

Rifted margin formation in the south Tyrrhenian Sea: A high-resolution seismic profile across the north Sicily passive continental margin

Fabrizio Pepe,¹ Giovanni Bertotti,² Federico Cella,³ and Ennio Marsella⁴

Abstract. A new, 150 km long seismic line across the continental margin of north Sicily has been acquired and interpreted. The overall structure of the margin is controlled by extension, which caused crustal thinning and widespread normal faulting. Two main thinned zones are observed in the south in correspondence with the Cefalù basin and farther to the north at the continent-ocean transition. Zones of thinned crust coincide with zones of intense normal faulting. Extension began in late Tortonian times and caused the opening of the Cefalù basin controlled by a northward dipping listric fault. Messinian stretching affected most of the future margin and provoked a widening of the Cefalù basin and normal faulting in the north. Following a phase of relative quiescence in the early Pliocene, renewed extension determined further opening of the Cefalù basin and subordinate normal faulting in the north. Here, however, the record is unclear because of the emplacement of the calc-alkaline Sisifo volcano with associated volcanoclastic deposits. Breakup took place in the late Pliocene and was followed by the deposition of postrift Pleistocene sediments. At the lithospheric scale the sites of extension/thinning did not migrate during rifting. On the smaller scale, on the contrary, the Cefalù basin displays a remarkably systematic pattern of migration toward the foot-wall of the listric fault, which controlled the opening of the basin. The spacing of 4-6 km between faults is also quite systematic. Elongation experienced by the continental part of the margin (presently ~97 km) has been derived by comparing the present-day and the preextensional lengths and is ~10 km. The corresponding strain rate is $5 \times 10^{-16} \text{ s}^{-1}$.

1. Introduction

The Tyrrhenian Sea is a Neogene to Quaternary oceanic basin developed in the central Mediterranean partly superimposed on the Alpine-Apenninic orogenic belt [Sartori, 1990; Gueguen *et al.*, 1998, and references therein]. A complex area of oceanic crust formed during Pliocene to

Recent times in the southern part of the basin (roughly south of 41°N latitude) and is surrounded by three rifted continental margins offshore eastern Sardinia, north Sicily, and western peninsular Italy (Figure 1). All continental margins show kilometer deep sedimentary basins basically controlled by normal faults (Peri-Tyrrhenian basins in the sense of Selli [1970]). Geophysical-geological surveys, the Deep Sea Drilling Project [Ryan *et al.*, 1973; Hsü *et al.*, 1978], and the Ocean Drilling Program [Kastens *et al.*, 1987] have produced a large, high-quality data set in the Tyrrhenian area. However, this wealth of data is mainly at the basin to subbasin scale and is in striking contrast to the lack of studies constraining the kinematic evolution of the continental margins and of the Tyrrhenian system as a whole. There is, for instance, an ongoing dispute about the relative importance of strike-slip versus extension deformation in the development of the north Sicily margin [e.g., Boccaletti *et al.*, 1990].

A first step toward a correct kinematic description of the Tyrrhenian system has recently been accomplished across the east Sardinia margin for which a quantitative scheme for horizontal and vertical movements now exists [Spadini *et al.*, 1995a, b]. No such picture is available for the other margins. It is thus not a coincidence that the three-dimensional (3-D) nature of the basin and especially kinematic events taking place at its southern border are often ignored in regional reconstructions [e.g., Faccenna *et al.*, 1996; Gueguen *et al.*, 1998] and that the dynamics of Tyrrhenian opening are disputed. End-member models are the anticlockwise rotation of the Adriatic plate on one side [e.g., Channell, 1996, and references therein] and the rollback and retreat of the NW dipping subduction of the Adria-Ionian plate underneath Calabria on the other (Figure 1) [Malinverno and Ryan, 1986; Patacca *et al.*, 1990; Faccenna *et al.*, 1996; Giunchi *et al.*, 1996].

This paper first focuses on the detailed description of the most relevant crustal features across the north Sicily offshore and of its Neogene to Recent sedimentary and tectonic evolution. Using unpublished seismic profiles integrated by gravity modeling we constructed a NNE trending section across the north Sicily continental margin reaching the adjacent oceanic crust. This section is well representative of the overall architecture of large parts of the margin. In Section 5 we provide a quantitative analysis of horizontal and vertical movements during and following rifting.

Data and interpretations we present also provide a tectonic frame for the development of the hitherto unexplained steep and rough morphology observed in the coastal areas of north Sicily. Such relief is necessarily associated with strong vertical movements, which took place during and following

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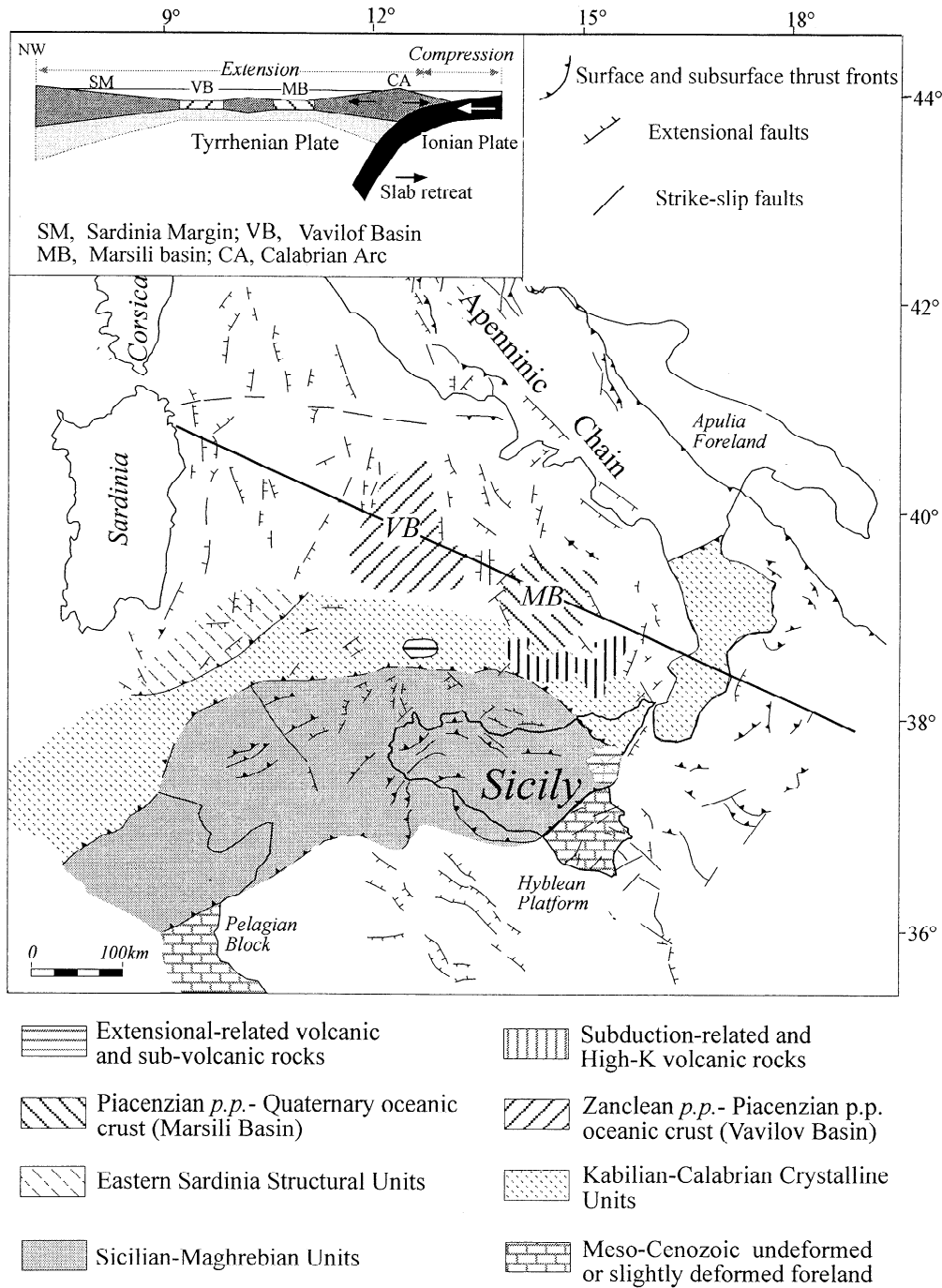


Figure 1. Structural sketch of the Tyrrhenian Sea and Apennines simplified from *Bigi et al.* [1983] and *Catalano et al.* [1995]. Inset: schematic section across the Tyrrhenian area (modified after *Spadini and Podladchikov* [1996]).

ripping, thereby suggesting a causal relation between extension and relief development. Similar features are observed in large parts of peninsular Italy and, less importantly, in Sardinia. *Spadini et al.* [1995a], for instance, suggested that continental rifting offshore Sardinia might have caused several hundred meters of uplift in the coast area.

Constraints on the kinematics of rifting in north Sicily are essential for a quantitative reconstruction of the 3-D evolution of the south Tyrrhenian and, more in general, for the tectonic comprehension of rifting processes and basin formation in back arc settings. Indeed, several characteristics of back arc basins such as duration of rifting, patterns of fault migration,

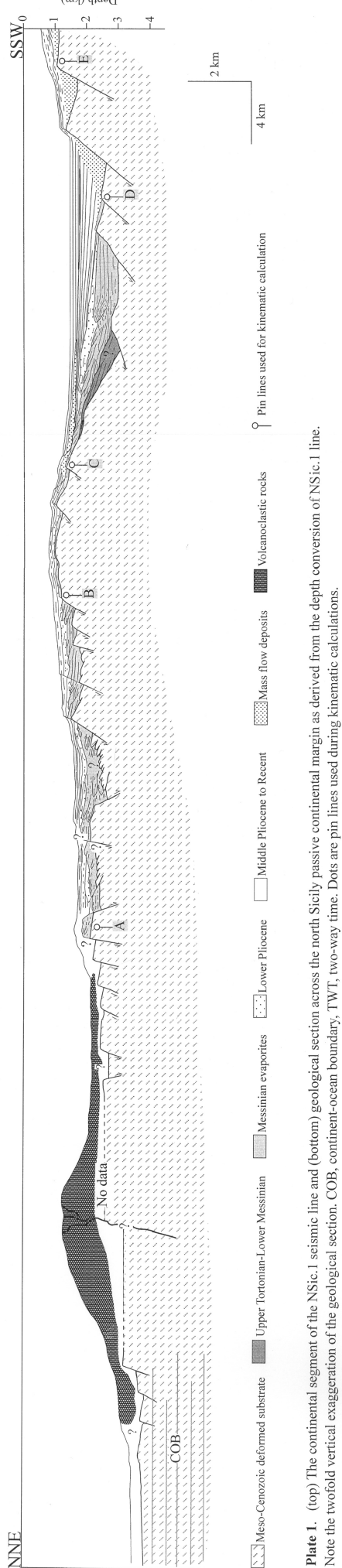
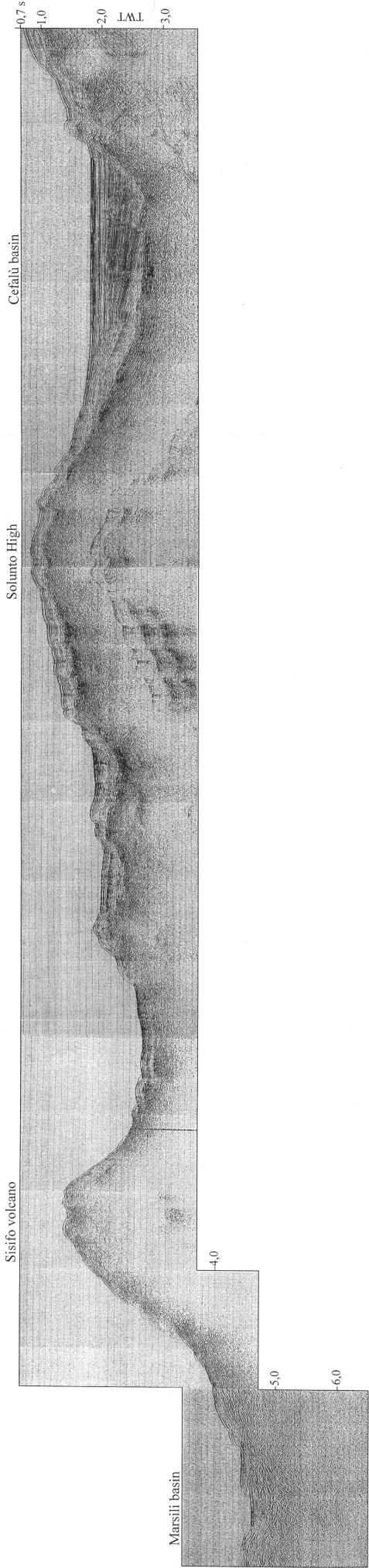


Plate 1. (top) The continental segment of the NSic.1 seismic line and (bottom) geological section across the north Sicily passive continental margin as derived from the depth conversion of NSic.1 line. Note the twofold vertical exaggeration of the geological section. COB, continent-ocean boundary. TWT, two-way time. Dots are pin lines used during kinematic calculations.

and duration of oceanic crust formation significantly differ from "normal" Atlantic-type passive continental margins [Tamaki, 1985].

2. Geology of the South Tyrrhenian Sea and of the North Sicily Margin

Large-scale tectonic features in the south Tyrrhenian are all compatible with its extensional origin. Both crust and lithosphere thin from the surrounding continents toward the center of the basin [Ansorge *et al.*, 1992, and references therein]. Similarly, heat flow increases toward the center of the Tyrrhenian where it reaches values up to 200 mW m⁻² [Della Vedova *et al.*, 1984, 1995; Hutchison *et al.*, 1985].

Extensional movements leading to the appearance of the Tyrrhenian ocean began in the late Miocene after the Corsica-Sardinia block ended its anticlockwise rotation away from Europe [Malinverno and Ryan, 1986; Patacca *et al.*, 1990; Faccenna *et al.*, 1996]. Extension affected the area to the east of the Corsica-Sardinia block partly dissecting the existing portion of the Alpine-Apennine orogenic belt [Patacca *et al.*, 1990; Sartori, 1990; Bartole, 1995]. Crustal separation first occurred in the Vavilov basin (Figure 1) where oceanic basalts have been emplaced since ~4.1-3.6 My ago [Shipboard Scientific Party, 1987a; Sartori, 1990]. At ~3-2.2 Ma the oceanic accretion ended in the Vavilov basin [Shipboard Scientific Party, 1987a; Sartori, 1990] and shifted some 150 km farther to the south, in the Marsili basin (Figure 1) where oceanic basalts are as young as ~2 Ma [Shipboard Scientific Party, 1987b]. Continental breakup did not correspond to the complete cessation of extension, and normal faulting persisted, mainly localized in peninsular Italy [e.g., Hyppolite *et al.*, 1994; Amato and Montone, 1997] and in north Sicily [e.g., Catalano *et al.*, 1998, and references therein].

Across the north Sicily margin both crust and lithosphere thin toward the north. The Moho is 25-30 km deep along the coastal areas and shallows to 9-12 km at the continent-ocean transition [e.g., Nicolich, 1985]. Similarly, the depth of the base of the lithosphere decreases from ~70 km underneath Sicily to less than 30 km in the central portions of the basin [Ansorge *et al.*, 1992, and references therein]. Mio-Pliocene normal faulting offshore north Sicily has been documented by several seismic studies [Bacini Sedimentari, 1980; Fabbri *et al.*, 1981; Barone *et al.*, 1982; Catalano *et al.*, 1985]. The most significant features are the NW-SE to E-W trending normal faults that define grabens and intervening highs (Figure 2). Extension affected also the northern part of continental Sicily where E-W to NE-SW trending normal faults are quite common and exert an obvious control on morphology.

3. Regional Seismic Section Across the North Sicily Rifted Margin

To construct a geological section across the north Sicily rifted margin, we have combined two data sets. The NSic.1 line high-resolution seismic, which we present here for the first time, revealed upper crustal features inclusive of the synrift and postrift successions. Moho and internal layering of the crust were imaged using an unpublished low-resolution

reflection seismic profile coupled with data derived from wide-angle profiles [Scarascia *et al.*, 1994]. The crustal section was tested and further defined with gravity modeling.

3.1. NSic.1 Seismic Line

3.1.1. Acquisition and processing of seismic data. The NSic.1 line was recorded in October 1996 by a joint project between the Consiglio Nazionale delle Ricerche (CNR) Institute Geomare Sud of Naples and the Marine Geology Group of Palermo University. The line runs in a SSW-NNE direction from Termini Imerese along the Sicilian coast to the continent-ocean transition and then in a N-S direction across the Marsili basin (Figure 2). The two legs are ~90 and 60 km long, respectively. The NSic.1 line passes close to Ocean Drilling Program (ODP) Site 650 [Shipboard Scientific Party, 1987b], allowing for partial seismic calibration. Only the continental part and the first 10-20 km of the oceanic part of the section are shown and discussed in this paper.

An air gun 75 cubic inches sound source, a six-channel streamer with 25 m interchannel distance, analog low pass (300 Hz), notch (50 Hz) filters, and the Seismic Treatment Method (STM) 96 system [Pepe, 1996] were the hardware components used during seismic prospecting. Both positioning and shot rate (12.5 m) were controlled by Differential Global Positioning System (DGPS). Seismic signals were recorded for 7.5 s at 1 ms time rate interval. Seismic data processing was also performed with the STM 96 system, running the following mathematical operators: dc removal, traces mixing, stack of the common depth point reflection (CDP), time variant gain, spherical divergence correction, and time variant filters. The obtained NSic.1 line is shown in Plate 1.

3.1.2. Seismostratigraphic analysis and depth conversion. In the absence of wells in the continental part of the section, we used seismostratigraphic analysis tools to define depositional sequences, infer their age, and estimate velocity values. The lowest part of the section (Plate 1) is seismically characterized by reflectors with variable amplitude and frequency. Signals are generally discontinuous and often covered by diffraction effects (facies A, Figure 3). We attribute this seismic facies to the Meso-Cenozoic prerift basement. Seismic profiles and dredge samples recovered on structural highs bordering the Cefalù basin indicate that the upper part of the prerift basement is composed of a complex stack of tectonized, mainly carbonatic nappes [Fabbri *et al.*, 1981]. No further information on the basement internal structure can be derived from the NSic.1 or other accessible lines.

The prerift basement is unconformably overlain by well-structured seismic units, which are obviously sediments. To assign ages to the various sedimentary units, a key role was played by a horizon of characteristic, very high amplitude reflections with intermediate frequencies and good lateral continuity (facies C, Figure 3). This horizon is known from large parts of the Tyrrhenian basin [Fabbri *et al.*, 1981; Malinverno, 1981] as well as of the Mediterranean [Ryan *et al.*, 1973; Hsü *et al.*, 1978], and it has been proven to correspond to the evaporites deposited during the late Messinian salinity crisis. On this basis, pre- and post- Late Messinian successions were defined.

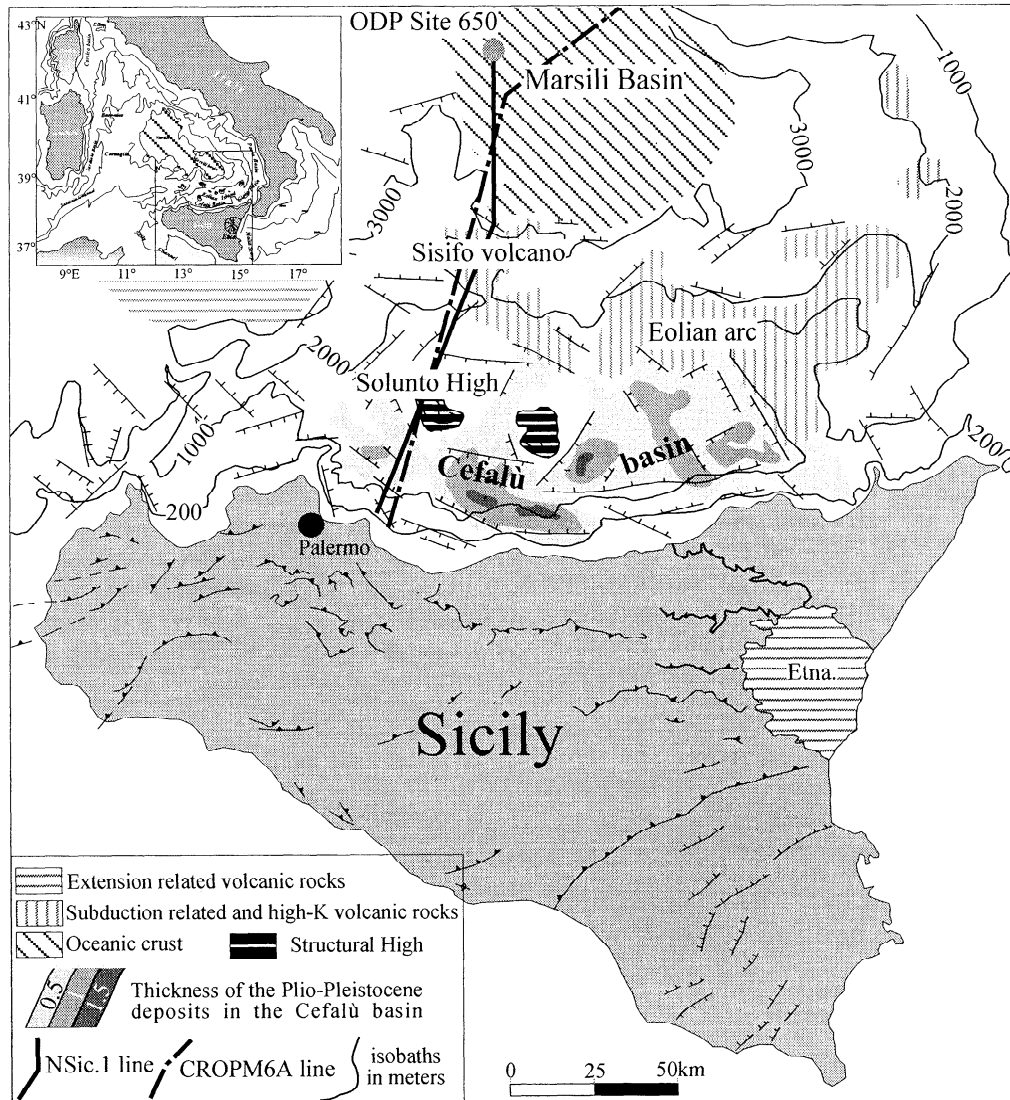


Figure 2. Schematic tectonic map of Sicily and of its northern offshore. Thick solid line is the NSic.1 profile; thick dashed line is the CROP6A profile.

The unit underlying the Messinian evaporites is seismically represented by discontinuous reflectors of medium amplitude and variable frequency (facies B, Figure 3) probably corresponding to heterogeneous lithologies. These sediments are observed only in the deepest portion of the Cefalù basin (Plate 1) where they unconformably overlie prerift substrate. In north and central Sicily the first sediments overlying the nappe stack are conglomerates, sandstone, and clays of late Tortonian-early Messinian age (Terravecchia Formation) [Schmidt di Friedberg, 1967; Catalano *et al.*, 1978, Ruggieri and Torre, 1984]. These clastics are topped by evaporitic rocks. Because of their stratigraphic position, we correlate seismic facies B sediments with the Terravecchia Formation and assign them a late Tortonian – early Messinian age.

The seismic response of evaporitic deposits has been described above. Upper Messinian evaporites are found over the entire profile unconformably overlying upper Tortonian-

lower Messinian clastics in the Cefalù basin as well as the prerift basement northward.

Two seismic units, with variable thickness and acoustic reflectivity, can be identified above the Messinian deposits. The lower one (facies D, Figure 3) is characterized by discontinuous, very low amplitude reflectors typical of homogeneous lithologies. Facies D sediments are found over most of the profile generally with thicknesses <200 ms two-way time (TWT) (Plate 1). In the Cefalù basin they unconformably overlie the Messinian evaporites (Plate 1). Because of their stratigraphic position and seismic signature, we correlate facies D deposits with the lower Pliocene widespread in the Tyrrhenian [Ryan *et al.*, 1973; Hsü *et al.*, 1978; Barone *et al.*, 1982] as well as on land close to the study area [Sprovieri, 1977]. Lower Pliocene sediments consist of pelagic deposits known in the region as Trubi, a rhythmical succession of limestone-marl couplets. In the

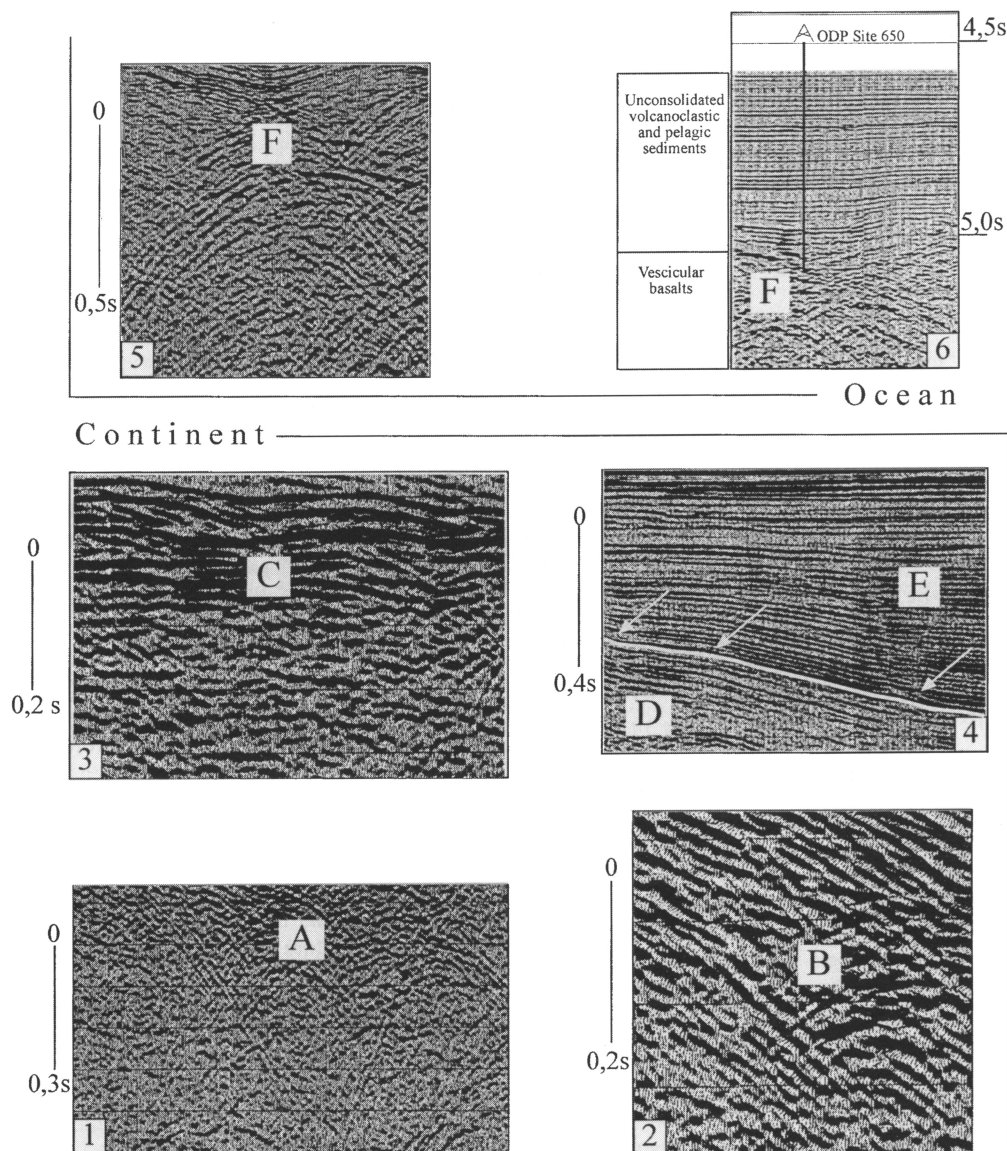


Figure 3. Seismic facies types observed on the NSic.1 profile: 1, acoustic basement (facies A); 2, pre-Messinian (facies B); 3, upper Messinian evaporites (facies C); 4, post-Messinian, lower Pliocene (facies D), and middle Pliocene-Recent (facies E) (arrows indicate the angular unconformity between lower and middle Pliocene); 5, oceanic crust (facies F); 6, segment of the NSic.1 seismic line crossing the Ocean Drilling Program (ODP) Site 650 and schematic stratigraphy of rocks encountered in the well.

Tyrrhenian they are generally imaged as a transparent seismic unit sometimes with low-amplitude seismic reflectors generated by terrigenous (marls) sediments [e.g., *Catalano et al.*, 1998].

The uppermost unit shows well-stratified reflectors with high-frequency low amplitude and very good lateral continuity (facies E, Figure 3) that can be correlated with a sandy and marly succession quite common in the Plio-Pleistocene of the Mediterranean area [Agate *et al.*, 1993, and references therein]. A middle (?) Pliocene to Pleistocene age is thus assigned to these sediments. Facies E is recognized over the entire section (Plate 1). It unconformably overlies older deposits and is internally subdivided into two subunits by an unconformity. Toward the south, facies E passes to

poorly structured bodies of roughly triangular shape (Plate 1). Because of their overall appearance and their position at the foot of large normal faults, they are interpreted as chaotic sediments remobilized and slumped during normal fault activity.

High-amplitude and low-frequency seismic reflectors, often covered by diffractions, were recognized in the north of the profile (facies F, Figure 3) and interpreted as representative of the oceanic crust. This seismic facies was calibrated with ODP Site 650 well data [Shipboard Scientific Party, 1987b].

Following the seismic facies analysis, the line drawing of NSic.1 was depth-converted. Seismic velocities in upper Tortonian and younger sediments were estimated from

Table 1. Seismic Velocities Adopted for Depth Conversion

Seismic Facies	Proposed Age	Lithology	Velocity, m s ⁻¹
A	(?) acoustic basement	mixed	-----
B	late Tortonian – early Messinian	clastic	3000
C	late Messinian	evaporites	4000
D	early Pliocene	hemipelagites	1900
E	middle Pliocene – Pleistocene	marls+sands	1800

surrounding wells of southern and western Sicily [see *Catalano et al.*, 1996] and by intervally stack velocities computed in commercial multichannel profiles shot close to the study area. Adopted values are shown in Table 1. The interpretative geologic section crossing the margin is shown in Plate 1. Major geological features are clearly documented along the resulting section.

3.2. The Position of the Moho

Available Moho maps from the north Sicily offshore provide only general trends and are insufficient for the quantitative analyses performed in this study. To constrain more precisely the crustal thickness along the investigated regional transect, we have used the CROP6A profile and modeled the gravity field. The Moho along the CROP6A profile is imaged by bright reflections recognized at ~11 s TWT in the south shallowing to ~8.2 s TWT in the north (Figure 4).

The resulting crustal section was depth-converted using velocities of the internal layering of the crust derived by the “Gargano-Pantelleria” wide-angle profile [*Scarascia et al.*, 1994]. The adopted crustal seismic velocities are as follows: upper crust, 5000 m s⁻¹, intermediate crust, 6000 m s⁻¹, and lower crustal basement, 6500 m s⁻¹.

3.3. Gravity Modeling

To test the crustal model across the north Sicily continental margin, we have modeled the density distribution of bodies

along the section using the Bouguer gravity map of the Tyrrhenian Sea [*Morelli*, 1970]. The regional gravity anomaly field was interpreted with a 2.5 debye inversion method [*Rasmussen and Pederson*, 1979; *Fedi*, 1989]. The gravity profile was digitized with a 3.75 km wide step and was bordered to allow a reasonable interpretation along its edges. Crustal density values have been estimated using generic relations between density and V_p values suggested by *Nafe and Drake* [1963]. Table 2 shows the resulting values.

Because of the regional character of the line and the significant changes in the position of the lithosphere-asthenosphere boundary, the distribution of subcrustal masses had also to be considered in the modeling. For the lithosphere a mid-ocean ridge basalt (MORB) pyrolyte containing olivine with 90% forsterite (MPY90) has been adopted [*Fallon and Green*, 1987; *Niu and Batiza*, 1991a, b, c]. Depth-related density changes in the lithosphere associated with phase transitions have also been accounted (Table 2). Lithosphere density values (Table 2) have been calculated taking into account the modal normative composition of the mantle rock and the temperature and the pressure. A thermal regime with $T_p=1280^\circ\text{C}$ was assumed in the calculations. The modal norm was derived treating the problem as the solution of a linear system of equations. This was done adopting the “minimum length” solution for undetermined problems [*Menke*, 1984]. The influence of composition, temperature, and pressure on the density of the mantle peridotite was estimated as suggested by *Niu and Batiza* [1991a, b, c]. Density values for the mantle rocks upwelling beneath the Tyrrhenian abyssal

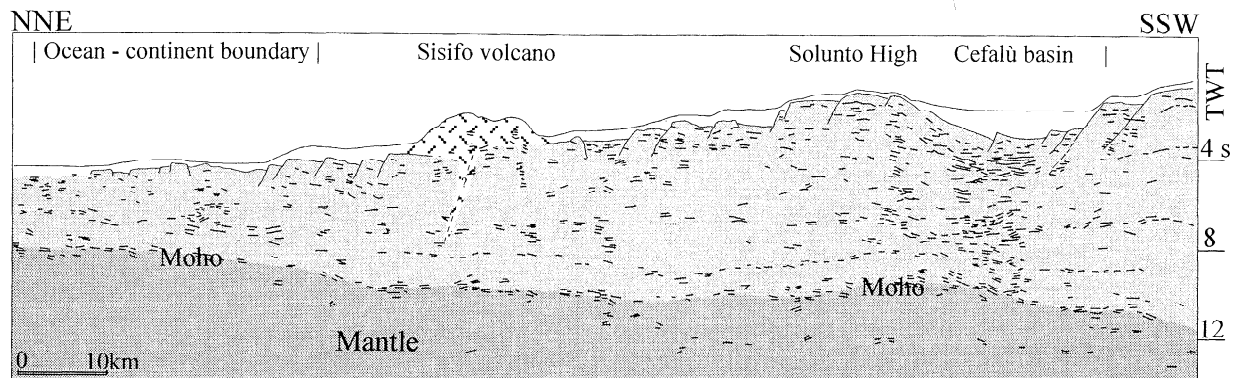


Figure 4. Line drawing of the unmigrated CROP6A reflection profile (see Figure 2 for location). Note that only the southern part of the line forms a high angle with respect to major normal faults. The northern segment, north of the Sisifo volcano, runs at a much smaller angle, and therefore its length is well above the real width of the margin.

Table 2. Density Values Adopted for Gravity Modeling

Lithology	Density, g cm ⁻³
Plio-Pleistocene deposits	1.75
Evaporitic rock	2.35
Late Tortonian–early Messinian deposits	2.20
Upper crust (carbonates)	2.50
Intermediate crust	2.70
Lower crustal basement	2.75
Subcrustal lithosphere < 30 km (plagioclase peridotite)	3.28
Lithosphere at 30km < depth < 70 km (spinel peridotite)	3.37
Lithosphere at depth > 70 km (garnet peridotite)	3.40
Upwelling asthenosphere from depth of 25 to 80 km	3.19 > 3.34

plain were calculated taking into account the anomalous thermal regime beneath the Tyrrhenian and the dependence of the vertical temperature profile on the potential temperature T_p . Furthermore, the stretching factor β and the mechanical boundary layer thickness before stretching, the change with depth in melting degree, the variation with depth in the composition of the melt, and, consequently, of the residual solid phase were all accounted for in calculations [McKenzie and Bickle, 1988; Niu and Batiza, 1991a; b; c]. A lithospheric thickness of 110 km was adopted underneath Sicily decreasing toward Tyrrhenian basin [Calcagnile and Panza, 1981; Panza, 1984; Panza and Suhadolc, 1990; Cella et al.,

1998]. Adopting the described density values and estimated dimensions of lithological bodies, we have obtained an excellent fit for gravity data observed and computed along the investigated margin (Figure 5).

4. The Geological Section of the North Sicily Rifted Margin

4.1. Main Features

The interpretative geological section constructed on the basis of the NSic.1 seismic line (Plate 1), begins a few kilometers north of the Sicily coast line, crosses in a NNE

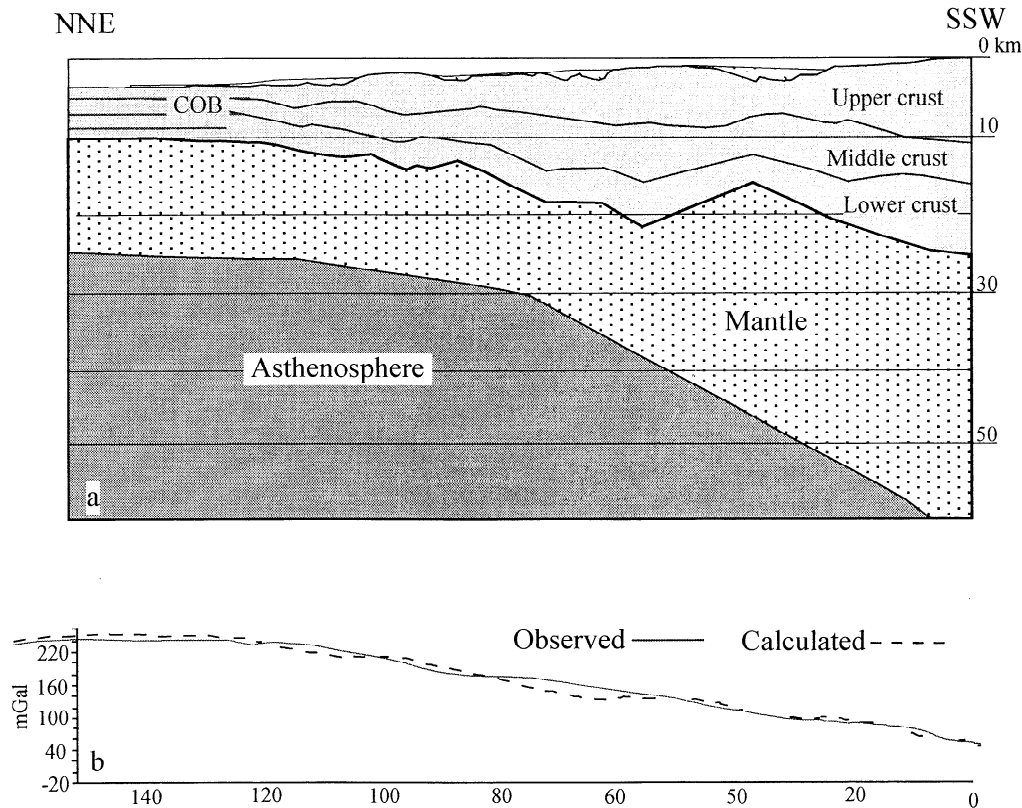


Figure 5. (a) Lithospheric section obtained from gravity modeling. (b) Observed and calculated gravity profiles. Observed data are derived from the Bouguer gravity map of the Tyrrhenian Sea [Morelli, 1970].

direction the north Sicily passive margin, and ends in the Marsili basin (see Figure 2 for location). The largest part of the crust imaged in the section is of continental nature. Oceanic crust is inferred north of Sisifo volcano.

In the south the seafloor is quite steep and reaches depths of 1500 m less than 15 km north of the Sicilian coast. This pronounced morphology is the northern continuation of the strong relief of north Sicily where up to 1500 m high mountains are found close to the coast. In correspondence with the Cefalù basin, the sea bottom is flat and ~1.5 km deep. This basin is the largest extensional feature developed along the margin and is controlled by a few listric normal faults (Plate 1).

Moving north, bathymetry decreases toward the Solunto High where the water column is only ~650 m thick, and then gradually increases toward the north and reaches ~2500 m south of Sisifo volcano. This forms a very elevated structure as its top reaches a depth of ~1120 m. North of Sisifo volcano, the sea bottom deepens very rapidly to >2000 m and then to the 3500 m of the Marsili ocean abyssal plain.

The north Sicily crust has clearly undergone substantial thinning (Figure 6). The Moho was inferred at ~26 km under the north Sicily coast and rapidly shallows up to 17 km in correspondence with the Cefalù basin. Northward, Moho depth increases to ~22 km under the Solunto High and then again shallows to ~11-12 km at the continent-ocean transition. The oceanic crust north of Sisifo volcano has a fairly constant thickness of 6-7 km. Two zones of substantial thinning are therefore present: the southern one coinciding with the Cefalù basin, and the northern one coinciding with the continent-ocean transition. These two zones of crustal thinning are fairly well defined and coincide with domains of intense normal faulting, that is, of stretching. A number of normal faults associated with small extensional basins have been developed north of Solunto High, a large part of which, however, is obscured by the volcanic edifice of Sisifo volcano (Plate 1).

4.2. The Continental Part of the Section

The high resolution obtained for the NSic.1 section allows for detailed documentation of the tectonic architecture and depositional geometries along the profile. The continental part of the section (Plate 1), in particular, is highly interesting for

the wealth of information it provides on the previously poorly known evolution of the margin.

4.2.1. Pre-Pliocene. The oldest sediments overlying the tectonized nappe pile of the acoustic basement are found in the deepest part of the Cefalù basin only (Plate 1 and Figure 7) and were seismically defined as facies B. These sediments form the infill of a <10 km wide half graben controlled by a north dipping normal fault. Maximal thickness of this interval is ~500 m. The internal geometry of these deposits suggests that faulting took place during deposition.

Messinian evaporites and other associated deposits are very widespread. They are missing in the southern part of the section but otherwise unconformably overlie the prerift basement and the upper Tortonian-lower Messinian deposits as in the Cefalù basin (Figure 7). Here they form the up to 750 m thick infill of a half graben limited toward the south by a northward dipping master fault. This is located ~4 km south of the late Tortonian master fault. Extension along the Messinian normal fault caused tilting of older sediments as well as of the late Tortonian master fault. Reflectors generated by evaporites sediments are quite disrupted and suggest that deposition took place during normal faulting. The basin fill thins toward the north, and Messinian sediments are 80-100 m thick over the largest part of the Solunto High. North of the Solunto High, a set of steep, mainly northward dipping normal faults allowed for the deposition of up to 400 m of Messinian sediments. Internal reflectors are very disturbed but the pre-late Messinian age of normal faulting is obvious. Thickness in the remaining part of the section is ~200 m.

Numerous small-scale thrusts and folds affect Messinian sediments in the Cefalù basin and, more substantially, north of the Solunto High (Plate 1 and Figure 7). The largest majority of these structures are vergent toward the north. In the Cefalù basin a clear unconformity between Messinian and lower Pliocene deposits is observed (Figure 7). Similar relations was also noticed in northern and southern Sicily [Abate *et al.*, 1991; Vitale, 1995].

4.2.2. Pliocene to Pleistocene. Messinian sediments are unconformably overlain by the 100 and 200 m thick package of Lower Pliocene sediments distributed along the entire section (Plate 1). The lower Pliocene is ~200 m thick in the Cefalù basin, <100 m over the Solunto High, and ~150 m in

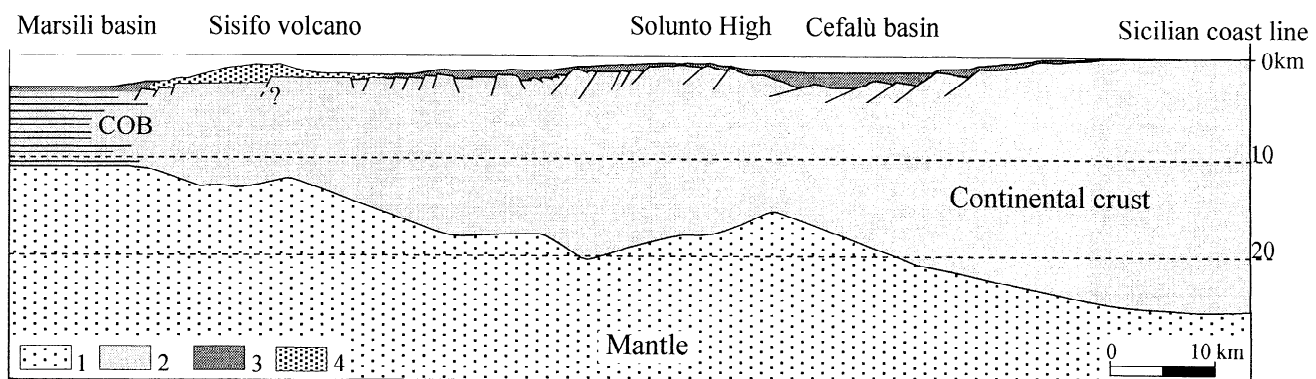


Figure 6. Interpretative crustal section across the north Sicily continental margin. 1, mantle; 2, continental crust; 3, upper Tortonian to Recent times deposits; and 4, volcanoclastic rocks.

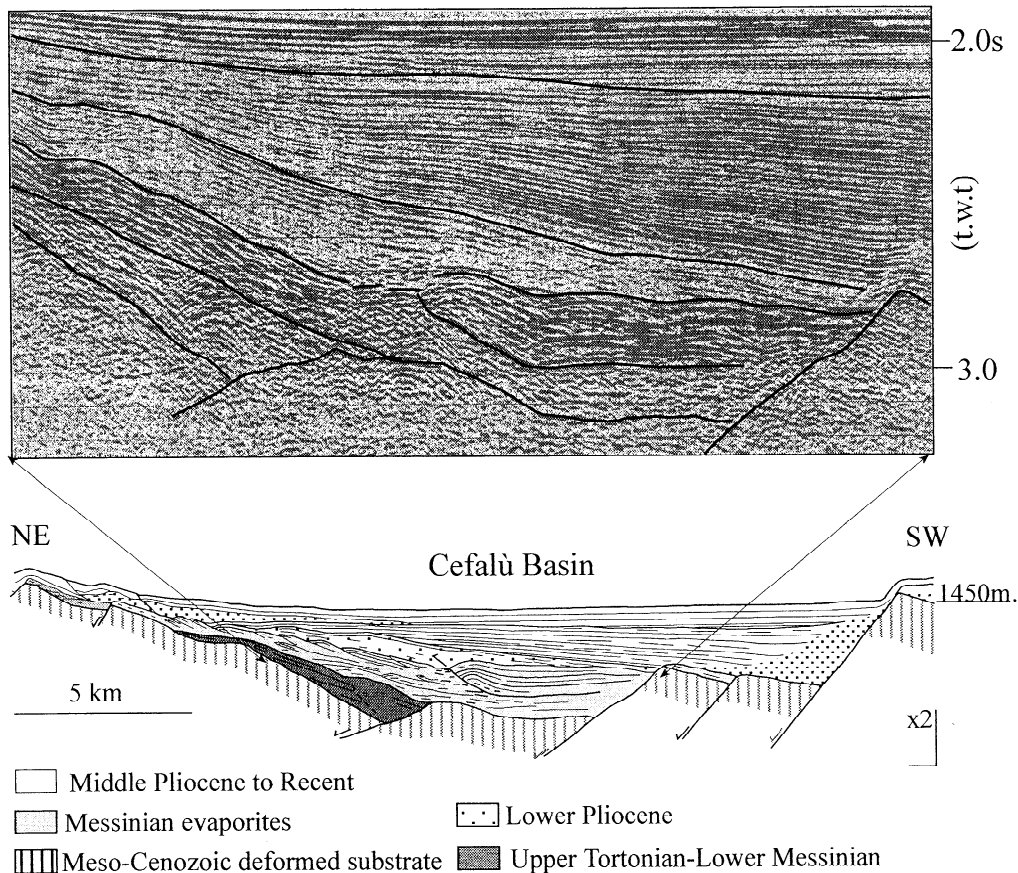


Figure 7. The Cefalù basin as imaged in the NSic.1 seismic line and its geological interpretation. Note the twofold vertical exaggeration.

the remaining part of the section. The fairly constant thickness and the unconformable character of its base suggest a significant slowdown of deformation during the early Pliocene. Only some thickness changes in the northernmost and southernmost parts of the profile could be indicative of limited normal faulting.

On top of the lower Pliocene a well-stratified sedimentary package is observed that can be subdivided into two subunits by a well-developed unconformity (Figure 7). These subunits are here tentatively considered as of middle-late Pliocene and Pleistocene age, respectively. In the Cefalù basin, middle to upper Pliocene sediments have been deposited in a half graben bordered by a fault. This fault is located a few kilometers south of the structure that controlled the Messinian graben (Figure 7), thereby continuing a pattern of southward migration of faulting. Up to 700 m of sediments were deposited in this half graben. Reflectors clearly diverge toward the normal fault demonstrating synextensional deposition. The occurrence of middle to upper Pliocene sediments in the southernmost blocks is disputable because no precise age can be assigned to the chaotic bodies covering the faults escarpment. North of the Cefalù basin, middle to upper Pliocene beds become very thin in the region of the Solunto High where they are virtually indistinguishable from underlying sediments (Plate 1). A slight thickness increase is observed north of the Solunto High, but no features

comparable to those described in the Cefalù basin are present. Some, very limited normal faulting caused the displacement of beds.

Upper Pliocene layers are overlain by well-stratified sediments of supposedly Pleistocene to Recent age, which drape and smooth underlying features (Plate 1). Thicknesses gently vary between 100 and 350 m. Layers typically seal normal faults marking the cessation of extension along the section. Obviously, this does not preclude more recent deformation to the south of the section [e.g., *Agate et al.*, 1993] as well as onshore Sicily.

4.3. The Distal Part of the Margin and the Oceanic Crust

The most distal part of the continental margin is occupied by the dominant mass of the Sisifo volcano (Plate 1). Dredge samples have demonstrated its calc-alkaline affinity and its K/Ar age of $1.3-0.9 \pm 0.2$ Ma [*Beccaluva et al.*, 1985]. Sisifo volcano is therefore one of the several volcanoes formed in the southeast Tyrrhenian in association with northwestward subduction of the Ionian plate [e.g., *Barberi et al.*, 1974]. Volcanoclastic rocks have been dispersed all around the volcano, thereby obscuring the background sedimentary record of the area. However, the basement top can still be recognized in several places and appears to be at quite different depths to the south and to the north of the volcanic

edifice. To the south, it lies at a depth of ~2000 m, while north of Sisifo volcano, it is >3000 m deep. The difference in elevation suggests the existence of a large northward dipping normal, possibly transtensional fault. Sisifo volcano marks the northern termination of the continental crust (Plate 1).

The northernmost part of the section is formed by oceanic crust belonging to the Marsili basin (Plate 1). The oceanic crust is composed of highly vesicular basalts, with calc-alkaline affinity, overlain by ~600 m of unconsolidated volcanoclastic and pelagic sediments [Shipboard Scientific Party, 1987b]. The MPI6 (*Globorotalia inflata*) biozone [Cita, 1973; Rio *et al.*, 1984] was recognized in the oldest sediments overlying oceanic crust [Shipboard Scientific Party, 1987b], thereby providing a lower age boundary for the onset of oceanic crust spreading at ~2.0 Ma.

5. Kinematic Evolution of the Margin

By palinspastically restoring the geological section obtained from the NSic.1 line, we have reconstructed the kinematic evolution of the north Sicily continental margin during and following rifting (Figure 8). Relevant kinematic factors such as amount, duration, and rate of extension are derived.

5.1. The Evolution

The area of the north Sicily continental margin was affected by early Miocene to early Tortonian shortening and

thrusting during the Sicilian-Maghrebian fold-and-thrust belt formation [Catalano *et al.*, 1985, and references therein]. The nappe pile was at or slightly above sea level following the cessation of thrusting as demonstrated by the absence of postcontractional, prerift sedimentary successions.

Extension affected the area since late (?)Tortonian times and caused the formation of a half graben, which was the oldest ancestor of the Cefalù basin (Figure 8a). The half graben was ~7 km wide, limited to the south by a northward dipping normal listric fault and hosted ~500 m of sediments in its depocenter. The absence of coeval deposits outside the Cefalù basin indicates that subsidence in these areas, if active at all, did not bring the region under sea level.

Generalized stretching affected large parts of the future margin during the Messinian (Figure 8b). Faulting was widespread and especially active in the Cefalù basin and north of the Solunto High. In the south, subsidence was basically controlled by a new, north dipping normal fault formed ~5 km south of the late Tortonian fault. Rotation of sedimentary layers suggests a listric shape for these faults. At the end of this rifting stage the Cefalù basin was ~15 km wide and filled with evaporitic sediments with a thickness of more than 700 m in its depocenter. South of the master fault, the footwall remained at or above sea level, preventing the deposition of Messinian sediments. To the north, the area of the Solunto High remained relatively unaffected by normal faulting and less subsident than adjacent regions. This pattern persisted throughout rifting. Further to the north, stretching was intense

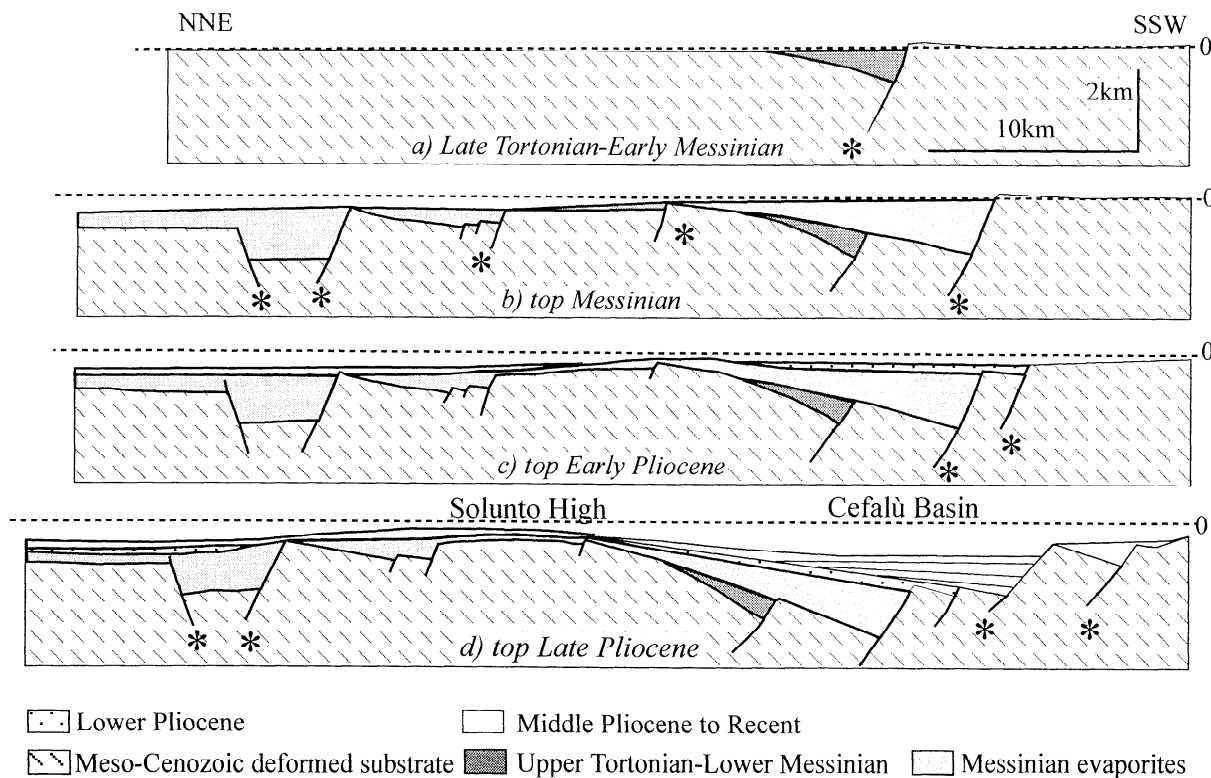


Figure 8. Simplified palinspastic reconstruction of the North Sicily rifted margin. (a) late Tortonian-early Messinian. (b) top Messinian. (c) top early Pliocene. (d) top late Pliocene. Stars indicate faults active during the various stages.

and caused widespread, mainly north dipping normal faulting and associated tectonic subsidence. Messinian sediments and paleobathymetries are poorly known because of the lack of wells. Seismic facies suggest only that the upper part of the evaporites could be composed by gypsum and marls, similarly to what is known from exposed sections in central Sicily [e.g., *Decima and Wezel, 1973*], and have been drilled in the Tyrrhenian basin [e.g., *Ryan et al., 1973*].

During the early Pliocene, extension slowed down. Subsidence continued according to the Messinian pattern, with the thickest lower Pliocene being deposited in the Cefalù basin and in the distal part of the future margin (Figure 8c). Correlation with coeval sediments exposed in close by areas suggests paleobathymetries of 200-500 m [*Ruggieri, 1960*]. The Solunto High remained a relatively elevated area, possibly emerging above sea level. Pre-middle Pliocene sediments in the Cefalù basin and in the distal part of the margin are affected by small-scale thrusting. This could be indicative of crustal shortening, but the deep continuation of the thrust surfaces is unclear, and therefore it cannot be recognized if they affected deeper levels. Alternatively, thrusting could be related to gravity gliding of soft sediments. In any case, deformation had ended in the early Pliocene, and middle Pliocene sediments seal underlying features with a clear unconformity of regional importance (see Section 3.1.2).

In the late Pliocene a new rifting stage began which eventually led to crustal separation and the formation of the north Sicily continental margin. Extension in the southern part of the section was again centered in the Cefalù basin (Figure 8d). Here, normal faulting continued the pattern of southward migration, thereby widening the Cefalù basin (~20 km) and bringing also the southernmost blocks below sea level. The footwalls of these faults, outcropping in north Sicily, outside the recorded line, were probably uplifted during this time, bringing marine lower Pliocene several hundred meters above sea level [e.g., *Abate et al., 1982*]. To the north of the Cefalù basin, the Solunto High was still a basically undeformed and significantly elevated area. In the most distal parts of the margin, normal faulting was active but quantitatively probably not very important. The limited normal faulting observed in the distal part of the section is at odds with the strong extension that must have affected the area in order to achieve crustal separation in the latest Pliocene. Possible normal faults could be concealed by thick volcanoclastic deposits of the Sisifo volcano that began its activity during this time.

In Pleistocene times, extension ended along the section and Pleistocene deposits draped existing structures. South of the section, a continuation of normal faulting is suggested onshore on the basis of the very rough morphology of the coastal areas.

5.2. Relevant Kinematic Quantities

The quantitative description of rifting is particularly important, not only to constrain the kinematics of Tyrrhenian opening but also to enable comparisons with other passive margins in similar as well as differing tectonic settings. A summary of the obtained estimates is given in Table 3.

5.2.1. Amount and rates of extension. The present-day length of the continental part of the N.Sic1 line is 97.5 km. By retrodeforming observed deformations, we derive a length of 87.5 km for the same section before the onset of extension. The total observed extensional strain is therefore 0.114. Assuming a total duration of rifting of ~7.0 My, from the late Tortonian (~9 Ma) (timescale by *Haq and Van Heysinga [1998]*) to the onset of oceanic crust formation (~2.0 Ma), a strain rate of $0.5 \times 10^{-15} \text{ s}^{-1}$ is obtained. This relatively low value is a lower boundary because it is influenced by the very limited extension observed in the most distal part of the margin.

The estimates provided above are averaged over the entire rifting stage and over the whole margin. However, geological data allow for the subdivision of rifting into two main stages separated by the ~4 Ma old Pliocene unconformity. The first rifting stage is assumed to have started at 9 Ma and ended at 5 Ma. The second one started at 4 Ma and ended at 2 Ma with the appearance of the first oceanic crust in the Marsili basin. Resulting strain and strain rate values for this subdivision are shown in Table 3 and in Figure 9. Values are still quite low and remain roughly constant. It is well known that constant strain rate implies an acceleration of the relative movement of the northern end of the section with respect to the southern one.

Extension along the north Sicily continental margin was not homogeneously distributed but was mainly concentrated in the Cefalù basin and, some tens of kilometers farther to the north, in the Sisifo volcano area. It is therefore useful to derive kinematic quantities for the most extending zones. In fact, crustal mechanical phenomena such as thinning-related hardening [*England, 1983; Bertotti et al., 1997*] depend on the kinematics of the extending zones rather than that of the entire margin. Pin lines used for calculations are shown in Plate 1;

Table 3. Kinematic Quantities of Rifting

	Strain			Strain rate, $\times 10^{-15} \text{ s}^{-1}$		
	Cefalù Basin	Distal Margin	Total	Cefalù Basin	Distal Margin	Total
Total	0.44	0.26	0.114	1.93	1.14	0.50
Pliocene-Pleistocene	0.18	0.08	0.037	2.59	1.15	0.53
Pre-Pliocene	0.35	0.16	0.072	2.78	1.27	0.57

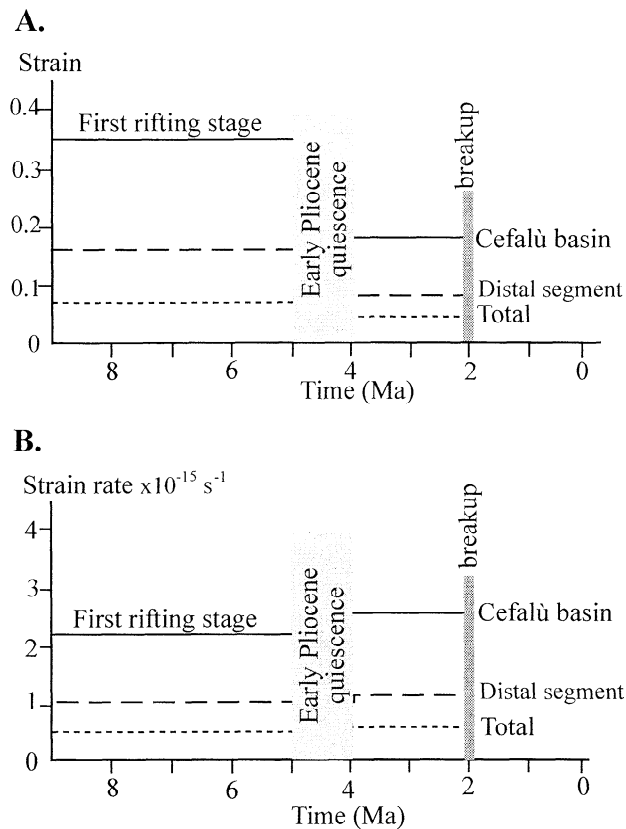


Figure 9. (a) Strain across the continental margin and for significant sectors. (b) Strain rate across the continental margin and for significant sectors.

results obtained are given in Table 3 and Figure 9. Calculations for the Cefalù basin produce strain rates of the order of $2 \times 10^{-15} \text{ s}^{-1}$, which is substantially higher than those of the entire margin. Kinematic analysis of extension in the distal part of the margin not including the poorly controlled faults underneath and north of Sisifo volcano (Table 3 and Figure 9) shows that substantial stretching took place, although definitely inferior to what was observed in the Cefalù basin. Strain rates are correspondingly lower.

5.2.2. Thinning and comparison with extension. Crustal thickness variations are here tracked by means of a thinning factor defined as $\delta = d_{\text{initial}} / d_{\text{final}}$. Assuming an initial thickness of 26 km, which corresponds to the present-day Moho depth underneath north Sicily, thinning factors along the north Sicily continental margin are shown in Figure 10. One kilometer wide boxes have been used for calculations. High values are observed in the area of the Cefalù basin where thinning of the crust is up to $\delta = 1.85$. Moho deepens again in correspondence with the Solunto High. Toward Sisifo volcano, total crustal thinning rapidly increases and reaches the maximum value of 3.54 just before the continent-ocean transition.

To compare thinning with extension, we plot in the same diagram the thinning factors and stretching factor values representative of the most extended parts of the profile (Figure 10). The first observation is that there is a first-order coincidence between zones of extension and zones of thinning. In the Cefalù basin there is also a good similarity between the numerical values of the two factors, thereby indicating a pure shear geometry of extension. Such compatibility does not exist in the most distal part of the margin where observed extension is by far insufficient to

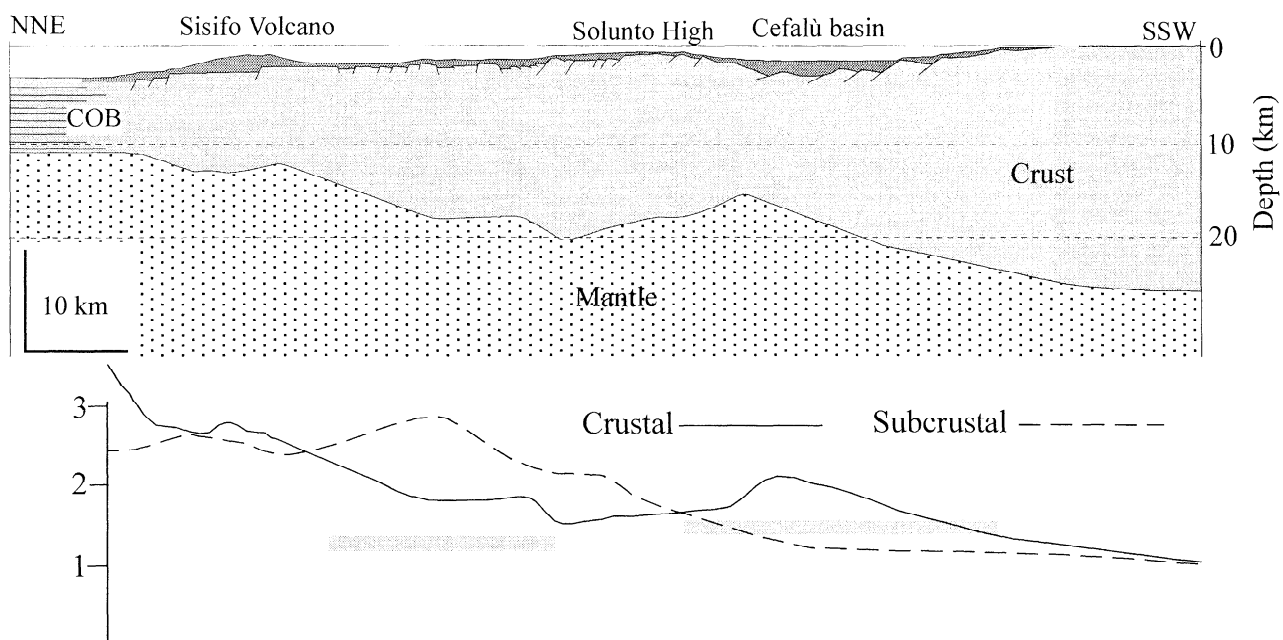


Figure 10. Crustal and lithospheric thinning factors along the NSic.1 profile. Lithospheric thinning factors have been derived from the lithospheric thickness map of *Ansorge et al.* [1992]. The horizontal bar in the diagram indicates the stretching factor measured in the Cefalù basin and in the distal part of the margin.

cause the observed thinning. We deduce from this that substantial extension must have been localized in parts of the margin where the record is unclear. This is the case, for instance, in the region of the Sisifo volcano and farther to the north toward the continent-ocean transition.

6. Discussion

6.1. Kinematics and Dynamics of North Sicily Rifting

Continental rifting affected the internal side of the Sicilian-Maghrebides nappe pile of north Sicily since late (?) Tortonian times. During these very initial stages, extension was localized in the area of the future Cefalù basin and was basically accommodated by north dipping normal faults. From late (?)Tortonian to Messinian times, extension persisted in the Cefalù basin but affected also the distal part of the future margin. These two areas will continue to undergo extension throughout most of the rifting stage. Following the early Pliocene interval of relative quiescence, renewed extension affected the Cefalù basin and the distal margin. Rifting lasted until the early Pleistocene when crustal separation occurred in the Marsili basin. The widespread normal faulting clearly imaged by seismic data and the obvious thinning of the margin toward the ocean demonstrate the importance of thinning and extensional processes in the Neogene to Recent times tectonic evolution of the north Sicily continental margin.

At the crustal scale the lateral distribution of strain remained fairly unchanged through time, and extension remained localized in the Cefalù basin and in the area around Sisifo volcano. This persistence indicates that lithospheric hardening did not take place during extension [England, 1983; Bertotti *et al.*, 1997]. The two zones, of stretching are ~60 km apart. The Solunto High, located between the two stretching zones, remained basically unaffected by extension and underwent limited subsidence and, possibly, relative uplift. As a consequence, sediments are here much thinner than in the surrounding areas. The record shows that the Solunto High remained undeformed and elevated throughout rifting and that it is not a younger feature. This could be due to some lithological control on the localization of extension or more likely could reflect a primary boudinage geometry of the extending crust [e.g., Martinod and Davy, 1992]. Alternatively, the Solunto High could be a rollover anticline associated with the north dipping normal faults of the Cefalù basin.

The Cefalù basin shows a very interesting discrepancy between large-scale and small-scale extension and faulting patterns. At the crustal to lithospheric scale it is clear that extension remained localized in the Cefalù basin throughout rifting. At a smaller scale, that of the upper crust, normal faults show an apparent pattern of migration toward the south. The pattern is very systematic with constant geometries and spacing between faults. This discrepancy between the behavior at different scales is related to the twofold control exerted on extension kinematics by the layered nature of the Earth's lithosphere [e.g., Ranalli and Murphy, 1987; Bertotti *et al.*, 2000]. At the large scale the persistence of extension in one specific area is controlled by the quantitative relations

between heating of the lithosphere and thinning of the crust (replacement of weak crustal material with strong mantle rocks) [England, 1983]. At a smaller scale, faulting patterns are controlled by the behavior of a broken elastic plate [e.g., Bott, 1997]. Maximum amount of displacement accommodated before migration and fault spacing are controlled by the flexural rigidity of the plate [Forsyth, 1992; Buck, 1993; Bott, 1997]. Recently advanced ideas [Bertotti *et al.*, 2000] suggest that fault migration patterns are diagnostic for the existence of flow in the middle crust. Fault propagation toward the footwall, as systematically observed in the Cefalù basin, is considered to be typical for crusts where flow takes place in the middle crust during extension. This is also compatible with the fairly stable position of footwalls during normal faulting. Such features are thought to occur when stretching affects crustal segments thickened and tectonized prior to extension and composed of a large part of soft rocks.

The southernmost fault imaged in the section is sealed by upper (?) Pliocene-Pleistocene sediments. However, the continuation of southward fault migration outside the NSic.1 section is suggested by the very steep morphology of the mountains in the region of Palermo, immediately south of the section (Figure 2). This relief could be associated with footwall uplift along Pleistocene and/or younger faults operating in a similar fashion to that observed in the seismic section. The presence of lower Pliocene deposits in mountains close to the investigated area at an elevation of 1500 m is a further indication of very recent tectonic activity [Abate *et al.*, 1991].

Neither our NSic.1 nor the CROP M6A lines provide clear images of the northern extending zone, between the Solunto High and the continent-ocean transition. Stretching seems to have been accommodated by relatively steep, predominantly north dipping normal faults. This is also the geometry of the largest fault of the area, presently buried under the Sisifo volcano. A striking feature of the northern extending zone is the very limited amount of extension that can be demonstrated. This is in contrast to the substantial thinning measured. The paucity of extension can be merely a consequence of the poor quality of the record, or it could be real. In this latter case one could envisage the existence of a low-angle normal fault cutting through the continental crust to the north of the Solunto High and accommodating extension during the final rifting stages or flow of crustal rocks through the system.

6.2. Implications for Tyrrhenian Evolution

The north Sicily margin is one of the continental segments bordering the Vavilov and Marsili oceanic basins (Figure 1). One major result of the NSic.1 seismic line is the notion that the overall configuration of the continental crust north of the Sicily coast line, namely, thickness changes and geometry of sedimentary basins, is primarily controlled by extension. As such, the north Sicily margin is a passive continental margin and well comparable to that of east Sardinia and SW peninsular Italy. More detailed comparisons are easy between north Sicily and east Sardinia but more difficult with SW Italy because no comprehensive tectonic description exists for this

margin. The timing of stretching is also well comparable. Both in north Sicily and east Sardinia, extension began in the Tortonian. Knowledge of the Tyrrhenian margin of peninsular Italy is more scanty, but extensional basins of Tortonian age are known from Calabria [e.g., *Ortolani et al.*, 1979; *Colella*, 1995]. The information derived from the north Sicily rifted margin represents a further necessary step toward a complete 3-D kinematic description of the formation of the Tyrrhenian Sea back arc basin.

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