano et al. 1979; Nigro & Renda 2000).

Stepped thrust faults with ramp-flat geometries and with kilometric spacing of the ramps are recognized.

Due to the occurrence of detachments within the multilayer, thrust-related folding produced multi-harmonic structures, splays and duplexes. In particular, folding (one to several hundred meters in size, related to the rheology of the local stratigraphic sequence) was accommodated by flexural-slip and buckling mechanisms. The normal limbs dip shallowly north-to-northeastward, whereas the forelimbs are steeply dipping southwards, or overturned northwards, defining a clear southern vergence (Fig. 6A). These structures generally nucleated by steeply N-dipping thrusts.

Faulting and folding developed under simple shear. Flexural shear related structures (such as striae on bed surfaces) orthogonal to the fold axes have been observed, mostly within the Cretaceous pelagic strata. The simple shear strain in the thrust hanging-walls may result in a reduction in the rate of displacement near the base of the asymmetric ramp anticlines and permits us to identify overturned thrust-related folds (Fig. 6A). Minor structures related to shear consist of layer-normal pressure-solution cleavage and layer-parallel shear planes. The spacing of the cleavage domains is generally 1 cm or less in the Upper Cretaceous deposits overlying the Jurassic basins (see Fig. 6). The mean bedding cleavage intersection lineation trends W–E. No axial-plane cleavage is recorded in the Upper Cretaceous strata overlying the slightly deformed carbonate platform in the Southern Trapani Mts (see Figs. 5 and 9). Folding-related cleavage is more and more developed northwards, in the Trapani Mts between Trapani and the S. Vito Peninsula, where the Western Sicily chain units are exposed.

Extensional strains locally form within contractional folding. Intra-folding extension is represented by small normal faults located near the hinge of the minor drag folds along the 100 m scale limbs (Fig. 6D). The high ratio of simple shear may have induced vertical thinning coupled to fold amplification and asymmetry.

In the fold outer arcs, the strong mechanically competent horizons are broken by extensional faults and fractures. Small-scale extensional faults located in the overturned fold limbs could result from fold amplification and/or fold-hinge collapse processes.

Extensional structures, corresponding to foreland-dipping normal faults (Fig. 7), in the forelimbs of the thrust-related folds, such as asymmetric ramp anticlines, have also been observed.

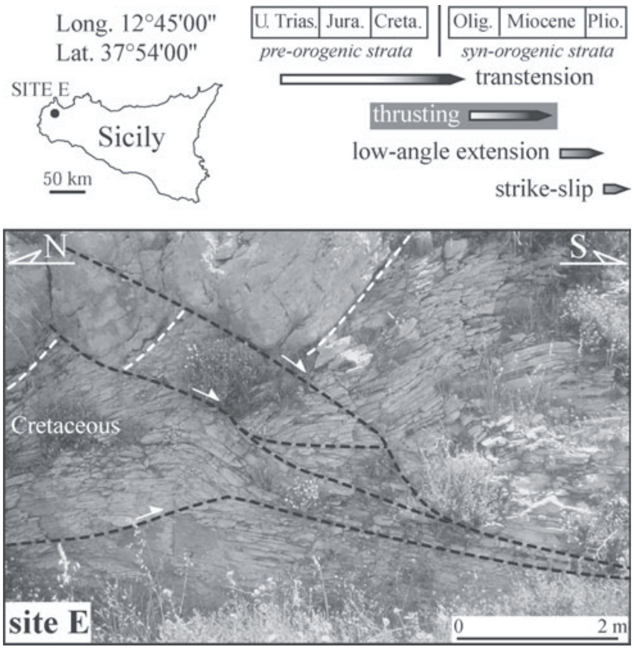

Fig. 7. Foreland-dipping normal faults in the forelimb of a metric-scale blind thrust (Southern Trapani Mts; site E). See text for further explanations.

Normal faults have also been recognized in the foreland deposits.

The abrupt change in thickness near the hinterland-dipping reverse faults has been commonly observed and interpreted by Giunta et al. (2002) as the result of normal fault positive inversion during contraction (Fig. 8).

Late Miocene extensional tectonics

Post-folding extension is mainly represented by normal faults with stepped geometry, generally northwards dipping, towards the Tyrrhenian Sea.

Stepped normal faults widely affect the Northern Sicily successions, where the lower terminations are generally isolated fault surfaces defining extensional fans. Sometimes, they are observed to merge within upper detachments to define extensional duplexes (Fig. 9B)

Steeply-dipping normal faults affect the back-limbs of the thrust-ramp anticlines with geometries which led to elimination of the effects of extensional deformation through passive back-tilting of the hanging-walls, and permit to reconstruct the original contractional architecture of the stacked thrust pile (Fig. 9C).

The extensional detachments are mainly located at the base of the Mesozoic carbonates, Cretaceous basin-plain deposits, and Oligocene-Miocene foredeep deposits.

Tilting and repeated faulting during extension are suggested by development of lozenge-shaped, fault-bounded basins (Fig. 10B). Mesoscopic normal faults are arranged to form two or more variously dipping fault systems, where fault overprinting relationships are common. Both systems of mesoscopic faults appear tilted and displaced by steeply dipping

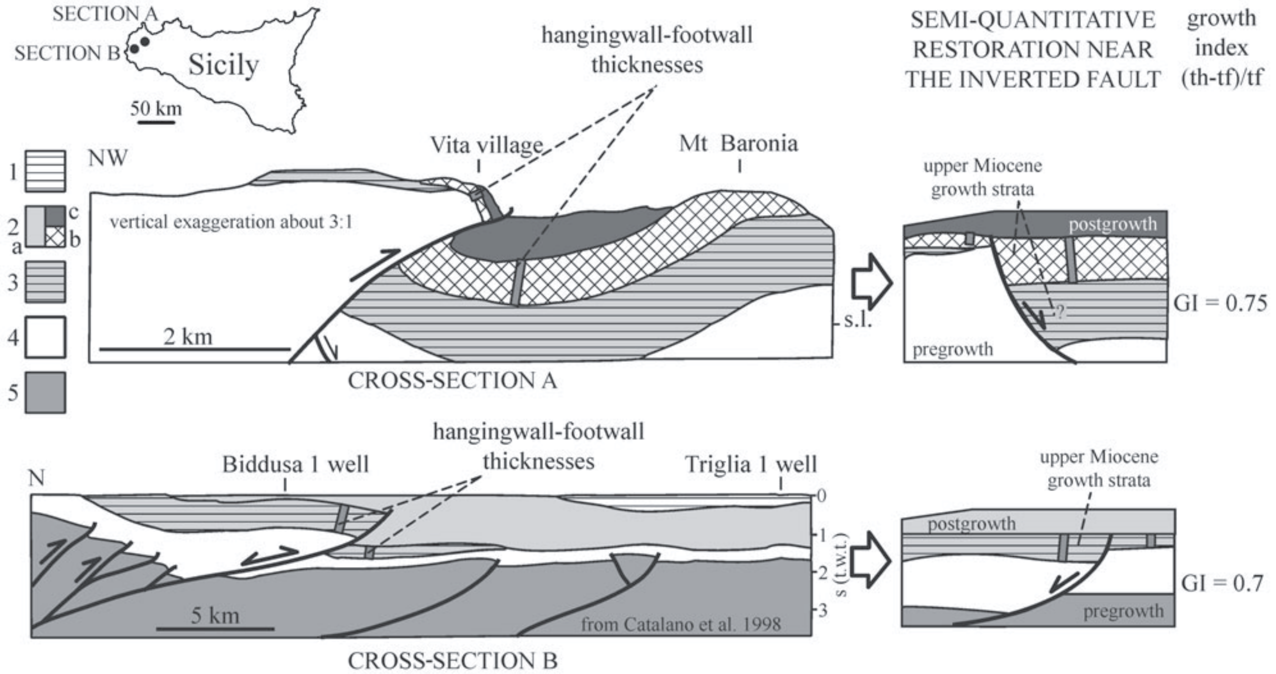

Fig. 8. Examples of inverted structures in Western Sicily. The two cross-sections show positive inversion of normal faults, foreland-dipping in example **A,** and chain-dipping in example **B. 1** — Pliocene-Pleistocene deposits; **2** — undifferentiated Upper Tortonian-Messinian deposits (a); distinguished in cross-section A in Tortonian deposits (b) and Lower Messinian sandstones (c); **3** — Serravallian-Lower Tortonian deposits; **4** — Oligocene-Lower Miocene deposits; **5** — Mesozoic carbonate platform deposits. GI in the right-hand side is the growth index, defined as (hangingwall thickness–footwall thickness)/footwall thickness. See text for further explanations.

normal faults, particularly developed in the Palermo-Madonie Mts towards the Tyrrhenian coast.

Cataclastic zones several meters thick are present at the base of the Mesozoic carbonate platform deposits. These cataclasites consist of cemented breccia, with clasts ranging from coarse- to medium grained.

Extensional faults are characterized by remarkable variations in strike, from W–E in Western Sicily to NW–SE in the more easterly domains. Fault-slip data indicate a normal kinematics. Locally, two sets of calcite fibres are superposed along the fault surfaces. The earlier kinematic indicators have a low pitch, suggesting re-activation of pre-existing oblique-slip faults under extensional deformation conditions.

The activity of these extensional detachments produced in places tectonic superposition of younger rocks above older ones, with cut-out of lithostratigraphic units present elsewhere within the Sicilian successions (Fig. 10A).

High-angle fault strands truncate the Oligocene-Miocene thrust faults, folds and the extensional detachments of the Northern Sicily belt, locally also producing metric to kilometric deformations within the Pliocene-Pleistocene deposits.

Regional-scale evolution

The structural data summarized in the previous sections allow us to reconstruct the paleotectonic evolution of northern Sicily.

Figure 11 shows the modes of extension recognized in Northern Sicily since the Mesozoic.

Strike-slip mechanisms, active in the Maghrebian passive margin during Late Triassic–Early Jurassic times (Fig. 11A), connected with the plate margin rifting and consistent with a general transtensional regime, controlled the development of high subsidence sedimentary basins. Fragmentation of the tidal platform, increasing of the subsidence (see the abrupt facies change in carbonates, from tidal to pelagic), local uplift and emersion episodes (see the hard grounds and paleokarst structures within the platform carbonate succession; Ferla & Bommarito 1988) and presence of irregular tectonic depressions within the carbonate platform (locally with deposition under anoxic conditions — Catalano & D'Argenio 1982) testify to these Late Triassic-Early Jurassic transtensional tectonics. Fault escarpments around these tectonic-controlled platform margins produced a progressive areal decrease of the neritic depositional domain and the consequent re-sedimentation of thick wedges of carbonate breccias (Fig. 2).

Transcurrent and orthogonal normal faulting developed since the Jurassic, as the shallow expression of the passive margin development. The orientation of these faults allow us to reconstruct the pattern, which is summarized in Fig. 11A. The Lias deformation acts through strike-slip faults (Fig. 11A1), which determinate roughly tectonic depressions. In Sicily the Upper Triassic-Jurassic extensional tectonics (strike-slip faults trending perpendicular to coeval listric normal fault systems) could be related to the rifting of the African margin induced by opening of the Neotethys Ocean. The available paleomagnetic data (Nairn et al. 1985; Grasso et al. 1987; Oldow et al. 1990), indicating the Sicilian belt experienced clockwise block rotations from 30° to up 120° during

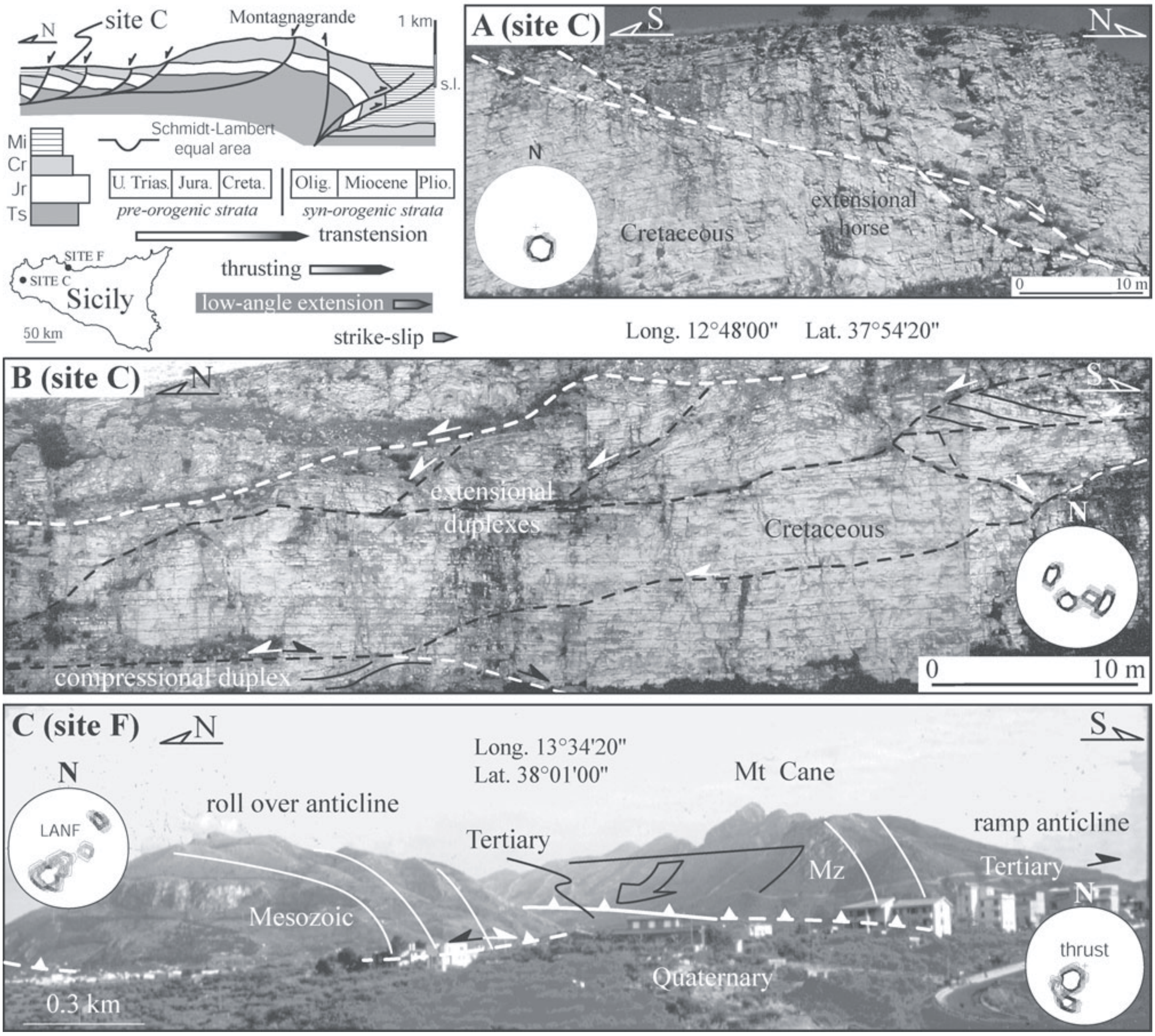

Fig. 9. Post-thrusting extension in the Southern Trapani Mts (**A** and **B**; site C) and Palermo Mts. (**C**; site F). In the Southern Trapani Mts, examples of normal faults are still well recorded in the Upper Cretaceous pelagic deposits of the Scaglia. Normal faults mostly have low-angles, wide flats and displace both the Mesozoic strata and the Middle-Upper Miocene clays deposits (see geological cross-section). The Miocene normal faults post-date the extensional structures of Figs. 4 and 5 because they cut the load stylolites and displace the Upper Cretaceous extensional veins, faults and fractures. Miocene extensional flats run along different stratigraphic levels, to form extensional horses (**A**) and duplexes (**B**). Local re-activation of previous compressional structures, such as roofs/floors bounding duplex, has been recognized (lower-left side of photo **B**). Scale invariance is represented in photo C, where a listric normal fault displaces the back limb of an older ramp anticline, determining the backslide of the tectonic unit, their passive rotation and in consequence roll-over geometries. See text for further explanations.

Neogene time, seem to support this hypothesis. The restored Jurassic strike-slip and normal fault trending, from N–S to NW–SE and from W–E to NE–SW, respectively, and their distribution indicate a WNW–ESE trending sinistral shear zone.

The Dogger-Malm up to Cretaceous tectonic subsidence related to crustal attenuation also dominated the Sicilian Maghrebian Chain. Normal fault activity represents the main mode of deformation in this time (Figs. 4 and 5) and roll-over anticlines developed around the edges of the carbonate platform, characterized by extensive re-deposition processes (Bernoulli & Jenkins 1974).

A high extension rate vs. subsidence rate is suggested by the vertical facies trend of Jurassic pelagic carbonates, indicating a progressive deepening of the pelagic sediments sharply superposed onto shallow-water neritic carbonates and a further drowning of relict, adjacent carbonate platform domains (Catalano & D’Argenio 1982; Casero & Roure 1994). This stratigraphic relationship is indicative of a more uniform, high rate of crustal attenuation.

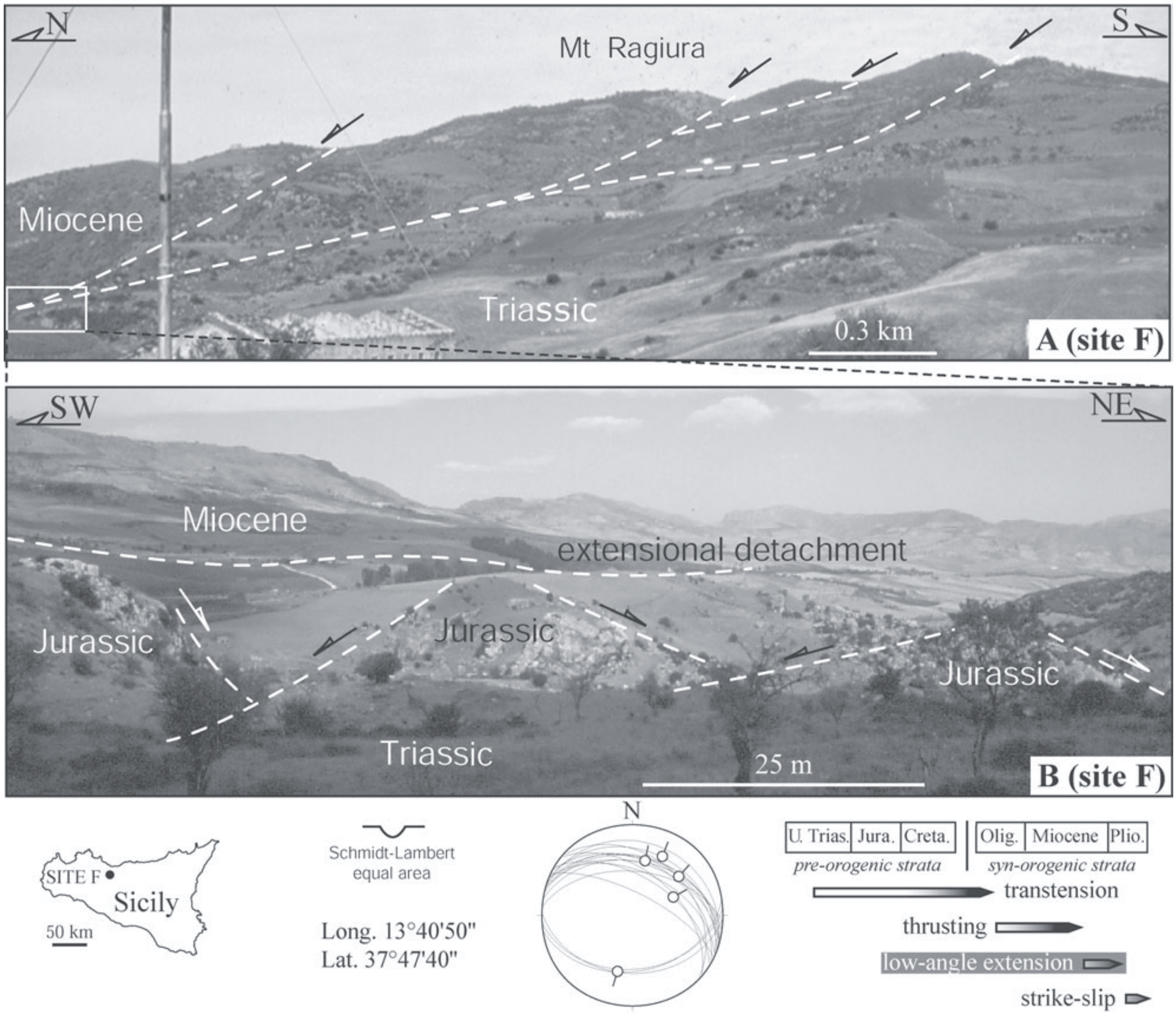

Fig. 10. Post-thrusting normal faults in places determined a high rate of stretching and chain decoupling. Low-angle normal faults (extensional detachments) are wide in length and are mostly located at the base or top of the less competent successions. Low-angle normal faulting (see stereonet) and passive rotation during extensional tectonics development seem to have determined tectonic elisions of lithostratigraphic members within the Sicilian successions and mechanical contacts with younger-on-older geometry **(A)**. Along ramps, repeated faulting and rotation may have determined lozenge geometries (chaos-like structures of Wernicke & Burchfiel 1982; photo **B**). See text for further explanations.

The high extension rate also led to a sudden physiographic uniformity of the passive margin during Cretaceous–early Tertiary times. This tectonics could be interpreted as a shear sense reversal of transform faults of the Neotethys Ocean.

The Cretaceous small extensional faults may represent the shallow expression of the activity of the roll-over anticlines which persisted from the Jurassic (Fig. 11A2).

Collisional tectonics and the consequent crustal asymmetrical thickening (Channel & Mareschal 1989) initiated during Oligocene times. The modes of extension during these collisional deformations, in both the back and frontal sides of the orogenic wedge (Figs. 6, 7, 9 and 10), controlled the depositional pattern of sediments within piggy-back and foredeep basin setting. The normal faults, similar to the “foreland-dipping” duplexes of Boyer & Elliott (1982) and particularly intense in the frontal parts of the orogenic wedge during Oligocene–Miocene times, dip away from the local tectonic transport (Fig. 7).

During the Neogene contraction, Mesozoic normal faults were reactivated for the thrust front migration towards the foreland (Fig. 11B) and the syn-depositional faulting is suggested by the abrupt thickness change of the deposits near the faults. The fold amplification under a simple shear allowed the formation of normal faulting in the limbs of the ramp anticlines (Fig. 11C).

As depicted in Figs. 12 and 13, basin formation during the Sicily chain building may be in part controlled by extension, both in the inner sector and external to the thrust front. The distribution of facies and thickness of Oligocene-Miocene syn-tectonic deposits supports the model of Fig. 13, where a

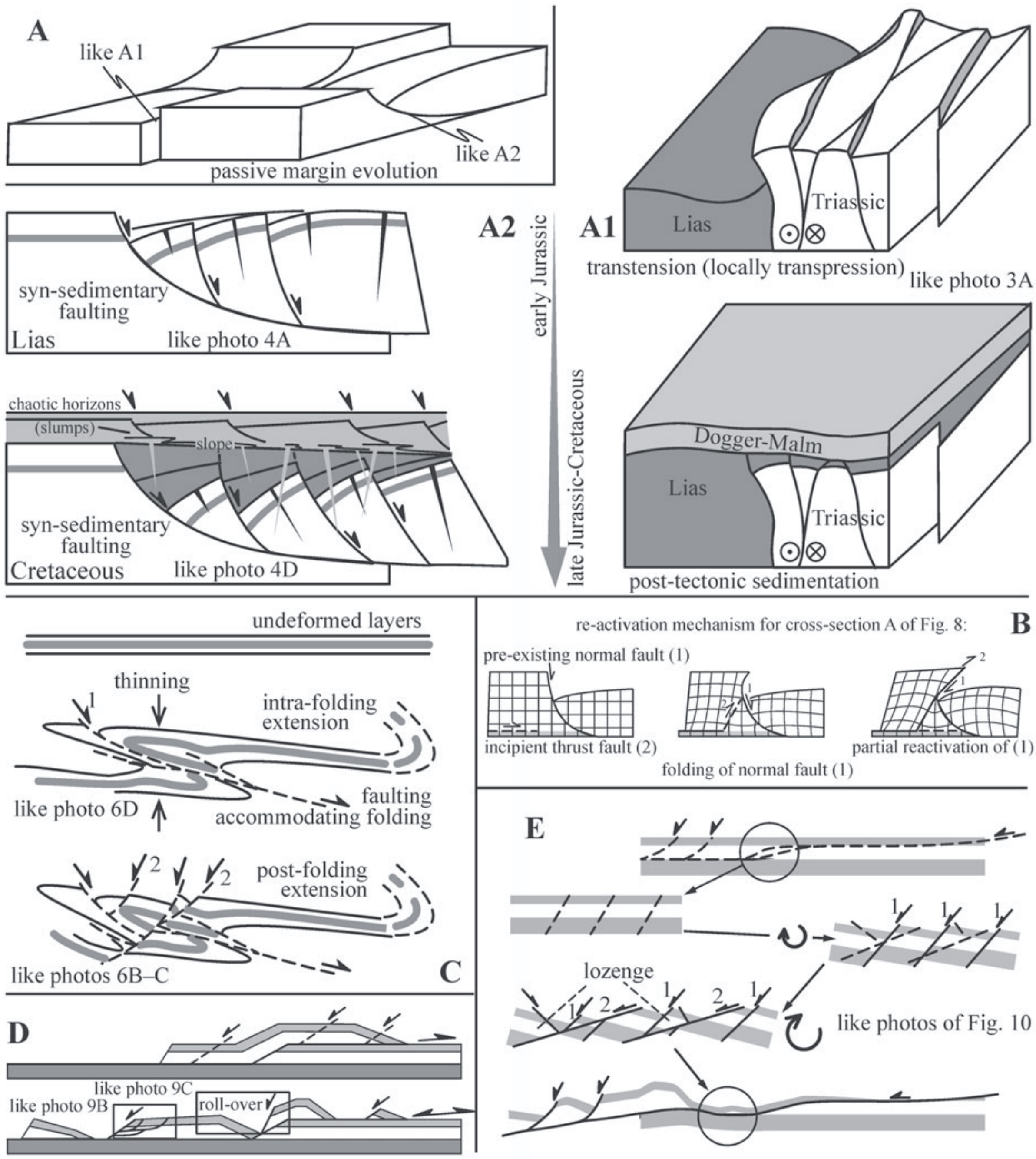

Fig. 11. Modes of extensional tectonics recognized in Sicily since the Mesozoic. (**A**) The scheme summarizes the fault pattern affecting the passive margin during the Jurassic. It is represented by transcurrent faults orthogonal to dip-slip normal faults. The tectono-sedimentary history is depicted in the schemes A1 and A2. Syn-sedimentary transtension affect the Triassic-Liassic strata. Then Dogger-Malm deposits represent the post-tectonic deposition and a new extensional tectonics developed in the Cretaceous. The Mesozoic normal faults were in places positively inverted during contraction, as depicted in (**B**). Extension due to normal faulting is suggested by growth strata inducing thickness change near the faults. Folding of foreland-dipping normal faults may occur during positive inversion for thrust front migration toward the foreland, as shown by the scheme in the lower part of the figure. The orientation of inherited structures with respect to the tectonic transport direction permits some remarks on the concepts of re-activation and inversion. If the older fault is antithetically oriented with respect to the new thrust faults, then it may be more easily rotated or folded (see scheme in the lower part of the Figure). Folding of the fault surface may apparently change the geometrical position of the fault-blocks, where a folded pre-existing extensional footwall block may partly seem to be a hangingwall during subsequent compressional tectonics. (**C**) Extension also occurred during contraction-related folding. The post-thrusting extension is represented mostly by the negative inversion of the thrust faults (**D**). It allows us to determinate roll-over geometries and the overall backsliding of the tectonic units. The stretching of the chain was realized through the repeated faulting and the passive rotation of blocks, allowing the formation of lozenge-like geometries and local elision of stratigraphic sequences within the multilayer (**E**). See text for further explanations.

mild lithospheric flexuring developed in response to the thrust-induced loading. The scheme of Fig. 13A indicates the thickness and facies distribution of foredeep deposits in Sicily. These deposits are composed of rocks eroded from the evolving thrust belt. Their thickening towards the foreland, and the vertical facies trends support the hypothesis of normal fault activity in both the thrust front and in the peripheral bulge. As shown in Figs. 7 and 8, foreland-dipping fault systems may have created the depressions where clastic deposition occurred. These faults are antithetic with respect to more conventional hinterland-dipping faults that were developed in the peripheral bulge. In Sicily, in domains located ahead of the advancing thrust fronts, the development of syn-thrusting normal faults occurred extensively. These structures (masters and minor antithetic) dip both foreland and hinterland (Fig. 8), leading to development of an asymmetric foredeep basin. The reactivation of the Mesozoic normal faults probably contributed to the development of the foredeep basin, as described by Scisciani et al. (2001) in the Apennines. These normal faults were inverted during the migration of the thrust fronts toward the foreland, as suggested by the data shown in Fig. 8.

The high crustal thickening due to thrust stacking (Fig. 13B) exceeded the critical taper of the orogenic wedge. The onset of Miocene extensional tectonics characterized by low-angle normal faults (Figs. 9 and 10) results from the collapse of the orogenic wedge related to excess of the critical taper threshold, and led to restoration of an internal sub-critical taper condition. The flats of these fault are regionally developed, defining km-scale extensional detachments (sensu Lister et al. 1991), usually forming low-angles with the bedding and locally reactivating pre-existing mechanical anisotropies, such as thrust surfaces (for example, lower-left sector of Fig. 9). This extensional episode is manifested by hinterland-dipping, low-angle detachments responsible for inducing a hinterland glide of the uppermost Maghrebide tectonic units. These normal faults cut downsection through the stratigraphic

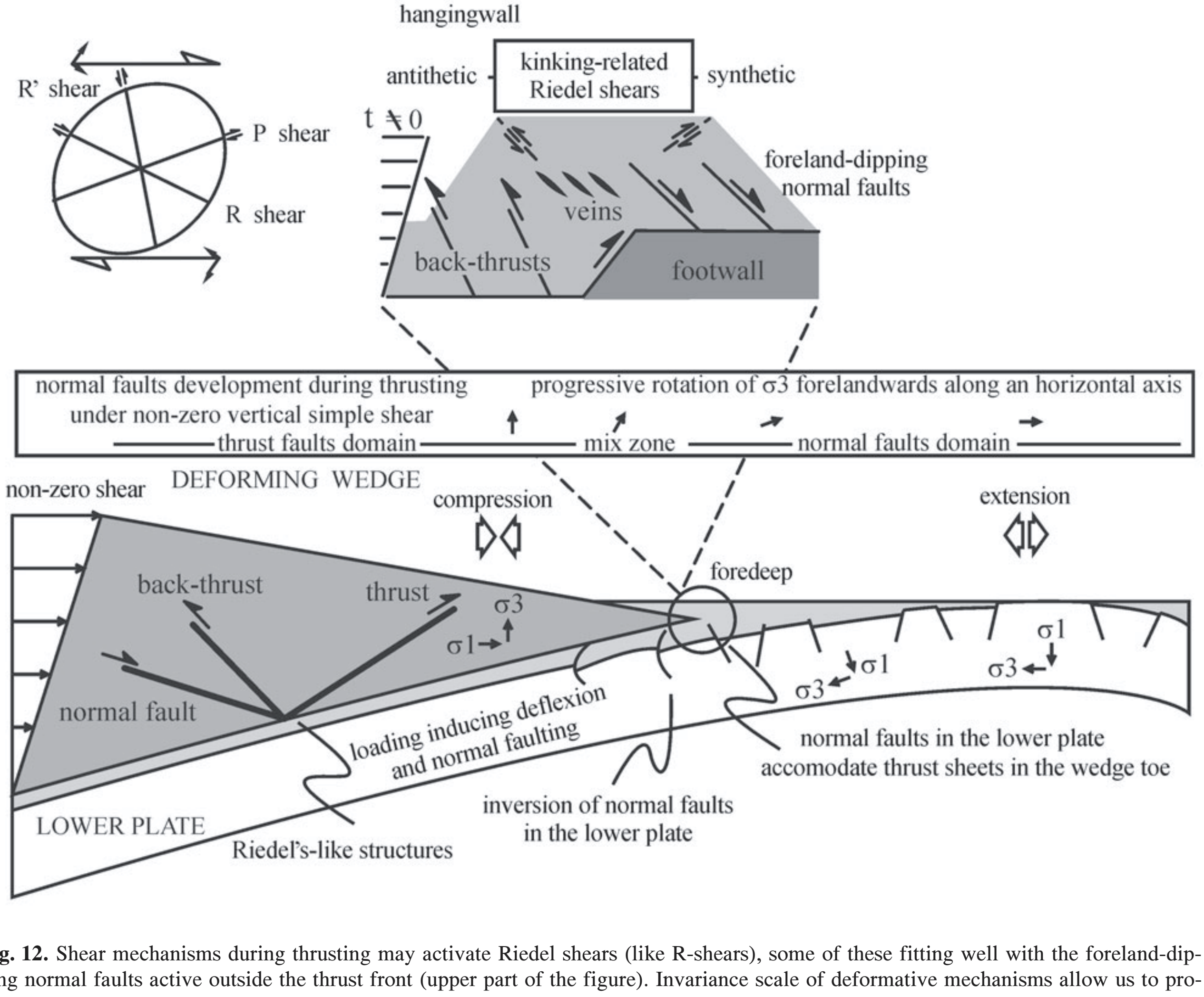

Fig. 12. Shear mechanisms during thrusting may activate Riedel shears (like R-shears), some of these fitting well with the foreland-dipping normal faults active outside the thrust front (upper part of the figure). Invariance scale of deformative mechanisms allow us to propose that normal faulting may occurs in the foredeep basin during emplacement (lower part of the figure). In an deforming wedge system, lithospheric flexure of the lower plate for chain loading is mostly realized through normal fault activation. Normal fault domain is present as far as toe region of the wedge, where extensional forces may propagate up into the foredeep deposits. Normal faulting produces accommodation space for clastic filling and may be more easily developed if the thrusting occurs under non-zero vertical simple shear. Positive inversion of normal faults in the lower plate occurs due to the thrust front migration forelandwards.

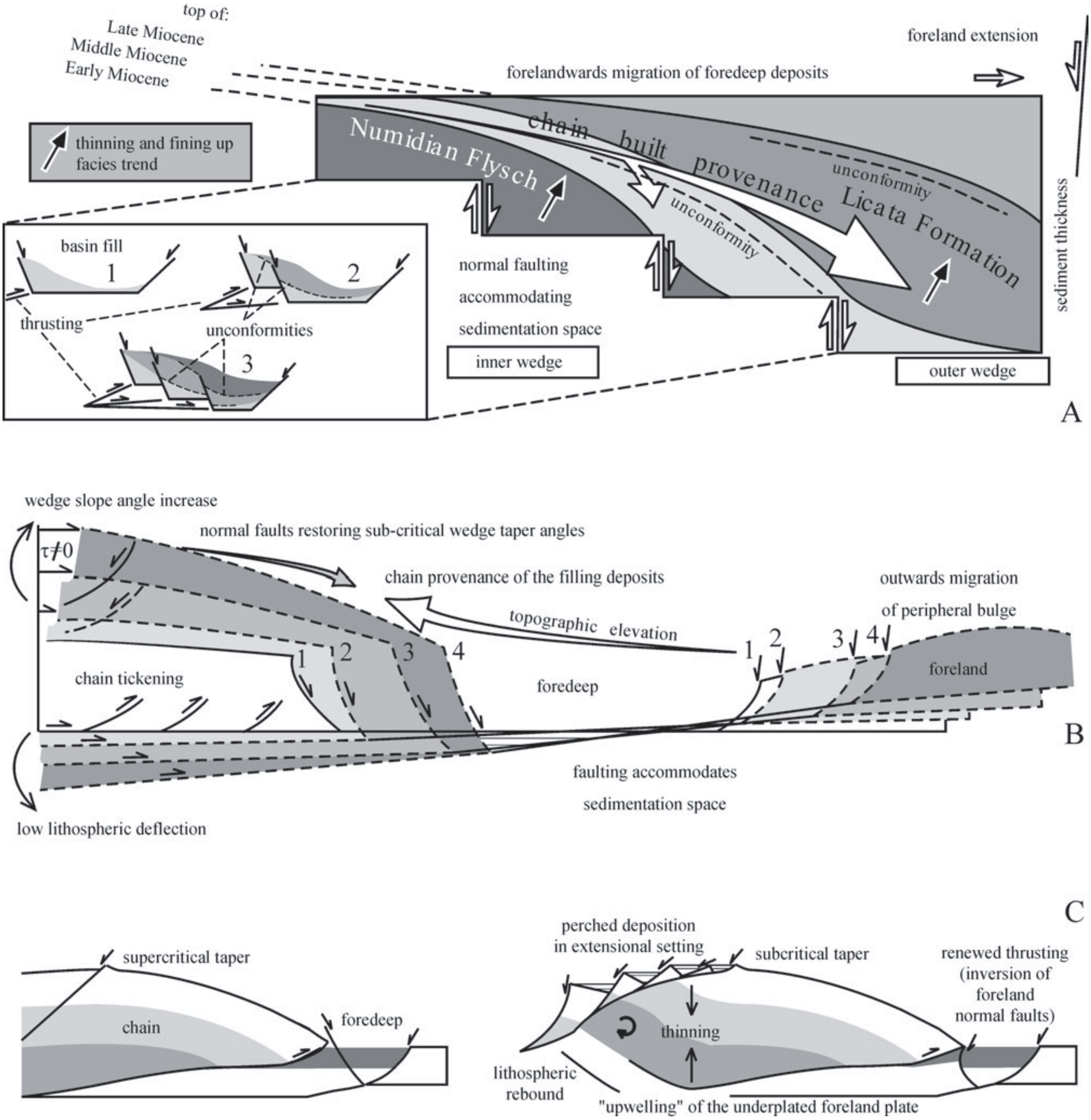

Fig. 13. **A** — This scheme shows the Miocene foredeep deposits and their stratigraphic thickness distribution in Sicily. The provenance of filling materials is mostly from the chain, allowing us to recognize extension outside the chain front by foreland-dipping normal faults. **B** — Foreland-dipping normal faults reduce flexure due to loading in the back of the wedge. Low deflection during thickening crust induces a rapid increase in the wedge slope, which becomes the main source area for sediment supply in the foredeep. **C** — For attainment of high values of the wedge slope angle, mechanical instability occurs, counterbalanced by extension in the inner sectors. The cyclical development of supercritical taper values in the Sicilian wedge occurred during the Pliocene–Pleistocene (Nigro & Renda 2001b) and has been expressed by extensional failure in its back and the coeval resedimentation processes in its toe region. See text for further explanations.

sequence of the tectonic pile towards the deepest parts of the orogenic system, where they are imaged at crustal depths, as shown by the crustal profile across the Sicilian belt (Fig. 1C). In the Sicilian mainland the detachment fault systems develop under brittle conditions, whereas in the Tyrrhenian offshore the upper level of necking recognized by Pepe et al. (2000) may represent the brittle-ductile transition zone.

Perched deposition (molasse) occurred within elongated depressions during activity of the low-angle detachments (Fig. 13C). The faulting development was accompanied by block tilting since Tortonian time and is suggested by the facies distribution of the clastic deposits and by their relationships to the mobile substratum. Upper Miocene deposits overlie the faulted back-limbs of thrust ramp anticlines (Giunta et al. 2000). The facies distribution of these sediments of Upper Miocene age implies that deposition was generally controlled by syn-sedimentary extensional tectonics and by a northward shift of the subsidence of the substratum made up of the piled tectonic units subsequent to the backsliding of the upper tectonic units. The tectono-sedimentary evolution of perched deposition was controlled by mobility of hanging-wall blocks during Tortonian extension. The age distribution of Upper Tortonian deposits in northern Sicily (with younger rocks systematically outcropping in the northernmost domains) may be interpreted as due to the interplay of detachment-bounded blocks, footwall uplift and hanging-wall subsidence.

Concluding remarks

A synthetic model for the modes of onset, based on these data (Fig. 14), shows the evolution of the extensional deformations in northern Sicily since Mesozoic times from the passive margin stage to the syn-orogenic basin formation.

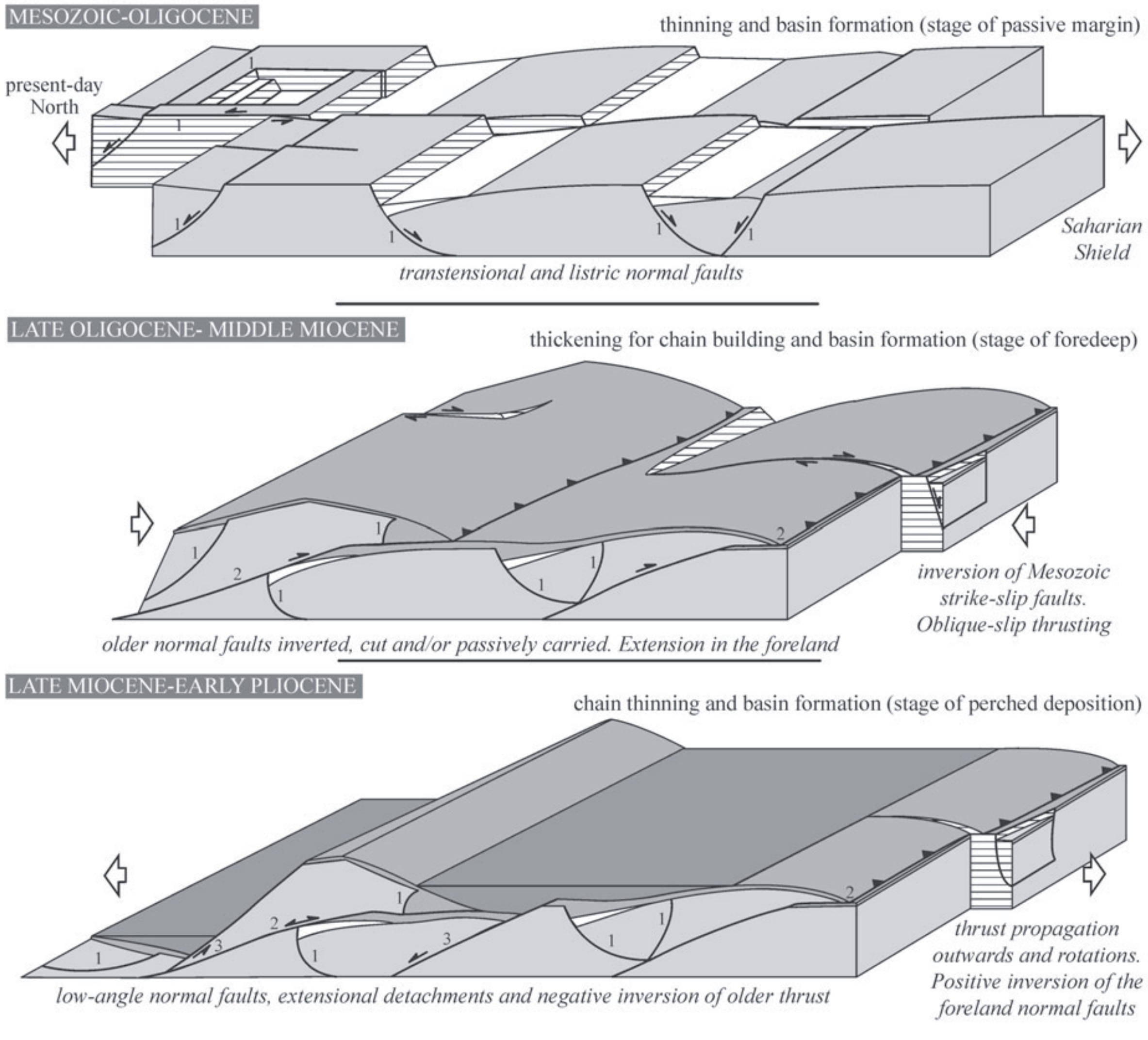

Fig. 14. Modes and sequence of extensional structures developed in Sicily from the Mesozoic. From top to bottom, extensional dynamics occurred during the Mesozoic, allowing basin formation during the rift stage of the Neotethys and the drifting of the African passive continental margin. In particular, during the late Triassic–early Lias, the basin formation was dominated by transtensional tectonics, as a consequence of the Maghrebides rifting stage. Transtensional tectonics continued during the Jurassic, when the passive margin had the maximum rate of extension. During the Late Cretaceous the further extension may have been related to the Sicilide basin opening. This tectonic episode may also represent the evolution of the Neotethys shear inversion. During the Neogene the Sicilian chain was built and propagated forelandwards under thrust tectonics. The building Sicilian wedge experienced extension both in the foredeep and in its back, reflecting collapse due to supercritical taper conditions. The wedge collapse during the Late Miocene (Giunta et al. 2000a) is represented by low-angle extensional faults, which thinned the chain towards the Tyrrhenian. During the Pliocene–Pleistocene, the different rates of rotations of the African and European plates controlled the development of the southern Tyrrhenian margin. It was affected by a W–E trending deep-seated shear zone (Giunta et al. 2000b), which induced transtension in the northern Sicily submerged sectors and transpression in the central mainland. Transtension characterized the basin opening and the present-day morphostructural settlement of Northern Sicily. See text for further explanations.

Crustal attenuation during Triassic–Early Jurassic time, related to north Africa rifting, was associated with transtensional faulting and great accommodation space filled by carbonate deposition. Late Jurassic–Cretaceous subsidence of the African margin was still dominated by a high extension rate, accommodated through activity of listric normal faults reflected by a minor deposition rate.

The Early Miocene thrusting, induced by the Sardo-Corso transpressional collision with the African continental margin, shows extensional deformations accompanying the onset and evolution of the Neogene orogenic belt, consisting mainly of normal faults affecting also the foreland and foredeep domains.

The Late Miocene extensional stage, induced by the exceeded critical taper values, shows low-angle simple shear deformations, in part represented by the backsliding of the Maghrebian tectonic units. In the back domains of the orogenic wedge normal fault activity was induced by mechanical failure of the critical wedge taper, and controlled clastic deposition within satellite (piggy-back) basins.

“Intra-thrusting” attenuation affected the uplifted orogenic belt favouring the opening of intramountain basins, where high subsidence and deposition rates were reached within intra-slope, fault-controlled basins.

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