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:IMPRINT: [Beaconsfield, Eng., Scientific Press]
:ARTICLE: Tortorici, L. "Timing and modes of deformation in the western Sicilian thrust system, southern Italy"
:VOL: 24 :NO: 2 :DATE: 2001 :PAGES: 191-211
:VERIFIED: OCLC ISSN: 0141-6421 [FORMAT: Serial]
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TIMING AND MODES OF DEFORMATION IN THE WESTERN SICILIAN THRUST SYSTEM, SOUTHERN ITALY

L. Tortorici*+, C. Monaco*, S. Mazzoli and M. Bianca***

Imbricate units in the western Sicilian fold-and-thrust belt originated on the southern continental margin of Neotethys, and were deformed during the Neogene-Recent in response to convergence between the African and European Plates. Neogene-Pleistocene syn-orogenic sediments, deposited in flexural foredeeps and satellite piggy-back basins, contain a record of the belt's evolution. Progressive migration of the thrust front southwards into the foreland has been documented, beginning in the Tortonian and continuing to the present-day particularly in western parts of the belt. In the eastern part, activity on Quaternary strike-slip fault zones has produced asymmetric flower structures and other interference structures.

In this paper, we present two regional sections across the western Sicilian foreland-thrust belt system. These structural cross-sections extend down as far as the top of the Hercynian basement and integrate our field observations with previously-acquired well log, magnetic and seismic data. We show that complex interactions between the foreland-migrating thrust belt, which developed between the Late Miocene and the Pleistocene, and Pleistocene strike-slip faults led to the development of structural traps which constitute potential targets for hydrocarbon exploration.

INTRODUCTION

The Sicilian fold-and-thrust belt is a generally east-west striking segment of the Apennine-Maghrebian orogenic belt (Fig. 1) which formed in response to Late Cretaceous-Quaternary, NNW-SSE oriented convergence between the African and European Plates (Dewey *et al.*, 1989; Mazzoli and Helman, 1994). The fold-and-thrust belt is divisible into a series of structural units which were accreted during the Palaeogene-Neogene, and which were later thrust southwards over a carbonate platform in the Pelagian foreland. Four major structural units can be recognized in Sicily (Fig. 1):

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(i) The uppermost unit, the Calabride Complex (Ogniben, 1960), is made up of crystalline rocks which originated on the European margin of NeoTethys. The complex is exposed in NE Sicily and forms the southern part of the Calabrian Arc (Ogniben, 1973; Bouillin *et al.*, 1986; Monaco and Tortorici, 1995).

(ii) Below this lies the Sicilide Complex (Ogniben, 1960) which is composed of a stack of allochthonous units. Despite the absence of ophiolites, this complex has been interpreted as the remnant of an accretionary wedge which developed during subduction of NeoTethyan oceanic crust (Ogniben, 1985; Roure *et al.*, 1990; Monaco and Tortorici, 1995). Oligo-Miocene turbidites (Wezel, 1974) interpreted as fore-arc and trench deposits (Numidian Flysch) are included.

(iii) The lowermost structural complex comprises Mesozoic-Palaeogene carbonates derived from the southern (African) margin of NeoTethys. These carbonates were deformed during the Neogene, and at the present day form the thickest and most dominant tectono-stratigraphic unit in the Apennine-Maghrebian thrust system (Catalano and D'Argenio, 1978; Mascle, 1979; Catalano, 1998).

(iv) The frontal part of the orogenic belt is composed of a post-Tortonian accretionary prism more than 3,000-m thick (Grasso *et al.*, 1995; Lickorish *et al.*, 1999). This involves the entire sedimentary cover of the African margin and is made up of pelagic deposits (Roure *et al.*, 1990; Monaco and Tortorici, 1996).

Mesozoic platform carbonates derived from the southern margin of NeoTethys have been the principal target for hydrocarbon exploration in Sicily since the 1950s. The first commercial discovery, made by AIFPCo in 1953 while drilling near an asphalt quarry, was the *Ragusa* oilfield located in the Hyblean Plateau, SE Sicily. Large, deeply-buried antiformal traps in the Triassic-Liassic carbonate foreland succession became targets for exploration in the 1960s resulting in important discoveries such as *Gela*, offshore southern Sicily. The principal source rocks in these oilfields are Lower Liassic euxinic argillites and carbonatic turbidites. Exploration of this play progressed in the 1980s with the benefit of improved seismic techniques, but few important discoveries were made and since 1990 drilling activity has more or less ceased.

However, significant discoveries have been made in the last two decades by AGIP in the Southern Apennines, where deeply-buried Mesozoic carbonates are exploration targets. These carbonates include both source rocks (Norian laminated bituminous dolomites and Cenomanian intra-platform lagoonal micrites: Katz *et al.*, 2000) and reservoir intervals (Upper Cretaceous carbonates with generally low porosities and permeabilities) (Monaco *et al.*, 2001; Billi and Salvini, 2001). Structural traps are mostly culmination domes resulting from the interference of Pleistocene strike-slip accommodation thrusts and folds with pre-existing structural highs resulting from Neogene duplexing of the Adria carbonate platform (Monaco *et al.*, 1998; 2001). Similar structural traps may occur in the study area in Western Sicily where two main stages of deformation involving the African palaeomargin are recognized. In SW Sicily, the ENE-WSW striking orogenic belt is composed of an imbricate thrust system (Catalano *et al.*, 1995; 1996) which was active from the Tortonian to the present-day. Rocks involved in the thrusting are dominantly Mesozoic-Palaeogene carbonates which originated on the southern margin of NeoTethys. The belt was further deformed in the Pleistocene as a result of activity on strike-slip fault systems (Monaco *et al.*, 2000).

In this paper, we analyse two regional sections which cross the western Sicily thrust belt from the Tyrrhenian coastline in the north to the Straits of Sicily in the south (Fig. 1), in order to understand the evolution of the thrust system and to assess its influence on petroleum accumulations. This study is based on detailed field mapping carried out at a scale of 1:25,000 and the re-interpretation of unpublished and published geological and structural maps (Mascle, 1974; Catalano *et al.*, 1978; Abate *et al.*, 1993, Di Stefano and Vitale, 1993). This surface data has been integrated with subsurface data including structural

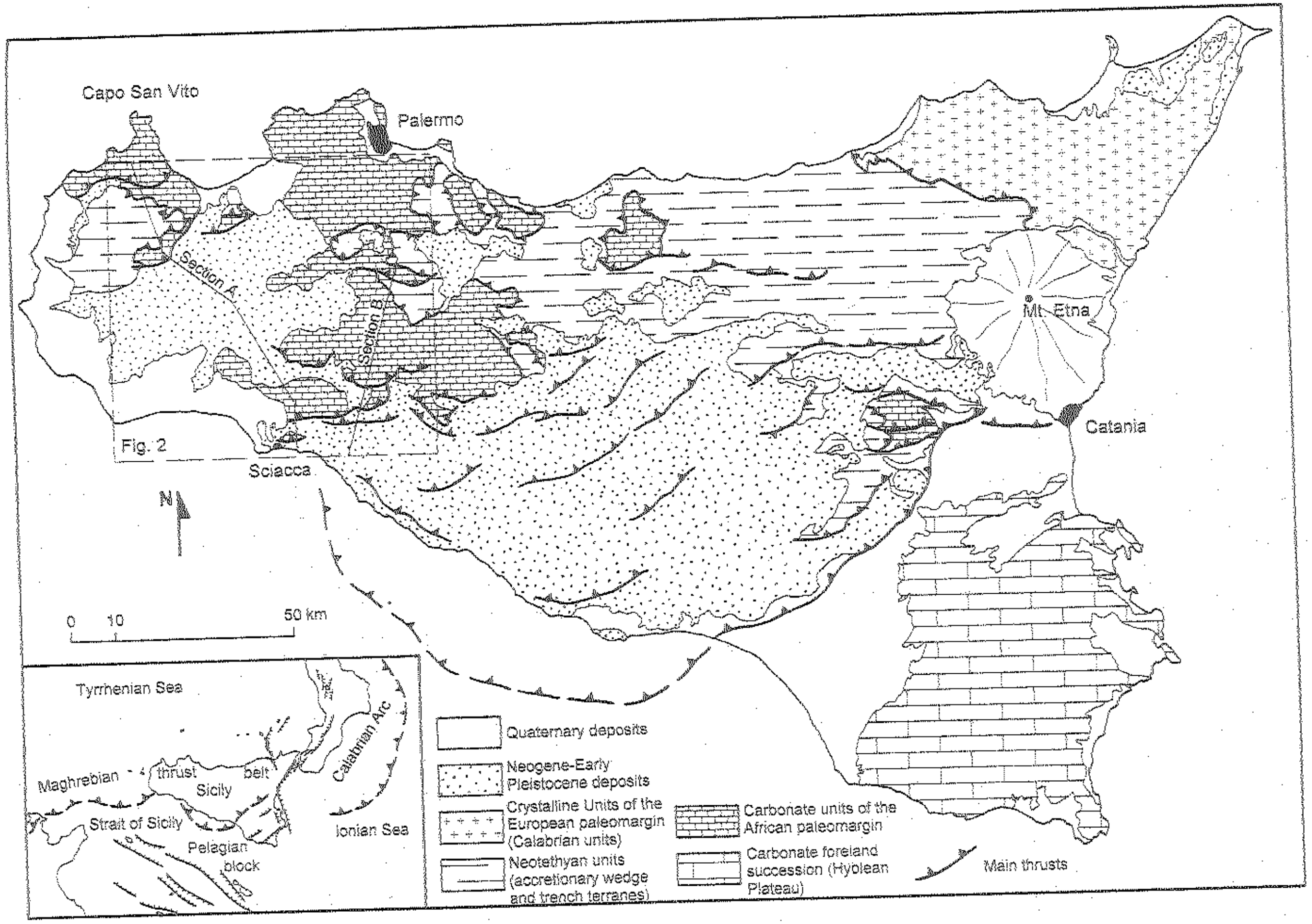


Fig. 1. Main map illustrates the general tectonic framework of Sicily; box shows the study area with profiles lines of Sections A and B (Figs 6 and 7) across the west Sicilian thrust system. Inset shows the central Mediterranean area with the frontal thrust of the Maghrebian orogenic belt (lines with triangles) and the main active normal faults (lines with barbs).

interpretations of well logs, seismic profiles (e.g. Catalano *et al.*, 1998a) and magnetic data (Arisi-Rota and Fichera, 1985).

GEOLOGICAL FRAMEWORK OF THE WESTERN SICILIAN FOLD-AND-THRUST BELT

Dominating the western Sicilian fold-and-thrust belt are Permian to Palaeogene carbonates and Miocene (up to Early Tortonian) terrigenous deposits (Fig. 2) which were derived from the southern NeoTethyan margin (Catalano and D'Argenio, 1978; Mascle, 1979). These are overlain by thrusted rock units of the Sicilide Complex including Numidian Flysch. The overlying Upper Tortonian-Pleistocene sediments were deposited in the foredeep and thrust-top basins which developed during foreland-directed migration of the thrust system. These units are described briefly in turn below:

Mesozoic to Palaeogene carbonates

Mesozoic-Palaeogene carbonates form the backbone of the Apennine-Maghrebian thrust belt in western Sicily and are preserved in a series of superposed thrust sheets (tectono-stratigraphic units of Mascle, 1974; 1979; Catalano and D'Argenio, 1978). On the basis of facies analysis, the carbonates are interpreted to have originated in a peritidal/pelagic carbonate platform and basin system (Santantonio, 1994; Monaco *et al.*, 1998) which developed during Mesozoic rifting and passive margin evolution (Fig. 3a).

Platform carbonates

Peritidal and pelagic platform carbonates form the major topographic highs in western Sicily, such as Mt. Sparagio, Montagna Grande-Segesta and Rocca Busambra in the north, and Pizzo Telegrafo, Rocca Ficuzza and Mt. San Calogero in the south (locations in Fig. 2). The carbonates can be divided into three lithostratigraphic units (Fig. 3b):

(i) Massive, Upper Triassic—Lower Liassic stromatolitic and *Megalodont*-bearing limestones, interbedded dolomites and dolomitic limestones which are up to 2,000-m thick (e.g. at the *Sciacca* well: Fig. 4).

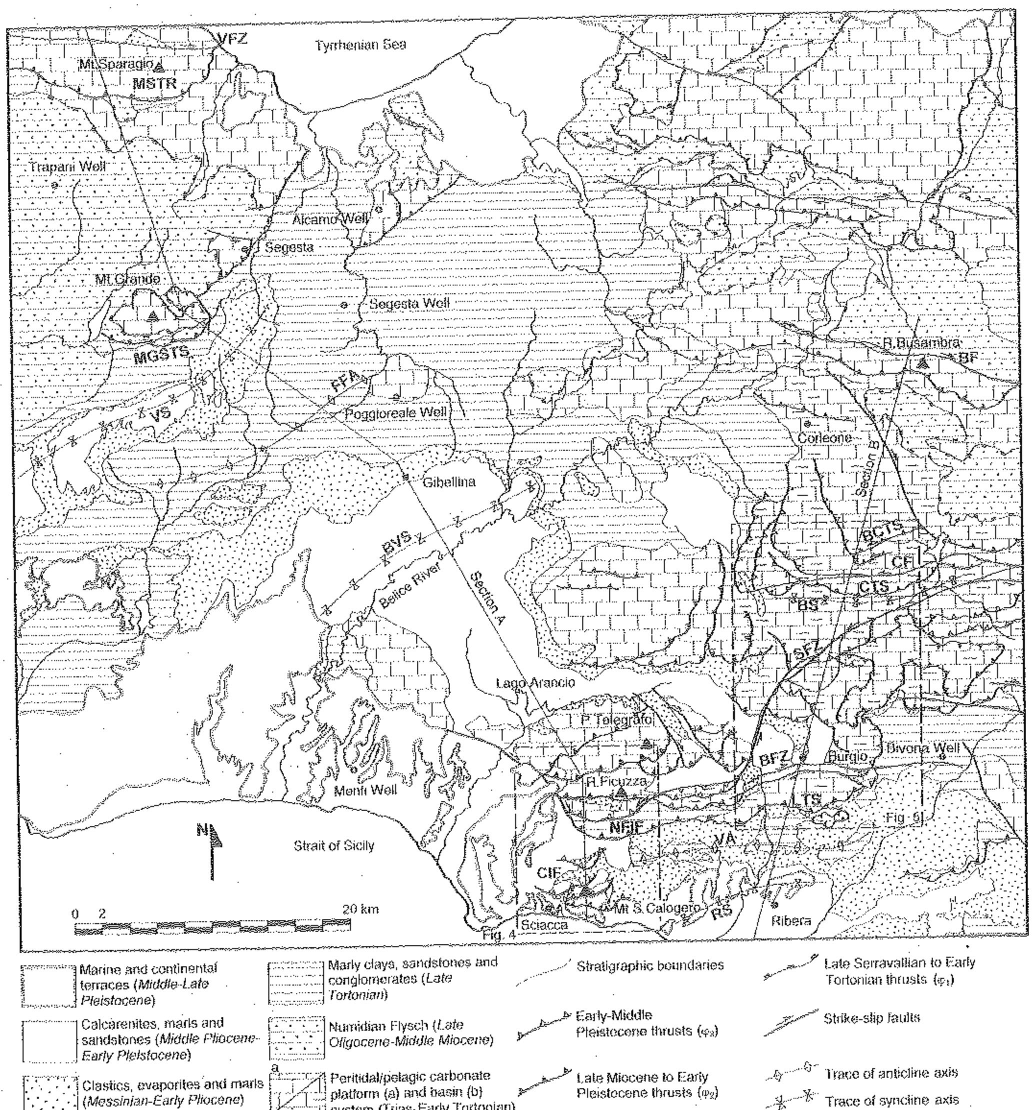
(ii) Condensed Middle Liassic—Lower Cretaceous pelagic deposits (including laminated crinoidal calcarenites, varicoloured marls and silicified limestones, and ammonitic and calpionellid limestones) which are 60-m to 120-m thick. They are characterised by the occurrence of cm-thick nodular Fe- and Mn-rich hardgrounds.

(ii) Reddish to white, Upper Cretaceous-Oligocene foraminifera-rich marls and marly limestones containing chert lenses and nodules (Scaglia Formation, about 100-m thick). This formation onlaps Jurassic—Lower Cretaceous platform carbonates, locally filling large canyons eroded in Jurassic carbonates as at Rocca Busambra). The formation contains olistoliths up to 150-m across made up of carbonate blocks derived from underlying units.

Basinal deposits

Pelagic deposits are exposed at the surface in the east of the study area (Fig. 2) between Rocca Busambra in the north and Mt. San Calogero in the south. Four lithostratigraphic units are recognized (Fig. 3c):

(i) Permian—Lower Triassic and Middle-Upper Triassic pelitic deposits of the Lercara and Mufara Formations (Schmidt di Friedberg, 1962; 1964). These crop out along the northern slopes of Rocca Busambra (Fig. 2), and around Palazzo Adriano in the Sosio Valley (Fig. 5) as basal levels of klippen resting on Lower Tortonian terrigenous deposits, and also near Mt. Triona (Fig. 5). These strongly deformed sediments contain algal limestones of Permian age (Catalano *et al.*, 1988), Middle-Upper Triassic *Halobia* limestones and olistoliths (1-10m in diameter) of Permian platform carbonates (Gemmellaro, 1888-1899; Di Stefano, 1914; De Gregorio, 1930).



BCTS, Mt. Barracù-Mt. Cangialoso Thrust Sheet; BS, Bisacquino Syncline; BF, Rocca Busambra Fault; BFZ, Burgio Fault Zone; BVS, Belice Valley Syncline; CF, Mt. Colomba Fault; CIF, Mt. San Calogero Imbricate Fan; CTS, Mt. Colomba Thrust Sheet; FFA, Fiume Freddo Anticline; LTS, Lucca Thrust Sheet; MGSTS, Montagna Grande-Segesta Thrust System; MSTR, Mt. Sparagio Thrust Ramp; NFIF, Rocca Nadore-Rocca Ficuzza Imbricate Fan; RS, Ribera Syncline; SFZ, Sosio River Fault Zone; VA, Verdura River Anticline; VFZ, San Vito Fault Zone; VS, Vita Syncline

Fig. 2. Structural map of the western Sicilian thrust system (location in Fig. 1). Note the areas of Figs 4 and 5 and the profiles lines of Sections A and B (Figs 6 and 7).

(ii) Upper Triassic—Lower Liassic cherty limestones form the main ridges in the Sicani Mountains (Fig. 5) such as Monte Barracù-Monte Cangialoso, Monte Colomba, Pizzo Gallinaro and the high area to the north of the village of Burgio. They have a thickness of c. 300m and are characterised by debris flows made up of calcareous conglomerates containing pebbles of *Halobia* limestones.

(iii) Middle Liassic—Lower Cretaceous red and green marls, radiolarites and marly limestones, up to 80-m thick. Locally, they rest on basaltic pillow-lavas and hyaloclastites, 100-m thick, which may represent an intrabasinal basaltic plateau;

(iv) Upper Cretaceous—Oligocene, reddish to white foraminifera-rich marls and marly limestones (Scaglia Formation), c. 100-m thick, which rest unconformably on the Middle Liassic—Lower Cretaceous succession.

Miocene terrigenous deposits

Miocene siliciclastics onlap the platform and basinal carbonate successions (Fig. 3b,c). They generally comprise Aquitanian-Lower Tortonian glauconitic marls and sandstones, up to 500-m thick, with conglomerates and breccias containing pebbles derived from the Mesozoic carbonates. Locally, glauconitic calcarenites occur and are 50- to 100-m thick. Lower-Middle Miocene algal biocalcarenites and biocalcirudites (between a few metres and 50-m thick) are present in places overlying either platform carbonates (e.g. at Montagna Grande-Segesta, Rocca Ficuzza and Mt. San Calogero: Fig. 2) or basaltic rocks (e.g. in the Burgio area: Fig. 5).

Numidian Flysch

The Numidian Flysch nappe (Ogniben, 1960) crops out in the northern part of the study area between Mt. Sparagio, Montagna Grande-Segesta and Rocca Busambra (Fig. 2). The Numidian Flysch tectonically overlies the Miocene sediments mentioned above and comprises c. 400 m of Upper Oligocene—Middle Miocene shales and silty clays alternating with fine- to coarse-grained quartzarenitic turbidites.

Upper Tortonian-Pleistocene sediments

These sediments are syn-orogenic deposits which were laid down in flexural foredeeps and thrust-top basins as the thrust belt migrated into the foreland to the south. They outcrop extensively in external parts of the western Sicilian thrust system (Figs 1 and 2) and comprise three main units:

(i) Upper Tortonian dark grey marly clays and sandstones which are c.1,000-m thick at the *Poggioreale* well (Fig. 2), passing up into conglomerates containing clasts of granitic and metamorphic rocks and less common Mesozoic to Palaeogene limestones. They form a thick (up to 2,500m) clastic wedge which crops out extensively to the south of the Montagna Grande and Segesta ridges;

(ii) Messinian evaporitic limestones, gypsum, gypsyferous marls, biocalcarenites and turbiditic gypsarenites which are unconformably overlain by Lower Pliocene, white to yellowish, *Globigerina*-bearing marly limestones and marls (Trubi Formation);

(iii) Middle Pliocene—Lower Pleistocene marls and sandstones, which crop out in the Belice Valley and around Sciacca on the south coast (Fig. 2), where they form a thick succession (up to 700m) of marls and marly clays containing thin intercalations of turbiditic sandstones. The basal part of the sequence unconformably overlies Lower Pliocene deposits near Gibellina (Di Stefano and Vitale, 1993) and consists of turbiditic quartzarenites. In the Rocca Ficuzza area, these marls contain blocks of resedimented carbonates. Along the southern rim of Lago Arancio, patches of Upper Pliocene *Amphistegina*-bearing biocalcarenites a few metres thick can be found on previously-developed fault scarps. South of the Belice River and in the Burgio-Ribera area (Fig. 2), the marls pass up into poorly-cemented Lower Pleistocene sandstones and calcarenites.

ANALYSIS AND INTERPRETATION OF SURFACE STRUCTURES

Two regional cross-sections have been drafted to show geometries and shortening across the western Sicilian thrust system, and the profiles are marked in Figs 1 and 2. The western transect (Section A: Fig. 6) is dominated at depth by deformed platform carbonates (Triassic-

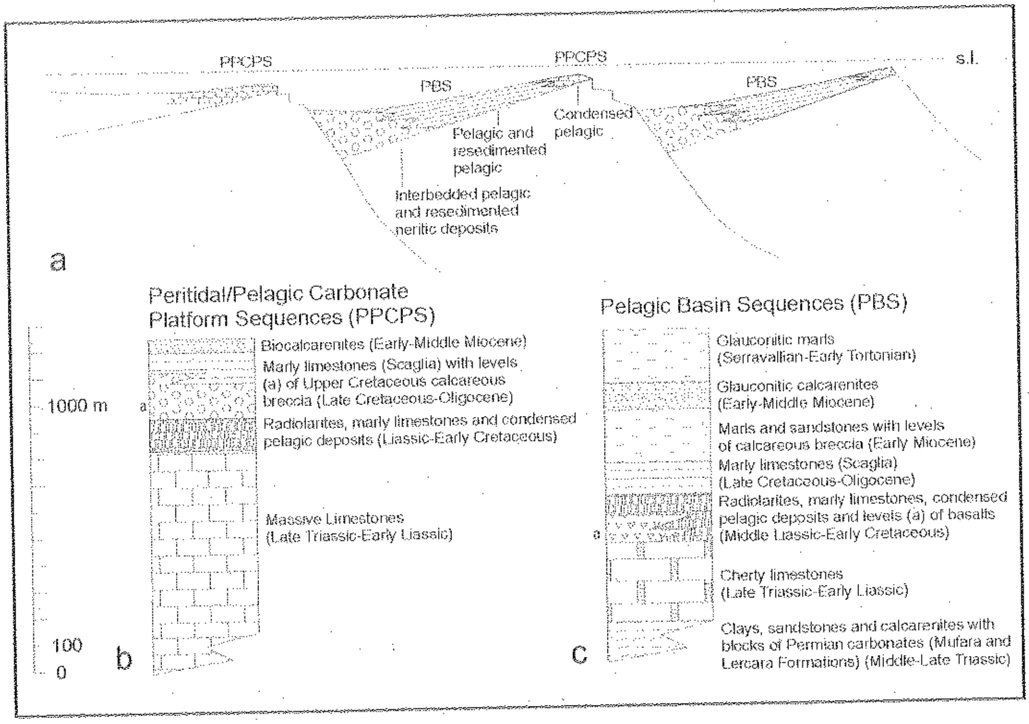


Fig. 3. (a) Model of a peritidal/pelagic carbonate platform and basin system (modified after Santantonio, 1994); (b) Schematic stratigraphic column of the Mesozoic—Middle Miocene peritidal-pelagic carbonate platform sequences in the area between Mt Grande-Rocca Busambra and Sciacca; (c) Schematic stratigraphic column of the Mesozoic-Lower Tortonian pelagic basinal sequences in the area between Corleone and Ribera near to Section B (see locations in Fig. 2).

Cenozoic), whereas the eastern one (Section B: Fig. 7) crosses both platform carbonates and basinal successions. The two sections are discussed below with respect to structural interpretation and timing of deformation.

Section A (Fig. 6)

This section runs from the Capo S. Vito area (Mt. Sparagio) in the north to Sciacca in the south (Fig. 2). The area has relatively smooth surface topography (Monaco *et al.*, 1996); the highest peaks are from north to south Montagna Grande (751m), Rocca Ficuzza (901m) and Monte San Calogero (386m) and these correspond to the major structural highs in the section. The profile is about 70-km long; it is oriented NNW-SSE from Mt. Sparagio to Montagna Grande, changing to NW-SE to Rocca Ficuzza, and then north-south to Sciacca. These changes in the profile's orientation ensure that it remains normal to regional structural trends.

In general this part of the thrust belt consists of ENE-WSW striking frontal ramps and NW-SE trending oblique ramps characterised by right-lateral displacement (Figs. 2 and 4). Surface structures in the southern sector of Section A are discussed below, followed by structures in the central and northern sectors of the Section.

Structures in the south of Section A

The southernmost segment of the profile, between the southern coastline and Rocca Ficuzza (Figs. 2, 4 and 6) is characterised by a series of WSW-ENE striking, tightly-spaced imbricate thrust sheets involving mainly Mesozoic to Palaeogene platform carbonates. Two major imbricate fan systems can be identified: the Monte San Calogero imbricate fan (CIF: Figs 4 and 6) to the south, and the Rocca Nadore-Rocca Ficuzza imbricate fan (NFIF: Figs 4 and 6) to the north.

A major south-verging thrust breaks the surface to the south of Monte San Calogero (Fig. 4) whose peak is composed of uppermost Triassic dolomites. In the thrust's hanging-wall, a ramp anticline incorporates Lower Pleistocene algal limestones and small Holocene lacustrine basins occur in the depressed backlimb area. According to Monaco *et al.* (1996), this structure was active in Early-Middle Pleistocene times and was reactivated during the Late Quaternary. A number of minor thrusts splay-out from the main fault defining a trailing imbricate fan which deforms Lower Pleistocene sediments along its front. In the footwall of the CIF, about 2,800m of Triassic platform carbonates have been penetrated at the *Sciacca* well (Fig. 4).

At the Rocca Nadore-Rocca Ficuzza imbricate fan (NFIF: Fig. 4), the footwall of the major frontal thrust is formed by the backlimb of the Monte San Calogero imbricate fan. At Rocca Nadore itself, Triassic dolomites and Jurassic-Lower Cretaceous condensed pelagic deposits are thrust southwards over Upper Tortonian sandy marls. At Rocca Ficuzza, Upper Cretaceous calcareous breccias are thrust over Lower Pliocene sediments in the hanging-wall of the Rocca Nadore thrust, whereas Upper Pliocene sediments are involved in this deformation in the backlimb. This suggests that thrust-sheet emplacement occurred at about 2Ma. It is worth noting that the front of the Rocca Ficuzza imbricate fan represents the southernmost exposure of the calcareous breccias interbedded in the Upper Cretaceous Scaglia Formation (see above).

The central portion of Section A

From Lago Arancio to the Montagna Grande thrust front (Fig. 2), the surface of the thrust belt is dominated by Upper Miocene-Pliocene sediments deposited in a thrust-top basin system. In the south of this zone is the Belice Valley syncline (BVS: Fig. 6), which is filled with Middle-Upper Pliocene terrigenous deposits that onlap southward against the Meso-Cenozoic platform carbonates in the backlimb of the NFIF. To the north, these deposits rest unconformably on Lower Pliocene marls (Trubi Formation) and Messinian evaporites, which are affected by close to tight south-verging folds, interpreted as fault-tip folds associated with decoupling blind thrusts. Turbidites in the lower portion of the Middle Pliocene-Lower Pleistocene sequence suggest the growth of a thrust-related ridge at the beginning of the Middle Pliocene (~3.5Ma).

Further north, the surface geometry is defined by a pair of moderately SW-plunging folds within a broad, gentle anticline whose core is exposed in the Fiume Freddo valley (FFA: Figs. 2 and 6), and by a close syncline near Vita (VS: Fig. 2). At the surface of the Fiume Freddo anticline, Upper Tortonian marls and sandy marls are exposed; these are about 1,000-m thick at the *Poggioreale* well. The anticline is interpreted as a fault-propagation fold related to the Middle Pliocene blind thrust bounding the Belice Valley syncline to the north. A large open kink, probably related to back thrusting at depth, affects the backlimb of the anticline. Messinian evaporites are incorporated in this structure.

The Vita syncline (VS: Fig. 6) is a NE-SW trending fold in the footwall of the Mt Grande-Segesta thrust. The syncline folds a clastic succession at least 1,300-m thick comprising Upper Tortonian coarse-grained terrigenous deposits and Messinian clastics and evaporites (Fig. 2). This succession was deposited directly in front of the uplifted active margin of a small foreland basin, implying major activity on the MGSTS during the Late Miocene (~7-5Ma). Deformed Lower Pliocene Trubi Marls in the core of the syncline suggest that the MGSTS was active until the beginning of the Middle Pliocene.

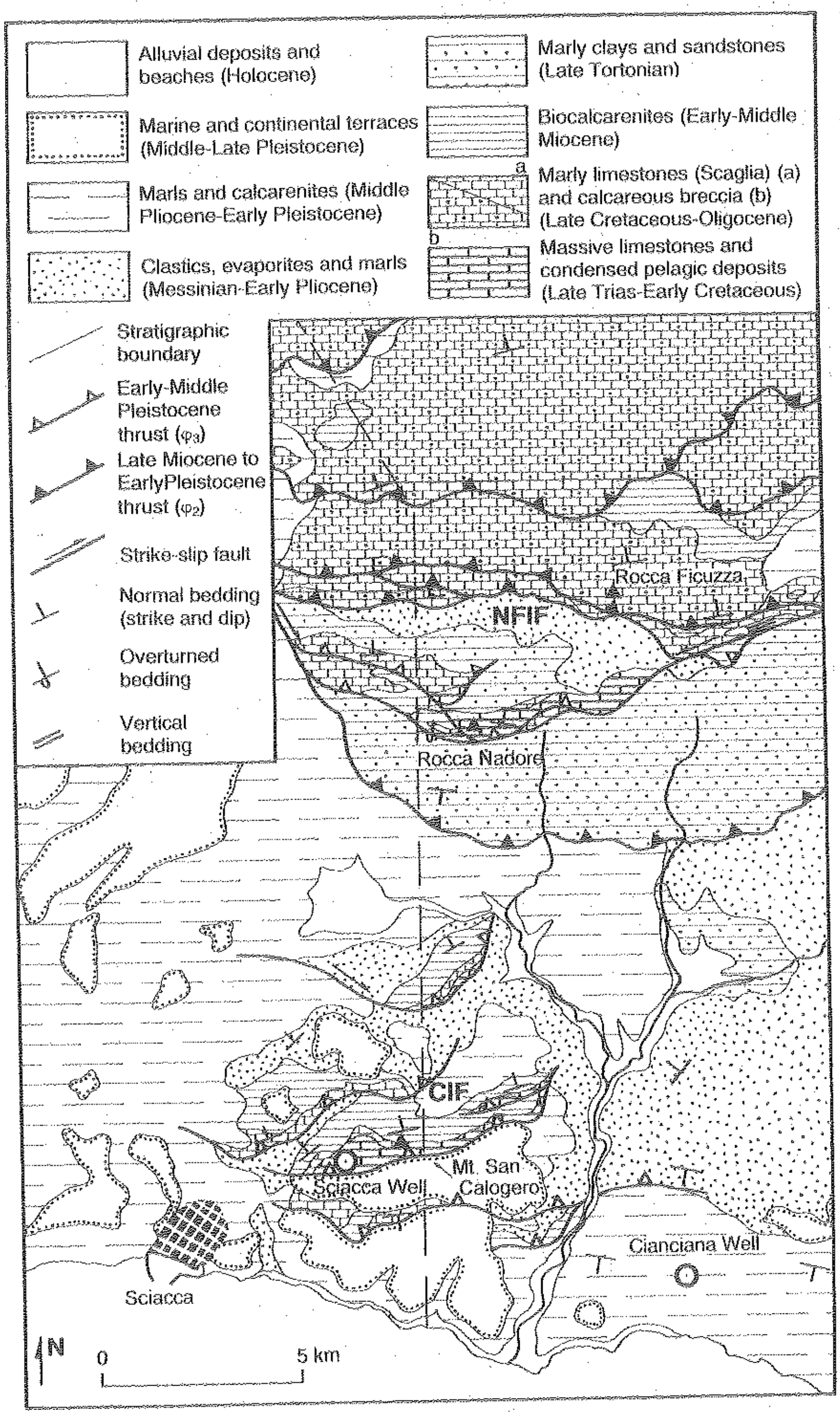


Fig. 4. Geological sketch map of the Sciacca area (location in Fig. 2). The trace of Section A is indicated. CIF: Mt. San Calogero imbricate fan; NFIF: Rocca Nadore-Rocca Ficuzza imbricate fan.

The northern portion of Section A

The northernmost part of Section A is dominated by the Mt Grande-Segesta thrust sheet (MGSTS: Figs 2 and 6) which is composed of Mesozoic to Palaeogene platform carbonates, together with the previously-emplaced (Middle-Late Miocene) Numidian Flysch nappe. The frontal thrust ramp bounds the northern edge of the footwall Vita syncline. Minor back-thrusts splay out from this main fault giving rise to a composite pop-up structure. A Pleistocene age for this structure is inferred from alluvial deposits related to a Pleistocene high-stand on the crest of the Segesta thrust sheet.

At the northern edge of the section (Fig. 2), Upper Cretaceous calcareous megabreccias crop out in the hanging-wall of the Monte Sparagio thrust ramp (MSTR: Fig. 6). The south-dipping monocline forming the frontal part of this structure is thrust southwards onto the Numidian Flysch nappe and the tectonically-underlying carbonate sequence. The Monte Sparagio monocline is bounded to the north by the highly deformed, roughly east-west trending San Vito fault zone (VFZ: Fig. 6), which overprints pre-existing structures related to the thrust system. This fault zone consists of a number of right-lateral oblique-slip faults which bound tilted blocks made up mainly of Mesozoic to Palaeogene carbonates but also including Lower Pliocene sediments.

Section B (Fig. 7)

This section illustrates structures in the eastern portion of the western Sicilian thrust system, and runs for about 40 km in a NNE-SSW direction from Rocca Busambra in the north to the town of Ribera in the south (Fig. 2). The section crosses a series of high peaks in the Sicani Mountains including Mt. Barracù-Mt. Cangialoso (1,450m) and Mt. Colomba (1,287m), then extends to the southern coast of Sicily.

The frontal southern part of this portion of the thrust belt is characterised by gentle folds that involve Upper Tortonian-Pleistocene deposits. The most important folds (Fig. 2) are the Ribera syncline (RS: Figs. 2 and 7) which affects Lower Pleistocene sediments, and the Verdura anticline (VA), in the core of which are Upper Tortonian clays. The northern limb of the anticline is cut by a thrust which brings the Palaeogene Scaglia Formation of the Lucca thrust sheet (LTS) over the Early Pliocene Trubi marls.

Further north, the thrust belt is characterised by a wrench zone (Monaco *et al.*, 2000) which is about 15-km wide (Fig. 5). In the south of this system is the 500-m wide, east-west striking Burgio fault zone (BFZ: Monaco *et al.*, 2000) which cuts across the rear of the Lucca thrust sheet giving rise to interference folds such as the domal structure at Lucca. The Burgio fault zone is characterized by highly-fractured Jurassic cherty limestones with tectonic slices of basalt, Palaeogene marly limestones (Scaglia Formation) and Lower Pliocene Trubi marls. Slickensides on faulted rocks reveal a prevalent right-lateral component of motion (Monaco *et al.*, 2000). To the north, a second strike-slip fault zone occupies a complex area of deformation known as the Sosio fault zone (SFZ, Fig. 5: Monaco *et al.*, 2000). This zone is characterised by sub-vertical, NE-SW to east-west trending faults with well-developed sub-horizontal striae and calcite shear fibres indicating left-lateral motion. Brittle fault rocks and cataclasites are present along the major fault segments. Several convex-upward thrust surfaces splay from the master fault producing south-verging asymmetric flower structures (Fig. 7). The southernmost thrust splay also offsets Lower Pleistocene deposits, indicating that the Sosio fault zone was active during the Early-Middle Pleistocene.

The Sosio fault zone cuts across pre-existing thrust and fold structures (Fig. 7) whose remnants are preserved in the Burgio area and around Palazzo Adriano (Fig. 5). North of Burgio, a thrust sheet made up of Triassic to Jurassic carbonates is exposed at the surface and overlies Lower Pliocene Trubi marls with a tectonic contact. This structure is sealed by Lower Pleistocene calcarenites, and the major activity of the thrust belt in this area can therefore be dated as Late Pliocene.

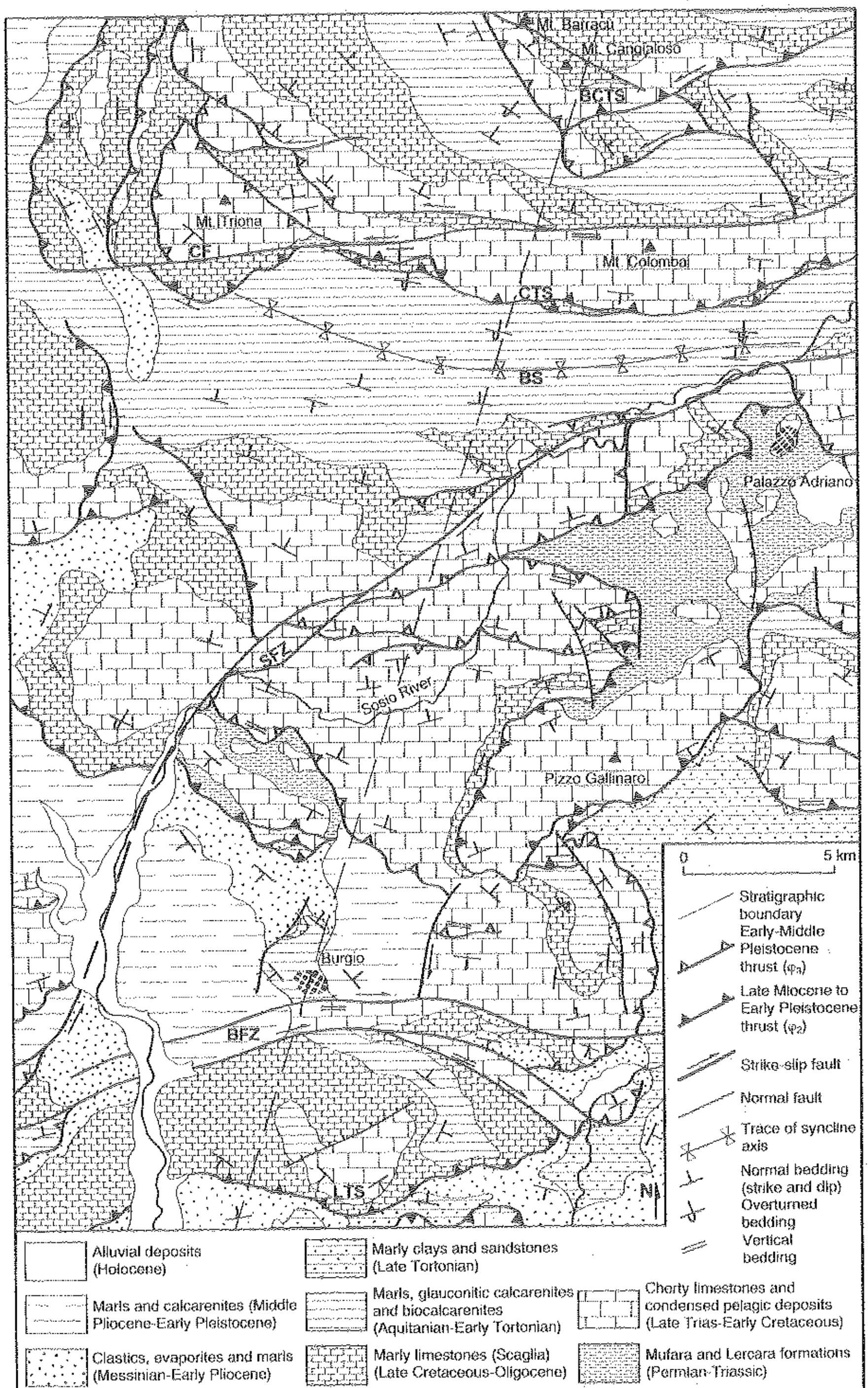


Fig. 5. Geological sketch map of the Sicani Mountains (location in Fig. 2). The trace of Section B is indicated. BCTS: Mt. Barracù-Mt. Cangialoso Thrust Sheet; BFZ: Burgio Fault Zone; BS: Bisacquino syncline; CF: Mt. Colomba fault; CTS: Mt. Colomba Thrust Sheet; LTS: Lucca Thrust Sheet; SFZ: Sosio River fault zone.

Near Palazzo Adriano (Fig. 5), relicts of the thrust belt are represented by a klippe of Permian—Lower Triassic clays and carbonates (Mufara-Lercara Formation), with Upper Triassic—Lower Liassic cherty limestones on the top, which rests above the sole thrust of a structurally-higher thrust sheet which was dismantled as a consequence of intense uplift and subsequent erosion related to activity on the Sosio fault zone. The northernmost structure of this zone consists of another left-lateral fault, the Monte Colomba fault (CF: Figs 5 and 7), which offsets the frontal part of the Monte Colomba thrust sheet (CTS) by about 3km as far as Monte Triona. This fault, from which several NW-SE trending thrusts splay-out to form a contractional imbricate fan, shows sub-vertical surfaces with sub-horizontal striae and shear fibres.

The Monte Colomba and the Sosio faults bound a 5-km wide block (Fig. 5) in which structures derived from thrust-belt deformation are preserved. This block consists of an imbricate structure containing the wide, overturned, asymmetric Bisacquino syncline (BS: Fig. 7), with Lower to Upper Miocene (Lower Tortonian) sediments in the footwall of the Monte Colomba thrust. In this area, the Monte Colomba thrust has resulted in a hanging-wall anticline made up of cherty limestones, with a footwall in which tectonic slices of Jurassic to Miocene sediments are present.

The northern part of Section B consists of a 20-km wide area of complex superimposed structures which developed as a result of the interference of late strike-slip deformation with the previously-formed Mt. Barracù-Mt. Cangialoso thrust sheet (BCTS: Figs 5 and 7). This is overthrust onto the north-dipping sequence in the backlimb of the Mt Colomba thrust. Strike-slip deformation has generated a series of NNW-SSE trending thrust faults accomodating horizontal displacement on east-west trending, left-lateral shear zones. The thrust fault which is developed on the western side of the BCTS (Fig. 5) accommodates a left-lateral strike-slip fault which has reactivated a pre-existing WSW-ENE trending thrust. A series of complex, NW-SE elongated domes and basins of kilometre wavelength have been formed as a result of interference between the strain related to ENE-WSW shortening associated with left-lateral strike-slip faulting and the pre-existing east-west striking fault-propagation folds of the thrust belt in the hanging-wall of the BCTS.

Structures at the surface of the northernmost part of Section B are controlled by the deep-seated, Rocca Busambra strike-slip fault zone (BF: Figs. 2 and 7) which trends roughly east-west to ESE-WNW. Sub-vertical fault planes with sub-horizontal striae and calcite shear fibres indicate right-lateral shear (Ghisetti and Vezzani, 1984). Pre-existing folds related to earlier thrust-sheet emplacement have been refolded by NE-SW trending, metre-scale folds associated with strike-slip deformation. The Rocca Busambra fault is characterised by a reverse component of motion which brings Mesozoic carbonates into contact with the Numidian Flysch nappe to the north. Remnants of the older thrust structures occur in the southern part of Rocca Busambra, where platform carbonates and overlying Cretaceous marly limestones (Scaglia Formation) are thrust onto Lower Tortonian marls (Fig. 2).

SUBSURFACE STRUCTURES ALONG SECTIONS A AND B

Surface stratigraphic and structural data, combined with available subsurface (deep-well logs) and geophysical information, have been used to extend cross-sections A and B to the top of the Hercynian basement. To do this we have made a number of general assumptions:

i. The first is that this segment of the thrust system has deformed since the Late Miocene.

ii. Second, at the surface, the thrust sheets juxtapose various elements of the carbonate platform and basin system but have preserved the original lithofacies distributions (i.e. platform, marginal and basinal areas).

iii. The nature of the Upper Miocene to Pleistocene deposits indicate that migrating foredeep basins associated with the thrust belt were either poorly developed or absent,

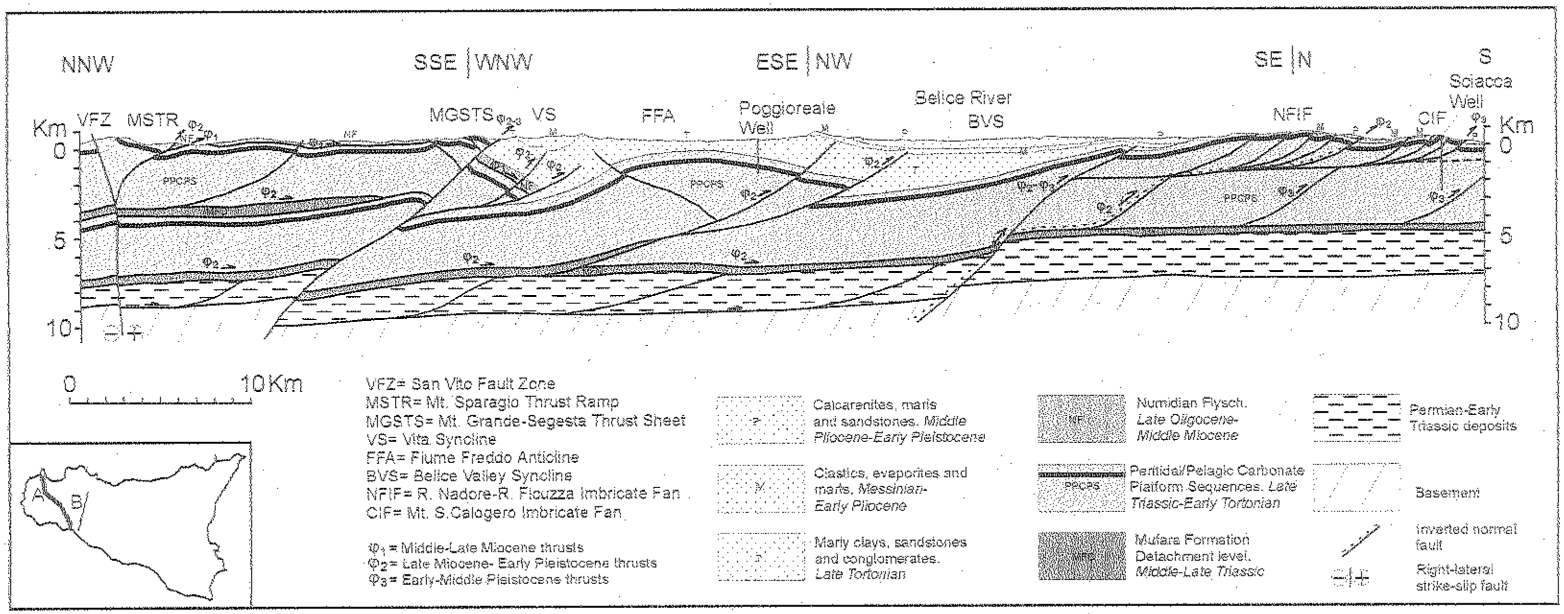


Fig. 6. Cross-section A through the western sector of the western Sicilian thrust system (location in Fig. 2). The thick black lines in Late Triassic-Early Tortonian sequences represent Middle Liassic-Early Cretaceous condensed pelagic deposits.

which suggests that there was very limited flexure of the foreland lithosphere and only modest loading on the foreland plate.

iv. The small volume of Upper Miocene to Pleistocene synorogenic deposits produced by erosion of the developing thrust belt, together with the subdued present-day topography in the area, indicate that there has been limited uplift during thrust belt evolution.

v. Finally, in regional terms, the thrust belt developed due to NNW-SSE convergence between the African and the European Plates which, over the time interval considered, took place at a rate of about 1cm/y (Mazzoli and Helman, 1994). This value represents a major constraint on our assessment of maximum shortening across the sections. Shortening should not exceed 70km even if it is assumed that all the convergence which occurred between the Late Miocene and the present day has been accommodated within the sections by thrusting processes. However, neither of these assumptions are entirely justified because part of the deformation has been accommodated by penetrative strain and strike-slip faulting; also, both towards the foreland and to the north (in the presently-collapsed Tyrrhenian margin) the thrust belt was wider than the segment represented in the cross-section.

Given these assumptions, the overall geometry of Neogene-Quaternary deformation can be described in terms of stratigraphic repetition due to thrust faults, which are interpreted as reactivated normal faults. This implies that a complete sedimentary succession must extend to the top of the Hercynian basement.

Depth to basement and deep-seated sedimentary sequences

Arisi-Rota and Fichera (1985) mapped magnetic basement at depths of 9-10 km in the frontal part of the thrust system and 8km in the northern part of the study area. Magnetic basement is unlikely to correspond precisely to petrologic basement; at the *Gargano* well in the Apulian foreland, for example, 3km of low-grade metamorphic rocks were found to occur between the base of the Permian carbonates and the magnetic basement marker. However, we estimate that the uppermost part of the basement above the magnetic marker is about 1.5-km thick. By taking into account the total thickness of the Meso-Cenozoic carbonate succession (3,000-4,000m in "platform" areas, and 1,000-1,500m in "basinal" areas: Catalano *et al.*, 1998b), a 2,000-m thick Permian-Lower Triassic sedimentary sequence can been assumed for both sections (see Figs. 6 and 7).

The Permian—Lower Triassic sediments were deposited in a basin which developed during the earliest stages of intracontinental rifting (Catalano and D'Argenio, 1982; Catalano *et al.*, 1988; 1995). The occurrence of Permian to Lower Triassic sediments beneath the Mesozoic carbonates is supported by several observations. For example, Permian carbonates are known to occur (Catalano *et al.*, 1988) near Palazzo Adriano in the Sosio Valley (Fig. 5). Also, more than 3,000m of Permian siliciclastics and carbonates (possibly tectonically thickened) crop out in western Sicily (Fabiani and Trevisan, 1937; Catalano *et al.*, 1988; 1995), while at least 100m of Permian siliciclastics have been recorded at the *Puglia* well in the Apulian foreland. Finally, more than 6,000m of Permian sedimentary rocks are known to be present in neighbouring parts of the Pelagian Block such as Tunisia (Douvillè *et al.*, 1933).

Deep geometry and thrusting processes

Interpretation of available well logs and seismic profiles (see Catalano *et al.*, 1998a) has allowed us to reconstruct the deep geometry of the western Sicilian thrust system. Two principal detachments have been assumed in the construction of the cross-sections: a deeper one at the basement-cover boundary, and a shallower one within the Middle-Upper Triassic shales of the Mufara Formation (the Mufara Formation Detachment, MFD: Figs 6 and 7). Minor detachments are also assumed to occur within the Mesozoic carbonates or condensed pelagic deposits at the front of the thrust system (Figs 6 and 7). The cross-sections have been drawn assuming that deformation is accommodated within two independent structural

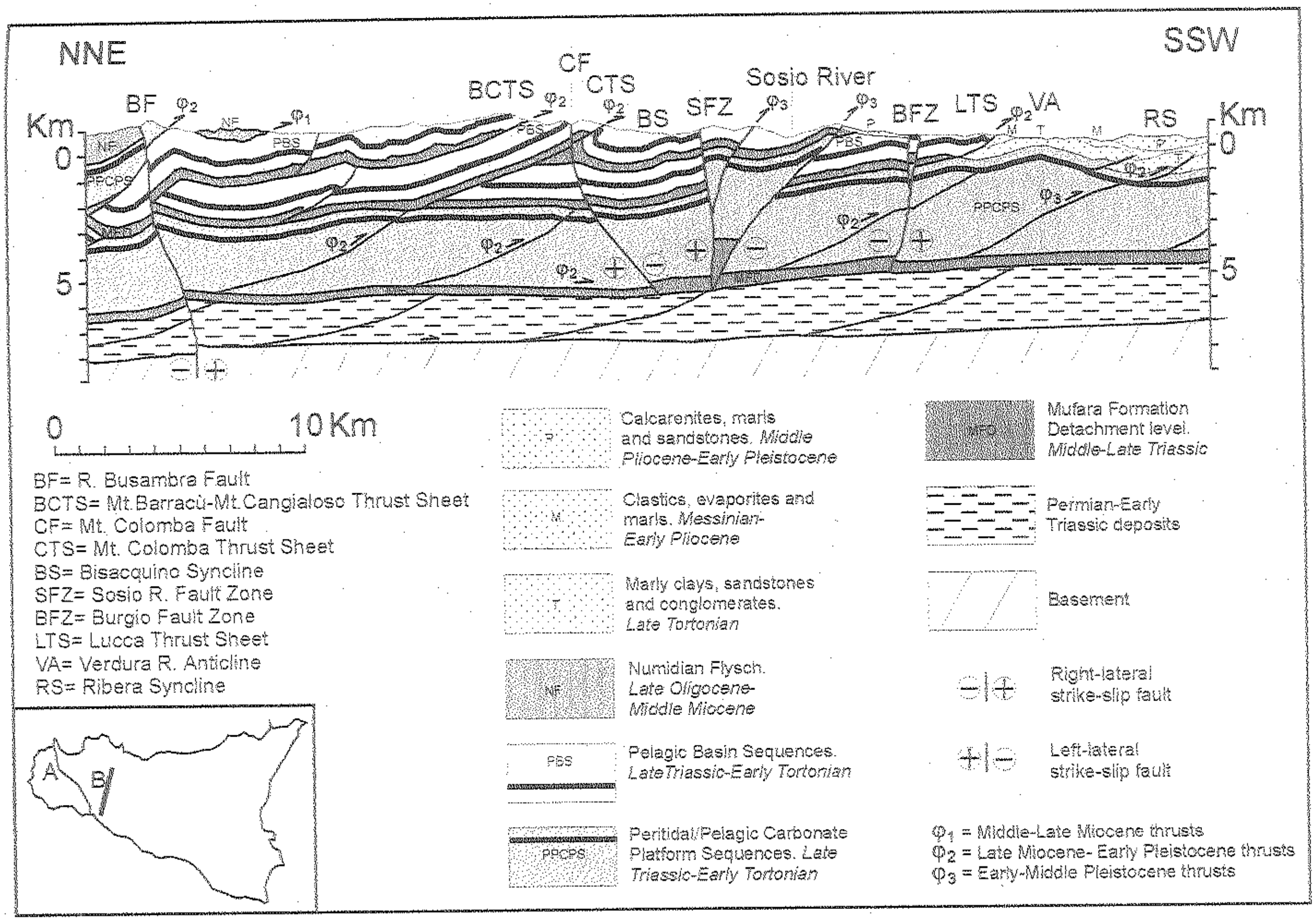


Fig. 7. Cross-section B through the eastern sector of the western Sicilian thrust system (location in Fig. 2). The thick black lines in Late Triassic-Early Tortonian sequences represent Middle Liassic-Early Cretaceous condensed pelagic deposits.

intervals defined by these detachments. The lower interval is confined between the basement sole-thrust and the MFD (roof thrust), and deformation by duplexing (e.g. Alvarez-Marron *et al.*, 1993) has been assumed. Deformation in the upper level is assumed to be related to thrust ramps and flats splaying out from the MFD.

Section A

Surface structures in the frontal part of Section A (Fig. 6) are interpreted to be related to three thrust ramps propagating up from the Mufara Formation Detachment. The most external of these is inferred to propagate to the south of the section (i.e. offshore Sciacca). The central thrust ramp has generated the Mt. S. Calogero imbricate fan (CIF) at the surface. The most internal ramp produced the second imbricate fan (NFIF), and is interpreted to represent a segment of a pre-existing basement-controlled normal fault (e.g. Gibbs, 1984). The latter structure probably defined an Upper Cretaceous basin margin to the south, thus controlling the resedimentation of calcareous breccias within the Scaglia Formation.

In the central part of Section A, an imbricate stack is inferred to splay out from the Mufara Formation Detachment, generating the Belice Valley syncline (BVS) and the Fiume Freddo anticline (FFA) in the footwall and hanging wall, respectively. In the northern part, major thrust duplication controlled the development of the Mt Grande-Segesta thrust system (MGSTS) and the evolution of the associated Late Miocene foredeep basin.

The geometry of Section A (Fig. 6) is disrupted by breaching faults of crustal magnitude. A northern breaching fault has deformed the frontal part of the Mt. Grande-Segesta structure, refolding the Vita syncline during the Early-Middle Pleistocene; a southern one corresponds to the above-mentioned Cretaceous basement-controlled normal fault (the dashed line in Fig. 6). Inversion of this structure probably started at the beginning of the Middle Pliocene (~3.5Ma), producing the R. Nadore-R. Fucuzza imbricate fan (NFIF) and is still continuing at the present day as indicated by the 1968 Belice earthquakes. Deep hypocentres related to these earthquakes (Anderson and Jackson, 1987) cluster around a north-dipping plane extending from depths of 13km to 36km. Shallower tremors, originating at depths of 3km and 1km, indicate a near-surface newly-formed splay. Fault-plane solutions have been interpreted in terms of thrusting on a high-angle, north dipping fault plane, whereas shallower tremors are the result of ramp and flat geometry of the seismogenic structure (Monaco *et al.*, 1996).

Section B

In the frontal part of Section B (Fig. 7), the substratum below the outcropping Upper Tortonian-Pleistocene sediments consists of platform carbonates which represents the eastward extension of those in the Sciacca area (e.g. at the *Cianciana* well: Fig. 4). These are inferred to be flexured to the north under the thrust system, and to be involved at depth in a Plio-Pleistocene duplex structure (see also Catalano *et al.*, 1995; 1996; 1998a; 1998b). At the surface, the Ribera syncline (RS) lies between hanging-wall anticlines associated with two underlying thrust ramps (the most external is inferred to propagate to the south of the section), whereas the Verdura anticline (VA) represents the expression of a more internal ramp anticline. The Lucca Thrust Sheet (LTS) represents the outermost of the higher thrust structures and brings Triassic-Cenozoic basinal sequences onto platform carbonates of similar age.

As mentioned above, the central part of Section B is characterised by strike-slip fault zones which cross-cut earlier thrust-related structures and generate asymmetric flower structures. At the surface, the strike-slip faults mainly affect the Meso-Cenozoic pelagic carbonate sequences, whereas at depth they also deform tectonically underlying carbonate platform sequences (whose presence at depth has been documented by Catalano *et al*, 1996; 1998a; 1998b), probably accommodating along the Mufara Formation Detachment (MFD) (Monaco *et al.*, 2000). In a few places, relicts of the previously-formed thrust structures can be observed at the surface, as in the Bisacquino syncline (BS) and the overlying Mt. Colomba Thrust Sheet (CTS), which dips northwards below the Mt. Barracù-Mt. Cangialoso Thrust Sheet (BCTS).

In the northernmost part of the section, thrust-belt structures are less deformed by strike-slip features. A major thrust sheet (BCTS), which splays off the Mufara Formation Detachment, extends north to Rocca Busambra where it is overridden by platform carbonates. This reflects the general superposition of the northern platform domain onto the southern basinal one. The contact is dissected by the R. Busambra Fault (BF), which is inferred to extend down to the basement (Ghisetti and Vezzani, 1984).

DISCUSSION

Evolution of the African palaeomargin

Before the onset of contractional deformation, the African passive margin consisted of a wide continental shelf dissected by basement-controlled normal faults, producing half-graben and tilted fault blocks on which a range of basinal, ramp and platform settings developed (Fig. 3a; see also Santantonio, 1994). This pattern is well documented for the Late Triassic when pelagic sediments (cherty limestones) were deposited in basinal areas which developed in collapsed portions of the continental margin. Reactivation of the normal faults in the Late Cretaceous was probably related to flexure of the African margin, possibly linked with a change in the relative motions of the African and European Plates (Casero and Roure, 1994). Normal faulting resulted in the development of calcareous breccias along major fault scarps. The submarine rift topography became partially buried during Palaeogene deposition of the Scaglia Formation, which reached maximum thicknesses in the basinal areas and minimum thicknesses on the platforms. This indicates that the submarine relief, which is mainly a product of Triassic rifting, roughly corresponded to the decompacted thickness of the basinal successions. Moreover, the Triassic-Jurassic basinal facies described above, and the small size of the basin as inferred by the cross-sections, suggest that the Mesozoic Sicanian depression can be interpreted as a relatively shallow, starved basin (Fig. 3) that belonged to a peritidal/pelagic platform and basin system (Santantonio, 1994). This interpretation is also supported by the occurrence of Lower-Middle Miocene shallow-water glauconitic calcarenites and biocalcarenites which further smoothed out the pre-existing basin-platform morphology.

The onset of convergent motion was marked by the emplacement of the Numidian Flysch nappe (φ_1:Fig. 6) related to the early stages of continental collision during the Middle-Late Miocene. During the Late Miocene (7-5Ma), the front of the western portion of the thrust belt (Fig. 6) was represented by the Mt. Grande-Segesta Thrust System (φ_2) and clastic material was shed into the adjoining foredeep. The most distal deposits in the south of this basin onlapped the foreland ramp of the peripheral bulge, corresponding approximately to the present-day Rocca Ficuzza-Rocca Nadore area. To the east, the thrust front involved the platform carbonates at Rocca Busambra and basinal deposits in the present-day Sicani Mountains, ultimately resulting in the formation of a number of imbricate fan systems (BCTS, CTS and BS: Fig. 7). At the beginning of the Middle Pliocene (~3.5 Ma), southward-migrating deformation generated a new thrust front (φ_2) linked to the development of a blind thrust ramp. This structure deformed the pre-existing foredeep clastic wedge, producing the Fiume Freddo anticline (Fig. 6) in the hanging wall and the Belice Valley syncline in the footwall. The latter constituted a minor foredeep depocentre in which Middle Pliocene-Lower Pleistocene turbidites were deposited. In the eastern portion of the thrust belt, the thrust front (φ_2) was located near Burgio. Here, Mesozoic pelagic deposits (including the Mufara Formation at the base) were thrust over Mesozoic carbonates during the deposition of the Trubi marls, which represent syn-thrust deposits. In this area, shortening generated the Lucca Thrust Sheet (Fig. 7) and a series of fault-propagation folds detached above the Mesozoic carbonates. Around the Plio-Pleistocene boundary (~2.0Ma), a new thrust front (φ2), related to the inversion of a Cretaceous basement-controlled normal fault, produce the R.Nadore-R. Ficuzza imbricate fan (Fig. 6). At this stage, the Belice River syncline became a satellite basin in which the youngest of the Upper Pliocene-Lower Pleistocene sediments were deposited as a thrust-top sequence.

The most external surface structure in the western portion of the thrust system is the Mt S. Calogero imbricate fan (CIF, Fig. 6: thrust φ3), which developed during the Early-Middle Pleistocene (~1.0-0.5Ma). During this time interval, the more internal Mt. Grande-Segesta Thrust Sheet was deformed as a consequence of the development of a crustal-scale thrust ramp (thrust φ3). Seismologic data from the 1968 Belice earthquake (Anderson and Jackson, 1987; Monaco *et al.*, 1996) indicate that present-day tectonic activity is mainly confined to the deeper part of the inverted normal fault which gave rise to the R. Nadore-R. Ficuzza imbricate fan and, at shallower levels, to a newly-formed thrust ramp splaying out from it (thrust φ3). To the east, the most external structures are the Verdura River anticline and the Ribera syncline, which are related to Pleistocene development of a duplex structure (thrust φ3) within the underlying platform carbonates.

Strike-slip deformation occurred during the Early-Middle Pleistocene coeval with the emplacement of the frontal thrust (φ3) which, in the Sciacca area (Fig. 6), involves various different portions of the carbonate platform sequences (Monaco *et al.*, 2000). Two strike-slip shear zones developed (Fig. 7): the sinistral Sosio River fault zone (SFZ) in the north, and the dextral Burgio fault zone (BFZ) to the south. These dissected the previously-formed thrust and fold structures. Strike-slip deformation in western Sicily has been interpreted (Monaco *et al.*, 2000) as a result of lateral escape processes involving the sedimentary cover and related to the indentation, during the latest stages of continental collision, of a more rigid portion of the continental margin (the Sciacca carbonate platform; Catalano *et al.*, 1996; 1998a; 1998b) into the front of the thrust belt. This caused the lateral extrusion of the southern sector of the Sicanian Mountains to the east, towards the unconstrained boundary of the Caltanissetta Basin which was filled with unconsolidated siliciclastic sediments and which formed the western area constrained by the thrust belt (see Fig. 6), formed mainly by an imbricated fan of thick carbonate platform sequences.

STRUCTURAL TRAPS AND HYDROCARBON POTENTIAL

In western Sicily (as well as in SE Sicily and the Southern Apennines), the principal targets for oil exploration are Mesozoic platform carbonates originating from the southern NeoTethyan margin. However, hydrocarbon exploration in this area has not been particularly successful. Unlike the carbonates in SE Sicily, the Mesozoic platform sequences in western Sicily are involved in the fold-and-thrust belt forming imbricate fans (section A: Fig. 6); alternatively, in common with the southern Apennines, they form duplex structures buried below thrust fans made up of Mesozoic-Palaeogene pelagic sequences (section B: Fig. 7). Structural traps formed by ramp anticlines developed above the Mufara Formation Detachment from the Tortonian to the Early Pleistocene, during foreland migration of the thrust-belt system, have not in the past been successfully targetted.

Both cross-sections (Figs. 6 and 7) show that the Mesozoic carbonate platform and basinal sequences are generally detached from the Permian—Lower Triassic carbonate and siliciclastic succession, which form a deep duplex structure confined between the basement sole-thrust and the Mufara Formation Detachment (roof thrust). In this context, alternative targets for oil exploration may be constituted by Permian—Lower Triassic sediments which, deposited in a wide continental shelf environment, contain both potential source rocks and reservoirs. Structural traps may be associated with deep-seated duplexes.

Mesozoic platform carbonates involved in interference structure may also constitute good reservoirs. Pleistocene strike-slip tectonics in SW Sicily has resulted in the development of a second group of potential structural traps, envisaged to have been generated as a result of the superposition of strike-slip related structures onto the pre-existing fold-and-thrust system. Primary potential traps are represented by large culmination domes located within the major contractional area between the Burgio Fault Zone and the Sosio Valley Fault Zone. Secondary potential traps are distributed along the positive flower structures developed along the major strike-slip fault segments. Strike-slip deformation increases the intensity of fracturing and thus improves the reservoir potential of the carbonates (Monaco *et al.*, 2001).

CONCLUSIONS

The western Sicilian orogenic belt is the result of a southward-propagating thrust system active between the Late Miocene and the present-day, which has deformed a segment of the African continental palaeomargin with shortening not exceeding c.70km. The oldest thrusting (φ_1) is related to the early stages of continental collision during the Middle-Late Miocene that caused the emplacement of remnants of an accretionary wedge (including the Numidian Flysch nappe) over the African palaeomargin. The subsequent foreland migration of thrusting (φ_2) deformed the African palaeomargin until Late Pliocene-Early Pleistocene times and was followed, from the Early-Middle Pleistocene onward, by breaching by major thrust ramps (φ_3), emplacement of the frontal thrust (φ_3) in the western part of the thrust belt and activity on strike-slip faults in the eastern sector. Two bedding-parallel detachments are recognized: at the basement-cover boundary, and within the Middle-Upper Triassic shales of the Mufara Formation. The latter has acted as a basal *décollement* for the imbricate fan systems developed at shallower levels, and a roof thrust for an underlying duplex system. Analysis of the surface geology along both sections shows that the thrust sheets have juxtaposed different portions of a carbonate platform and basin system, suggesting an important role for inversion processes.

The tectonic evolution of this portion of the African continental palaeomargin has controlled the development of two main groups of structural traps suitable for hydrocarbon exploration. The first group includes structural traps developed from the Tortonian to the Pleistocene during foreland migration of the fold-and-thrust system, and are represented by the large ramp anticlines and duplexes formed above or below the MFD. The second groups of traps developed during the last stage of continent-continent collision in Pleistocene times. During this stage, potential traps were produced by the superposition of strike-slip related structures onto the previous fold-and-thrust system. They are represented by large culmination domes and by positive flower structures developed along the major strike-slip fault zones.

ACKNOWLEDGEMENTS

We wish to thank David Beckett and Barnaby Philps (*BG*) for useful comments and suggestions, and Chris Izatt (*BG*), Hemin Koyi (*Uppsala University*), Livio Vezzani (*Turin University*) and Ed Jones (*BP, Sunbury)* for thorough critical reviews of a previous version of the paper.

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