

## RESEARCH ARTICLE

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## Key Points:

- First clear observations of surface tectonics of a slab tear
- High-resolution bathymetric and seismic images of unprecedented quality
- Two active fault systems at the seafloor (60 and 80 km long) may pose seismic hazard

## Supporting Information:

- Figures S1–S5

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# Tectonic expression of an active slab tear from high-resolution seismic and bathymetric data offshore Sicily (Ionian Sea)

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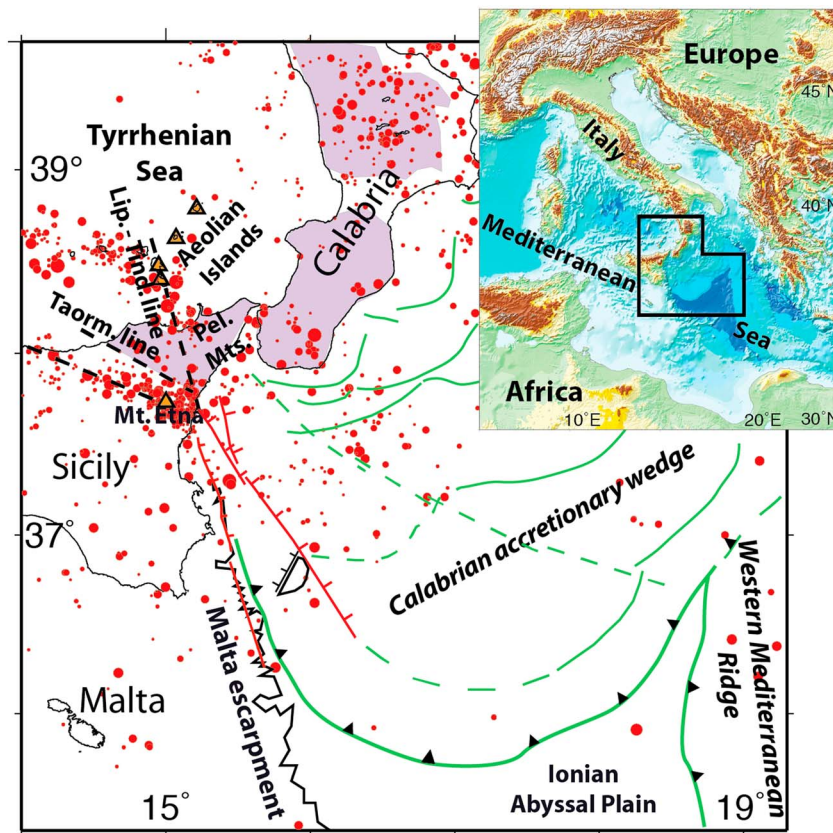
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**Abstract** Subduction of a narrow slab of oceanic lithosphere beneath a tightly curved orogenic arc requires the presence of at least one lithospheric scale tear fault. While the Calabrian subduction beneath southern Italy is considered to be the type example of this geodynamic setting, the geometry, kinematics and surface expression of the associated lateral, slab tear fault offshore eastern Sicily remain controversial. Results from a new marine geophysical survey conducted in the Ionian Sea, using high-resolution bathymetry and seismic profiling reveal active faulting at the seafloor within a 140 km long, two-branched fault system near Alfeo Seamount. The previously unidentified 60 km long NW trending North Alfeo Fault system shows primarily strike-slip kinematics as indicated by the morphology and steep-dipping transpressional and transtensional faults. Available earthquake focal mechanisms indicate dextral strike-slip motion along this fault segment. The 80 km long SSE trending South Alfeo fault system is expressed by one or two steeply dipping normal faults, bounding the western side of a 500+ m thick, 5 km wide, elongate, syntectonic Plio-Quaternary sedimentary basin. Both branches of the fault system are mechanically capable of generating magnitude 6–7 earthquakes like those that struck eastern Sicily in 1169, 1542, and 1693.

## 1. Introduction

Subduction of oceanic lithosphere beneath tightly curved orogenic arcs is common in the Mediterranean region, where overall plate convergence between Africa and Eurasia is slow (~5 mm/yr) [D'Agostino et al., 2011] and where narrow slabs sink down into the upper mantle causing rollback and back-arc extension [Wortel and Spakman, 2000; Faccenna et al., 2004]. Slab rollback can only occur if the small oceanic basin detaches itself from the adjacent (commonly continental) lithosphere along subvertical tear faults also known as "STEP" faults [Govers and Wortel, 2005]. This type of lithospheric scale fault is thought to be present at the edge of numerous subduction systems around the world (Caribbean, South Sandwich, Sulawesi, Fiji-Tonga, New Hebrides). As first discussed by Govers and Wortel [2005], a STEP fault includes a deep (20–100 km) component—the edge of the subducting slab and a shallow expression alongside the kinematically independent upper plate block, which typically advances toward the foreland due to slab rollback. Many consider the Calabrian arc of southern Italy (Figure 1) as the type example of a narrow, retreating slab [Faccenna et al., 2004; Rosenbaum et al., 2002, 2008].

The geodynamic evolution of the Western Mediterranean and Italy was largely controlled by a NW dipping subduction zone beneath southern France and Iberia, which began around 35 Ma [Malinverno and Ryan, 1986; Jolivet and Faccenna, 2000]. As the slab of Tethys oceanic lithosphere between Africa and Europe retreated to the SE, it opened a series of back-arc basins and left several small continental blocks in its wake (e.g., Corsica-Sardinia) [Faccenna et al., 2001, 2004; Rosenbaum et al., 2002]. Tomographic studies of the upper mantle image a steeply NW dipping slab descending beneath Calabria and the SE Tyrrhenian Sea to depths of >500 km and with a sharp SW boundary at depth below Mount Etna [Wortel and Spakman, 2000; Neri et al., 2009]. Several workers have proposed a causal effect between the lateral slab tear, creating an asthenospheric



**Figure 1.** Simplified tectonic map of southern Italy region, showing seismicity (red circles) from PDE-NEIC earthquake catalog (1973–2014,  $M \geq 2.5$ ), accretionary wedge thrust structures (green lines, with black teeth at the deformation front) [Polonia et al., 2011; Gallais et al., 2012], active volcanoes (yellow triangles), normal faults proposed as likely surface expressions of the STEP fault (red lines with barbs), possible prolongations of the STEP fault, north of Mount Etna in NE Sicily [Jenny et al., 2006; Palano et al., 2012] (black dashed lines) Lip.-Tind. line = Lipari-Tindari Line, Taorm. line = The Taormina Line, forming the SW boundary of the Variscan crystalline basement of Calabria and the Peloritan Mountains (Pel. Mountains) shown in magenta. Inset shows the study area located in southern Italy and the Central Mediterranean Sea (Ionian Sea).

window and enhancing toroidal flow in the upper mantle and the presence of Mount Etna in northeastern Sicily [Gvirtzman and Nur, 1999; Faccenna et al., 2011]. Today most of the oceanic lithosphere has been consumed, and there remains at most a narrow corridor (150 km to 300 km wide) connecting the oceanic domain of the Ionian Sea to the slab observed beneath the SE Tyrrhenian Sea [Wortel and Spakman, 2000; Neri et al., 2009; Giacomuzzi et al., 2012].

The combination of NW directed subduction and the southeastward advance of the Calabrian-Peloritan block drove shortening and thrusting in the thick layers of marine sediments within the Ionian Sea, leading to the construction of a large accretionary wedge imaged by deep seismic reflection lines [Finetti, 1982; Cernobori et al., 1996; Nicolich et al., 2000; Minelli and Faccenna, 2010]. A broad belt of undulating seafloor occupies a gentle slope down to the Ionian abyssal plain and is characterized by anticlinal ridges as seen in high-resolution seismic profiles and bathymetry [Hieke et al., 2005; Gutscher et al., 2006; Loubrieu et al., 2007]. Some researchers interpreted this compressional deformation as caused by regional gravitational sliding [Chamot-Rooke et al., 2005]. However, more recent studies have concluded that deformation in this outer Calabrian arc is caused by large-scale compression affecting the Plio-Quaternary and Messinian sediments above a decollement at the base of the Messinian [Polonia et al., 2011; Gallais et al., 2012]. While the position of the outer deformation front in the Ionian abyssal plain is well documented by seismic profiles and existing bathymetric compilations [Loubrieu et al., 2007; Polonia et al., 2011; Gallais et al., 2012], the position of the lateral ramp offshore eastern Sicily is largely uncertain and has been interpreted in a wide range of locations by different workers [Chamot-Rooke et al., 2005; Minelli and Faccenna, 2010; Polonia et al., 2011; Gallais et al., 2012, 2013].

According to available geodetic data, there is slow, but significant convergence ( $\geq 3$  mm/yr) occurring between the Hyblean platform (SE Sicily) and NE Sicily (the Peloritan Mountains domain) and slow (3–5 mm/yr) southeastward motion of the Calabrian block with respect to the Apulian and Hyblean domains [D'Agostino *et al.*, 2011; Devoti *et al.*, 2011; Palano *et al.*, 2012]. These authors attribute most of this motion to the Calabria subduction, with rollback of the Ionian slab inducing southeastward motion of the Calabria-Peloritan block. However, Sicily itself and the neighboring regions appear to be composed of a mosaic of microblocks with slow moving, but complex kinematics [Serpelloni *et al.*, 2010].

Researchers have been seeking for the lithospheric scale tear fault associated with subduction rollback, presumably located offshore eastern Sicily, since it was first suggested [Gvirtzman and Nur, 1999; Orecchio *et al.*, 2014]. Many have proposed the Malta Escarpment to be the active tear fault, primarily due to its striking morphological expression as a 3–4 km high step on the seafloor [Argnani and Bonazzi, 2005; Govers and Wortel, 2005; Argnani, 2009; Argnani *et al.*, 2012]. The Malta Escarpment is widely considered to be an ancient Tethyan passive margin formed by rifting in the Mesozoic (or earlier) [Catalano *et al.*, 2001; Nicolich *et al.*, 2000; Frizon de Lamotte *et al.*, 2011; Gallais *et al.*, 2013]. Several studies have reported active normal faulting on the northern portion of this escarpment [Argnani and Bonazzi, 2005; Argnani, 2009; Argnani *et al.*, 2012]. Other researchers have identified major normal faults imaged in seismic profiles farther east and interpreted these as the tear fault [Cernobori *et al.*, 1996; Nicolich *et al.*, 2000; Polonia *et al.*, 2011; Gallais *et al.*, 2013] (Figure 1). The exact geometry and degree of activity of the network of faults offshore Sicily in the Ionian Sea remain uncertain and highly controversial [Argnani, 2014; Gallais *et al.*, 2014; Orecchio *et al.*, 2014]. These faults pose a significant seismic and tsunami hazard in this region where nearly 200,000 deaths have occurred over the past five centuries [Jenny *et al.*, 2006]. However, the sources of many of these earthquakes and tsunamis remain unknown or disputed to this day [Piatanesi and Tinti, 1998; Gutscher *et al.*, 2006; Argnani *et al.*, 2012; Aloisi *et al.*, 2013], with some workers arguing for a contribution from submarine landslides in some cases [Billi *et al.*, 2008, 2010]. There is no consensus on the surface expression of the STEP fault and its trace through eastern and northern Sicily is uncertain (Figure 1) [Orecchio *et al.*, 2014]. The objective of this study is to map active faults offshore eastern Sicily, which may pose as a seismic hazard, and to identify the tectonic expression of the lateral slab tear or STEP in the Ionian Sea.

## 2. Data/Methods

A marine geophysical survey was conducted onboard the French research vessel *Le Suroit* in October 2013 using high-resolution seismic reflection profiling and bathymetric swathmapping. The seismic data were acquired using a 450 m long, 72 channel Sercel seismic streamer with an average geophone spacing of 6.25 m and towed 150 m behind the vessel. The seismic source was a six mini-GI airgun array with a total volume of 111 cubic inches (1.8 liters) fired at a cadence of once every 6 s, for an average shot spacing of 16 m and a 24-fold coverage for each common midpoint. Quality control of the seismic data, including processing of the navigation files (shot position and streamer geometry), was performed with the SISPEED software (Ifremer). The seismic data were subsequently band-pass filtered (70–425 Hz), stacked and time migrated using a water velocity of 1500 m/s, using the Seismic Unix software package.

The bathymetric data (Figure 2) were acquired using an EM302 Simrad bathymetric echosounder. It emits 860 beams at an aperture commonly between 50° and 70° to each side and typically covers a 6 km wide swath at 3000 m water depth, with a resolution of 10–30 m. The Simrad echosounder software automatically performs an initial quality control, which flags doubtful data. Thereafter, swaths of pings are reprocessed by hand to remove data outliers using CARAIBES software. The processed depth soundings were then gridded using GMT software at a grid spacing of 2 arc sec (about 60 m).

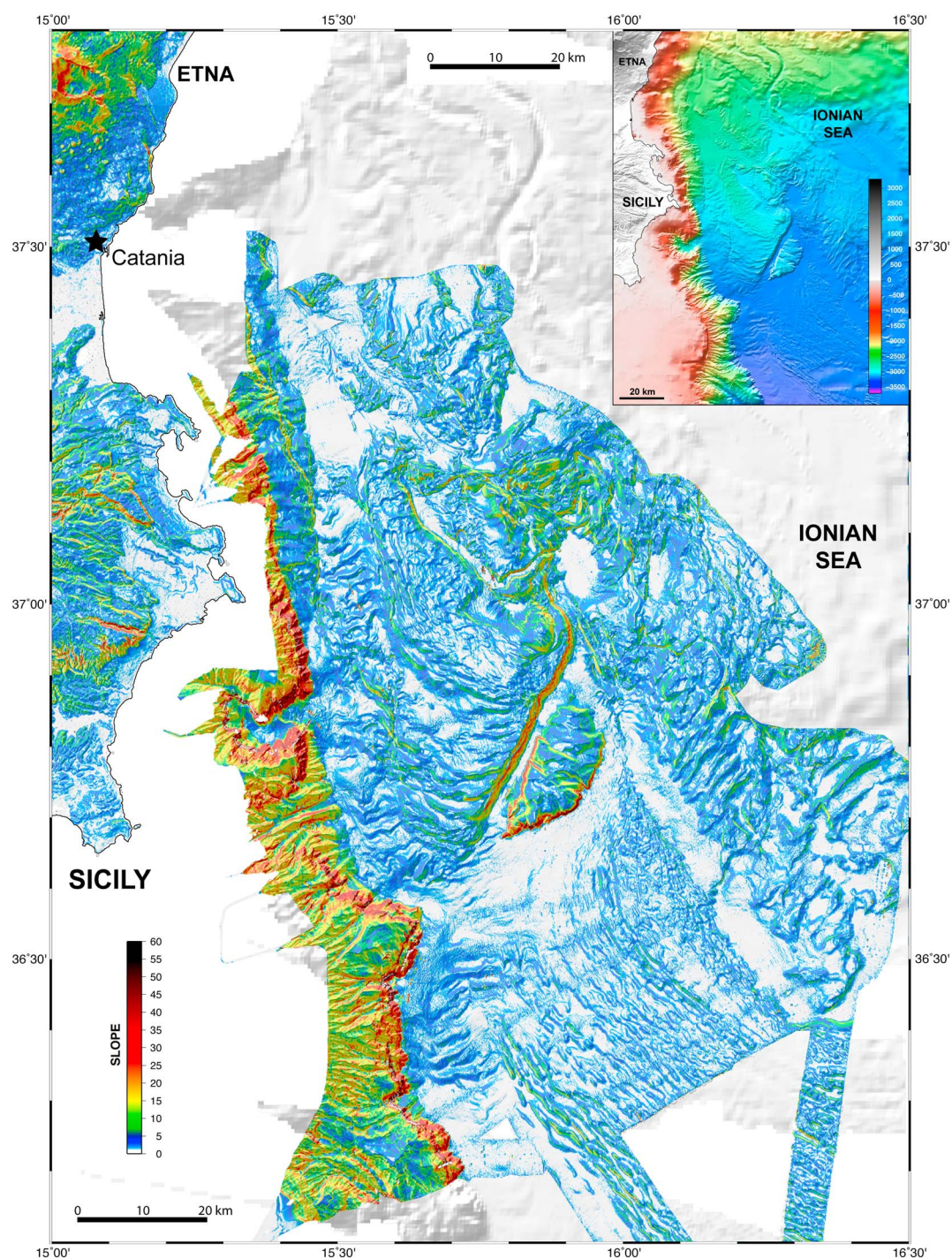
## 3. Results

The seismic and bathymetric data were used to probe several morphotectonic provinces offshore eastern Sicily: the  $\geq 3$  km high bathymetric step formed by the Malta Escarpment, broad flat-bottomed turbidite valleys and the western portion of the Calabrian accretionary wedge (Figures 2 and 3).

### 3.1. Morphobathymetry

The most striking feature in the bathymetry is the  $> 150$  km long, Malta-Hyblean Escarpment (Figures 2 and 3), which over a lateral distance of 20–30 km marks the transition from the Hyblean continental platform

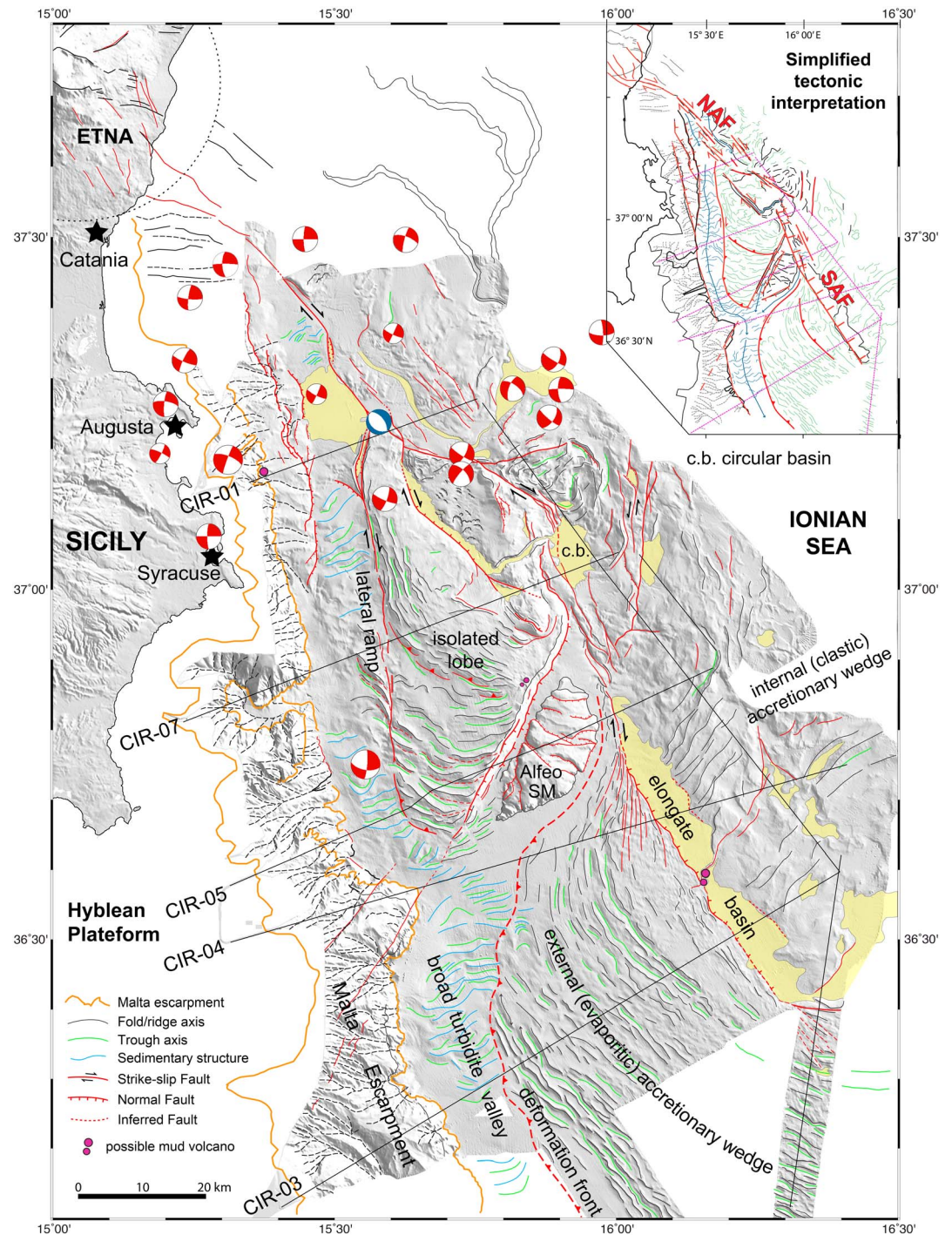




**Figure 2.** High-resolution swath bathymetry (color slope map) acquired with R/V *Suroit* and a Simrad EM302 echosounder (90 m grid, NW illumination) superposed on the gray shaded relief from MediMap bathymetric compilation [Loubrieu et al., 2007] (500 m grid). (inset) Color shaded relief of new swath data and existing compilation [Loubrieu et al., 2007], (NW illumination).

(with shallow water carbonates) on the west to a deep marine environment to the east with water depths of 3000–4000 m. The slopes here are 10–20° on average and can locally reach 30° (Figure 2). The escarpment is deeply incised by submarine canyons, commonly running orthogonal to the escarpment and locally joining together to form large amphitheater-like structures (e.g., at 36°48'N). This incision may be





**Figure 3.** Morphobathymetric interpretation showing: position of seismic profiles (straight black lines), sediment waves (alternating green and blue lines), accretionary wedge anticlines and synclines (black and green lines), likely faults (red lines), the upper and lower limits of the Malta Escarpment (orange lines), flat lying sedimentary basins (yellow shading), and earthquake focal mechanisms, taking a representative subset (20 out of 80) of the earthquakes at sea and along the coast from a published study [Musumeci et al., 2014]. (inset) Simplified morphotectonic interpretation. Symbols: minor thrust faults in the accretionary wedge (green lines); sedimentary structures, (blue lines); basin boundaries and other tectonic lineaments (black lines); major faults (red lines) with kinematics indicated (barbs for normal faults, arrows for strike-slip faults, teeth for thrust faults) NAF = North Alfeo Fault system and SAF = South Alfeo Fault system; position of seismic profiles (straight magenta lines), Faults on the SE flank of Mount Etna are from mapping and InSAR studies [Bonforte et al., 2011; Chiocci et al., 2011; Barreca et al., 2013] and show dextral strike-slip motion.

in large part due to erosion during the Messinian salinity crisis when sea level was approximately 1500 m lower than today [Lofi *et al.*, 2011]. Offshore SE Sicily (south of 36°30'N) the escarpment is highest (nearly 4000 m) and most rugged. To the north between Syracuse (37°00' N) and Augusta (37°15'N), the slope is less steep and divided into a subplatform at 1500–2000 m depth and a larger step at the base of the escarpment (Figure 2).

At the foot of the Malta Escarpment is a 10–20 km wide, curvilinear trough running gently downslope to the south (Figures 2 and 3). This broad valley is marked by abundant sinusoidal ridges and troughs, oriented roughly orthogonal to the downslope direction. They have a characteristic spacing of 2–3 km and an average height of about 30 m and represent deep water sedimentary structures known as sediment waves (bed forms created either by downslope flowing turbidity currents, or alongslope-flowing bottom currents in deep water settings) [Wynn *et al.*, 2000]. Originating from gently sloping regions farther east, some smaller tributary channels and broad valleys (locally marked by sediment waves) join this main N-S trending trough known hereafter as the “broad turbidite valley.”

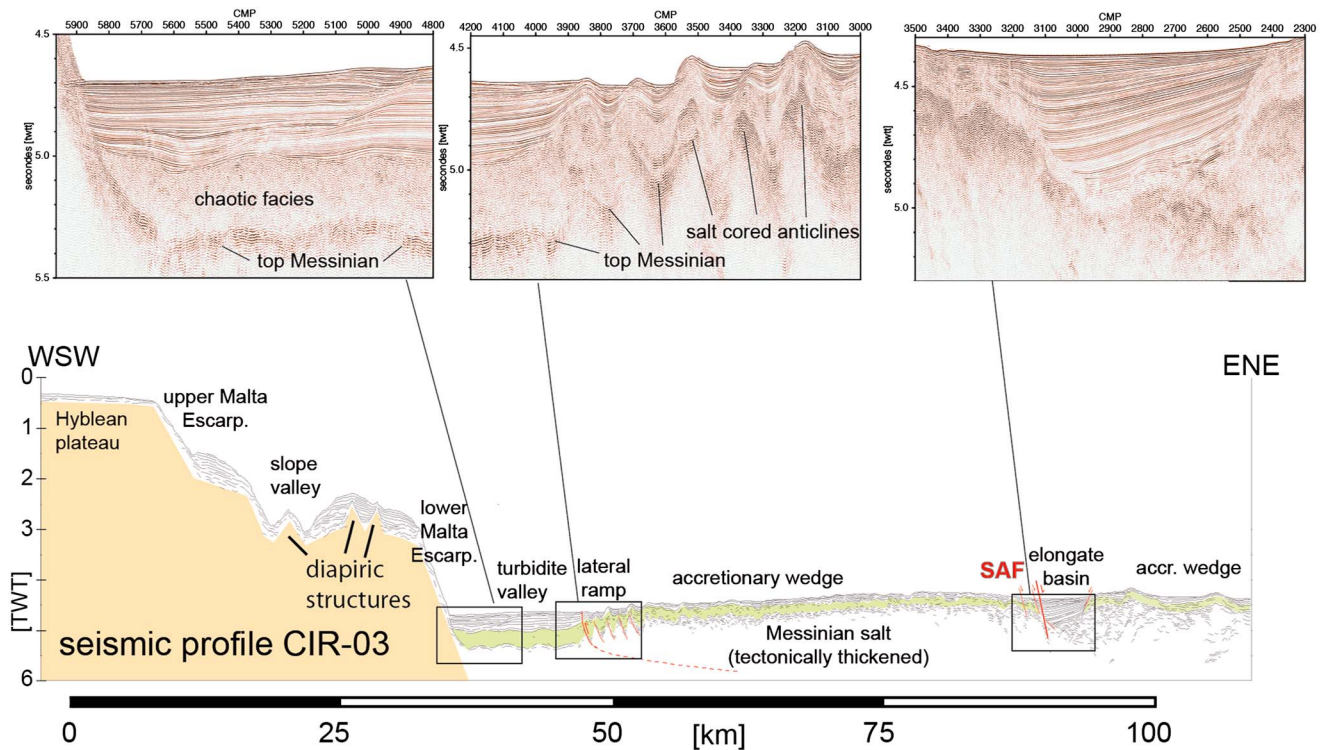
The morphology east of the broad turbidite valley is irregular and rugose in general but has certain clearly identifiable structural patterns. The region immediately east is mostly dominated by N170° to N140° trending subparallel ridges, typically spaced 0.5–2 km apart and which locally curve into a lobe-like pattern (e.g., at 36°45'N and between 36°20'N and 36°30'N) (Figure 2). A small but striking feature which emerges from this gently folded pattern is a morphologic high named Alfeo Seamount and known from Italian dredging work in the 1970s to contain shallow platform carbonate rocks, which suggests a continental affinity [Argnani and Bonazzi, 2005]. Steep, linear scarps bound Alfeo Seamount on three out of four sides, the steepest located on its west side where a narrow linear graben feature is observed. Beginning directly east of Alfeo Seamount and extending to the SSE is an elongate basin, 60 km long, 5 km wide, oriented N150° which ends abruptly at 36°24'N. East of this elongate basin, a series of subparallel NE-SW trending ridges, spaced about 2–3 km apart is observed and extends to the eastern limit of our mapped area. The narrowly spaced (~1 km) N160° trending ridges and troughs, as well as the 2–3 km spaced NE-SW oriented ridges are located within the tectonic domain known as the Calabrian accretionary wedge [Polonia *et al.*, 2011; Gallais *et al.*, 2012] and have a structural pattern consistent with compressional folding. Two zones of tightly spaced folds seem to wrap around Alfeo Seamount and form two distinct lobes. The structural pattern at the northern and eastern limits of our mapped area, within the accretionary wedge, is generally rugged and chaotic, though local basins (including a roughly 5 × 8 km subcircular basin) and submarine channels are present. East of the elongate basin, fold axes are oriented primarily NE-SW, nearly orthogonal to fold axes west of the basin.

### 3.2. High-Resolution Multichannel Seismic Profiles

Five multichannel seismic profiles, oriented ENE-WSW and crossing the morphostructural domains described above are presented here (Figures 4–6). They allow a better understanding of the tectonic and sedimentary processes that shaped the morphotectonic provinces. The southernmost profile, CIR-03 (Figure 4) begins on the Hyblean platform, where well-laminated, undeformed reflectors are observed. The rugged 3.5 km high drop of the Malta Escarpment is crossed in two half steps, with a prominent midslope valley overlain by 0.5–0.8 s TWT (Two Way Travel time) of slope sediments. Three enigmatic diapiric structures are observed here, which may be serpentine diapirs related to the transform margin origin of the Malta Escarpment. Nearby, in outcrops onshore in SE Sicily, serpentine-rich mud diapirs have been reported [Barreca, 2014]. At the foot of the Malta Escarpment three separate seismic units can be identified. The shallowest unit consists of 0.4 s TWT thick, finely laminated, horizontal to slightly undulating strata, typical of turbiditic infill. Next is a nearly transparent unit, about 0.3 s TWT thick with a chaotic seismic facies. Below this are a series of about 0.1–0.2 s thick strong, subhorizontal, but slightly discontinuous reflectors. This seismic pattern is well known throughout the Mediterranean and in particular here in the Ionian Sea to mark the top of the Messinian evaporites [Lofi *et al.*, 2011; Gallais *et al.*, 2011, 2013].

On its eastern side, the broad turbidite valley ends, where tightly spaced sinusoidal folds appear affecting the top Messinian reflector and the Plio-Quaternary strata above (Figure 4). The boundary between the folded and unfolded strata forms the lateral ramp of the accretionary wedge. Although this fault appears as a blind thrust (not directly cutting through to the seafloor), it affects even the most recently deposited turbidite sediments and thus appears to be active. The central part of the profile is dominated by these evenly spaced salt-cored anticlines, comprising the external (evaporitic) part of the Calabrian accretionary wedge as described previously [Finetti, 1982; Polonia *et al.*, 2011; Gallais *et al.*, 2012, 2013].





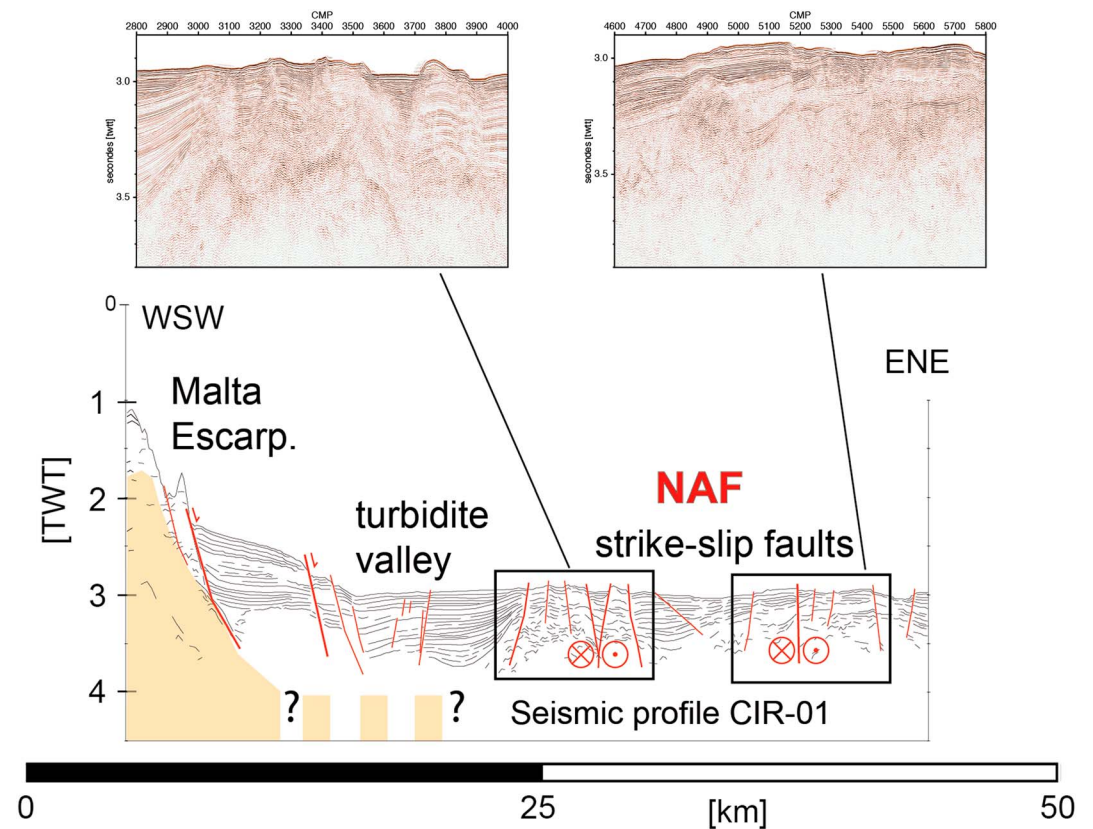
**Figure 4.** Seismic line CIR-03. Line drawing showing continental basement (orange shading); the Pliocene unit with a transparent, chaotic seismic facies (light green shading), representing post-Messinian detritic infill; and major interpreted faults (red lines with sense of motion). Boxes show zooms of the original 72 channel seismic data.

In the eastern portion of the profile, a remarkable deep narrow basin is observed (Figure 4). Well-laminated and gently west dipping reflectors are observed providing evidence of syntectonic sedimentation (tilting and fanning of the strata) with a thickness of about 500 m (0.6 s TWT). The basin is bounded by a master normal fault on the WSW side, though at a very fine scale, steeply dipping subfaults can be observed on both sides of this half-graben. The sense of motion appears to be predominantly normal, though some strike-slip component (transensional deformation) cannot be excluded. The eastern end of the profile ends in a much more gently undulating domain, consistent with folding in the main Calabrian accretionary wedge. Here the mean fold spacing appears much larger (10 km) though the anticlinal ridges are cut rather obliquely and the true spacing is closer to 2 or 3 km.

The northernmost seismic line CIR-01 (Figure 5 and Figure S1 in the supporting information) begins on the midslope offshore Augusta where 0.5–0.7 s TWT of well-laminated and gently dipping reflectors are imaged and represent slope sediments. On the midslope and at the base of the Malta Escarpment, where the observed sediment thickness increases slightly to 0.8 s TWT, the strata are crosscut and slightly tilted by a network of two major and several minor faults. These faults all show a predominantly normal sense of motion. Farther east (Figure 5, zooms) a series of tightly spaced, steeply dipping faults is observed, showing alternating normal and reverse motion. These resemble transpressional and transtensional flower structures common in strike-slip environments.

Between these two lines, three other high-resolution seismic profiles were acquired making a total set of five lines roughly orthogonal to the East Sicily Margin. All lines are displayed together as line drawings below (Figure 6) and are shown individually as seismic sections in the supporting information (Figures S1–S5). Taken together, these profiles illustrate nicely the juxtaposition of the morphotectonic domains and the major bounding faults in the study area and how several structures converge in the north (Figure 6).

The southern seismic reflection profiles (CIR-03 and CIR-04) distinctly image three tectonic elements separated by distances of 10–40 km: the base of the Malta Escarpment, the lateral ramp of the accretionary wedge, and the deep, narrow (5 km wide) basin marked by normal faults (Figures 4, S4, and S5). Farther north these three structures become progressively more tightly spaced and nearly overlap (profiles CIR-05 and CIR-07,



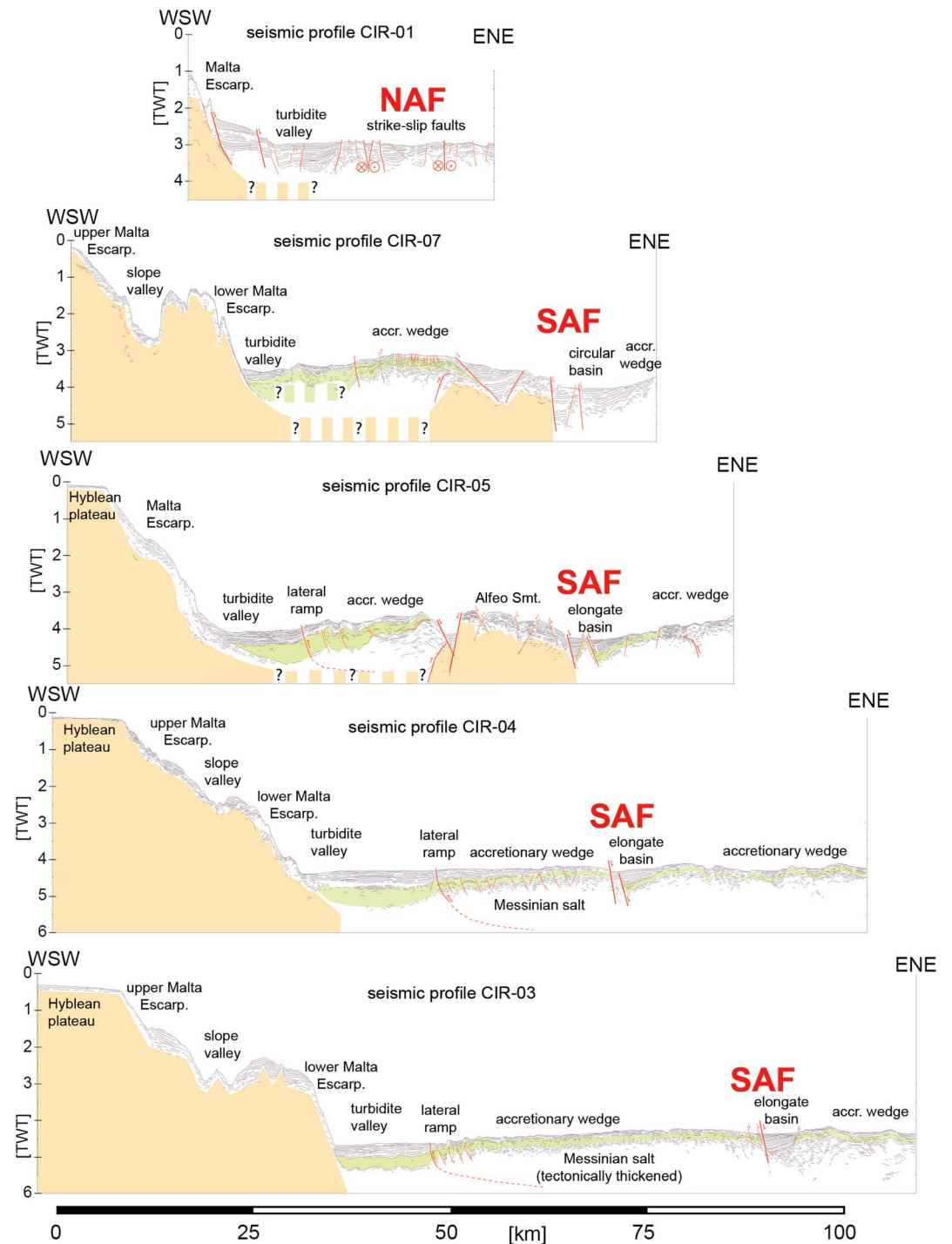
**Figure 5.** Seismic line CIR-01. Line drawing showing continental basement (orange shading, dashed when uncertain); and major interpreted faults (red lines with sense of motion). Boxes show zooms of the original 72 channel seismic data.

Figures 6, S2, and S3). The deep narrow basin, with syntectonic sedimentation thickens from about 500 m (0.6 s TWT) in the south, to 800 m (1.0 s TWT) in the north. The seismic profiles commonly show one or two closely spaced master normal faults on the WSW side, which control the generally WSW dip of the growth strata (Figure 4, zoom at bottom right). This deep, narrow basin imaged in the three southern profiles (CIR-03, CIR-04, and CIR-05) coincides spatially with the 60 km N150° trending elongate basin and for the next profile north (CIR-07) with the circular basin (Figures 3 and 6). Earlier seismic studies had already mapped normal faulting here [Cernobori *et al.*, 1996; Nicolich *et al.*, 2000; Polonia *et al.*, 2011; Gallais *et al.*, 2013]. However, the associated elongate syntectonic basin imaged by our new bathymetric data (Figure 3) was unmapped. In the northernmost profile (CIR-01) this syntectonic basin is absent and the central and eastern part of the profile is dominated by a network of tightly spaced steep-dipping faults, offsetting the seafloor, resembling a transtensional strike-slip fault system (Figures 5 and S1).

The seismic profiles image the top of the Messinian evaporites at the foot of the Malta Escarpment and within the outer lobe of the accretionary wedge (Figure 6). Previous deep seismic surveys showed that Messinian evaporites form the basal detachment of the external Calabrian accretionary wedge [Minelli and Faccenna, 2010; Polonia *et al.*, 2011; Gallais *et al.*, 2012]. Above the evaporites, there is a nearly transparent layer about 250–300 m thick (0.3 s TWT) with a chaotic facies, and above this a 0.3–0.5 s TWT thick, highly reflective, well-stratified Plio-Quaternary turbiditic series, with some internal sedimentary structure.

These seismic profiles and the morphobathymetry of the seafloor reveal two kinematically distinct fault segments: an 80 km long southern segment, the South Alfeo Fault (SAF) with primarily down to the east normal faulting, and a set of previously unmapped, en echelon strike-slip faults extending from a circular basin in a roughly N50°W direction toward Mount Etna, the North Alfeo Fault (NAF) system (Figure 3) with a cumulative length of about 60 km. This latter fault system appears to connect to a 15 km long strike-slip fault on the continental slope offshore east Sicily, which in turn links to a system of dextral strike-slip faults on the SE flank of Mount Etna [Chiocci *et al.*, 2011].





**Figure 6.** Line drawings of five seismic profiles acquired perpendicular to the East Sicily margin (for location see Figure 3) showing continental basement (orange shading, dashed when uncertain); the Pliocene unit with a transparent, chaotic seismic facies (yellow-green shading), representing post-Messinian detritic infill; and major interpreted faults (red lines with sense of motion).

## 4. Discussion

### 4.1. Malta Escarpment

The activity of the Malta Escarpment has long been a subject of debate [Argnani and Bonazzi, 2005; Argnani, 2009; Argnani, 2014]. We interpret the chaotic facies layer at the foot of the escarpment (green layer in

Figures 4 and 6) as Pliocene detritic infill after the Messinian salinity crisis, when sea level was ~1500 m lower than today. During the reflooding event, extensive mass wasting from the exposed continental shelf edges must have occurred filling the broad trough between the foot of the escarpment and the approaching and rapidly growing accretionary wedge.

In the southern part of our study area, the top Messinian reflector, the chaotic facies layer, and the overlying turbiditic sediments are perfectly horizontal and undisturbed (profiles CIR-03 and CIR-04), implying no significant reactivation of the Malta Escarpment here since the late Messinian (5.2 Ma) (Figure 4). In the northernmost profile (CIR-01) there are two major and a set of minor normal faults bounding and crosscutting the sedimentary basin at the foot of the escarpment in agreement with earlier interpretations of normal faulting here [Argnani and Bonazzi, 2005; Argnani, 2009; Argnani et al., 2012] (Figures 5 and S1). The Malta Escarpment is not currently active along its entire length but only shows signs of recent normal faulting north of Syracuse.

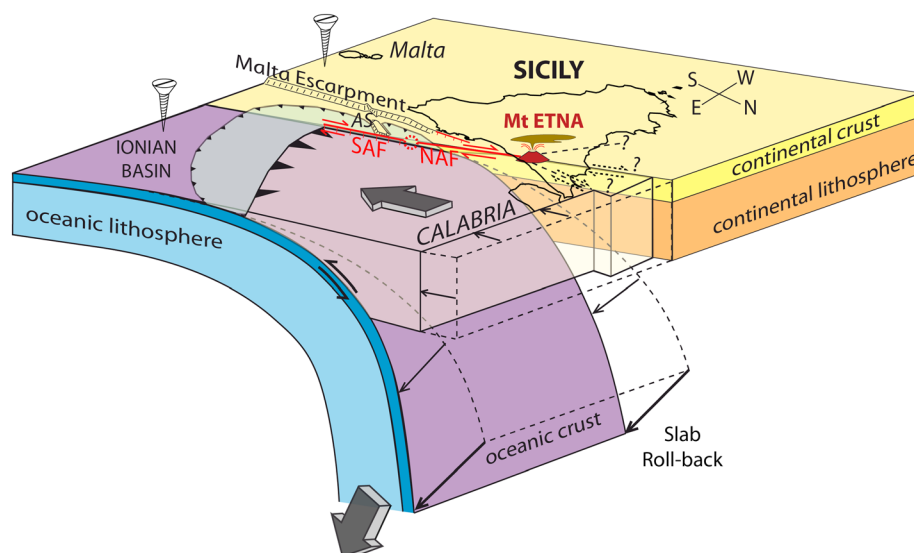
#### 4.1.1. Lateral Ramp and Lateral Lobe of the Accretionary Wedge

As noted in section 1, the lateral ramp of the accretionary wedge was poorly described until now. This work clearly images the lateral ramp in the three southern seismic profiles and somewhat less clearly in line CIR-07 (the secondmost northerly profile) (Figure 6). The lateral ramp forms the eastern boundary of the broad turbidite valley, which is filled with abundant sediment waves (Figures 2 and 3). To the west of Alfeo Seamount there is a V-shaped domain about 50 km (N-S) by 15–30 km wide (E-W) (Figure 3) and marked by more than a dozen anticlinal folds, as imaged on seismic profiles CIR-05 and CIR-07 (Figure 6). This structural domain has all the same characteristics as the outer (evaporitic) Calabrian accretionary, and we interpret it as a lateral lobe of the evaporitic accretionary wedge that has been isolated from the rest of the accretionary wedge. This has been achieved via two processes: first, the insertion into a formerly sheltered domain between Alfeo Seamount and the Malta Escarpment and second, the isolation and separation by translation of the remaining part of the accretionary wedge along the NAF dextral strike-slip fault (see also below). This isolated lobe of the accretionary wedge (Figure 3) has not been previously described and represents an important structural element in this portion of the East Sicily margin that is distinct from the Malta Escarpment. The clear expression of the lateral ramp in the bathymetry (as a long sharp lineament with up to 10° slopes) suggests recent activity, since it would otherwise be rapidly buried by the sediment waves filling the turbidite valley (Figures 2 and 3).

#### 4.1.2. Surface Expressions of the STEP Fault

We interpret the two-part fault system (NAF and SAF) described above, as surface expressions of the STEP fault (Figure 7). These two fault systems are distinct from the Malta Escarpment, passing 10–50 km farther east over the majority of our mapped area (Figures 3 and 5). Southeast of Mount Etna, the NAF intersects the Malta escarpment and here normal faulting is observed. The strike-slip NAF system has a length of about 60 km (as mapped by our new data) with a possible prolongation of 30 km, 15 km mapped offshore [Chiocci et al., 2011] and 15 km flank faults on Mount Etna [Bonforte et al., 2011]. The dextral sense of motion we interpret for the NAF system is based partly on focal mechanisms of earthquakes for the offshore portion [Palano et al., 2012; Musumeci et al., 2014] (Figure 3). It is also based on structural interpretation of linear fault strands linked to transtensional (pull-apart) basins indicating dextral strike-slip kinematics (Figure 8). These detailed images show the fault strands crossing the broad turbidite valley, which serves as a channel for downslope transport of turbidity currents like the one triggered by the 1908 Messina (M7.2) earthquake, with associated submarine cable rupture [Ryan and Heezen, 1965]. The clear morphological expression of faults here testifies to ongoing tectonic activity. Farther to the NW, along the coast and in shallow water, field mapping and scuba diving studies have shown dextral offsets in young basalt flows [Chiocci et al., 2011]. Finally, a set of NW-SE trending dextral strike-slip faults on the SE flank of Mount Etna are known from interferometric synthetic aperture radar (InSAR) studies and may represent the NW termination of this segment [Bonforte et al., 2011].

Previous workers have proposed a variety of fault traces in the study area and offered contrasting interpretations for the surface expression of the lithospheric tear or STEP fault. The two most common interpretations are along the Malta Escarpment [Argnani and Bonazzi, 2005; Argnani et al., 2012; Argnani, 2014] or faults located farther east in the vicinity of our NAF system [Chamot-Rooke et al., 2005; Polonia et al., 2011; Gallais et al., 2013]. The fault maps proposed by these previous studies have been compiled in order to compare to our new structural interpretation (Figure 9). As can be seen, in all these previous publications, the interpreted faults and the proposed surface expression of the STEP fault were normal faults. Our results show



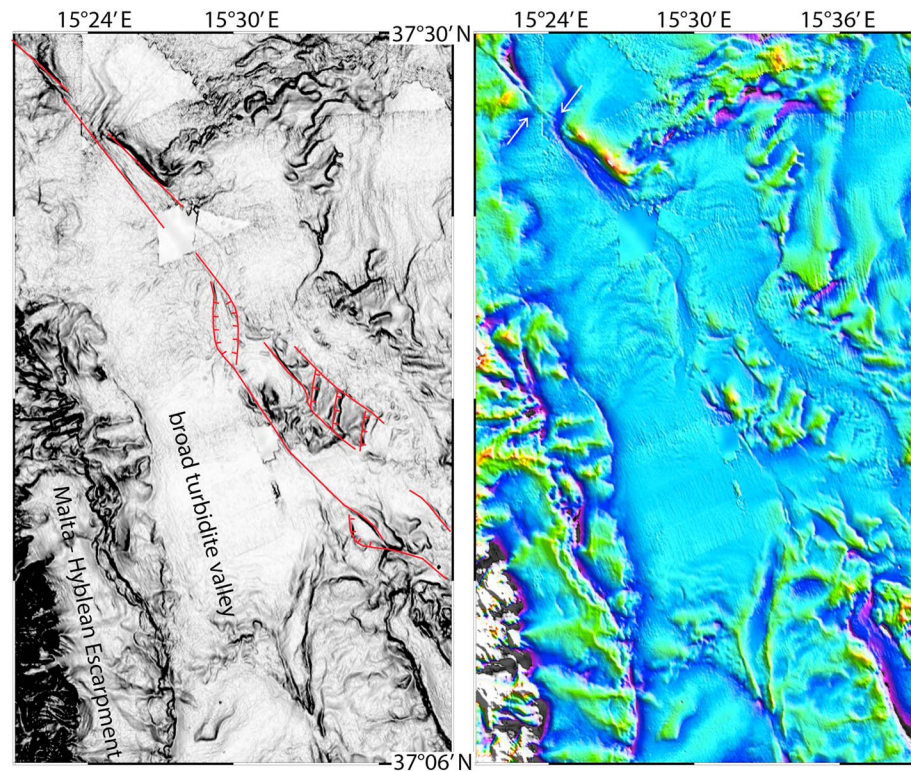
**Figure 7.** Schematic block diagram (view looking SW) of the Sicily-Calabria area showing the regional kinematics and fault activity related to the STEP. Slab rollback induces a SE advance of the Calabrian-Peloritan block driving shortening in the external Calabrian accretionary wedge (light green shading). The Ionian oceanic slab progressively detaches from the adjacent Malta-Sicily (Hyblean) continental lithosphere. An isolated lobe of the accretionary prism has been inserted between a small continental horst (AS-Alfeo Seamount) and the Malta escarpment. Note the mostly normal faulting SAF = South Alfeo Fault system which veers (at the red dashed circle, representing the circular basin) into the strike-slip NAF (North Alfeo Fault system) extending directly to Mount Etna. The volcano sits atop the lithospheric tear fault and asthenospheric window [Gvirtzman and Nur, 1999]. The continuation of the STEP fault north of Mount Etna is uncertain and three possible prolongations are shown schematically here.

three parallel, N160°E striking normal faults reactivating the base of the Malta Escarpment north of Syracuse, in good agreement with the active faults mapped here by earlier studies [Nicolich *et al.*, 2000—their faults F3, F4, and F5] (Figure 9c) [Argnani and Bonazzi, 2005; Argnani, 2009; Argnani *et al.*, 2012; Minelli and Faccenna, 2010] (Figure 9d), though our detailed bathymetry allows the fault traces to be followed more accurately toward the south where they merge. Our newly mapped and roughly N130°E oriented, dextral strike-slip NAF system was not reported previously. All prior work had one or several N150°E trending normal faults in this area, most commonly following the fault F6 (Figure 9c) [Nicolich *et al.*, 2000]. Our N150°E trending SAF system is located close to previously identified normal faults [Nicolich *et al.*, 2000; Minelli and Faccenna, 2010; Polonia *et al.*, 2011, 2012; Gallais *et al.*, 2013], though there are common shifts of 5–10 km in location and a few degrees in strike. The most novel aspects of the SAF system are the newly mapped associated elongate basin imaged in the bathymetry and the interpretation of large-scale dextral displacement along this boundary. Other limits that were poorly constrained or even unmapped in earlier work include the outer deformation front of the evaporitic (external) Calabrian accretionary wedge, the lateral ramp, and the isolated (evaporitic) lobe of the accretionary wedge (Figure 9).

#### 4.2. Seismic Hazard

Considering the length of the two identified fault systems offshore eastern Sicily (60 km long NAF and 80 km SAF), empirical scaling relationships suggest that each of these could be capable of generating magnitude 6.5–7 earthquakes [Wells and Coppersmith, 1994]. This corresponds well to the estimated magnitudes of several large historical earthquakes in eastern Sicily; 1693 ( $M7.4$ ), 1542 ( $M6.6$ ), and 1169 ( $M6.6$ ) [Jenny *et al.*, 2006]. Given that the 1693 earthquake produced a major tsunami with 5–10 m high waves, a strike-slip origin seems unlikely and indeed some workers argue in favor of a major normal fault along the Malta Escarpment [Piatanesi and Tinti, 1998]. It has also been suggested that this powerful  $M7.4$  earthquake occurred on the subduction fault plane [Gutscher *et al.*, 2006], which would be consistent with historical reports of an extremely long shaking duration of 4 min [Bonajutus and Malpighius, 1694]. Interestingly, on 9 January 1693, two days before the  $M7.4$  event, a magnitude 6.2 earthquake struck causing damage in eastern Sicily, apparently a foreshock. An intriguing hypothesis proposed here is that the  $M6.2$  earthquake may have occurred on



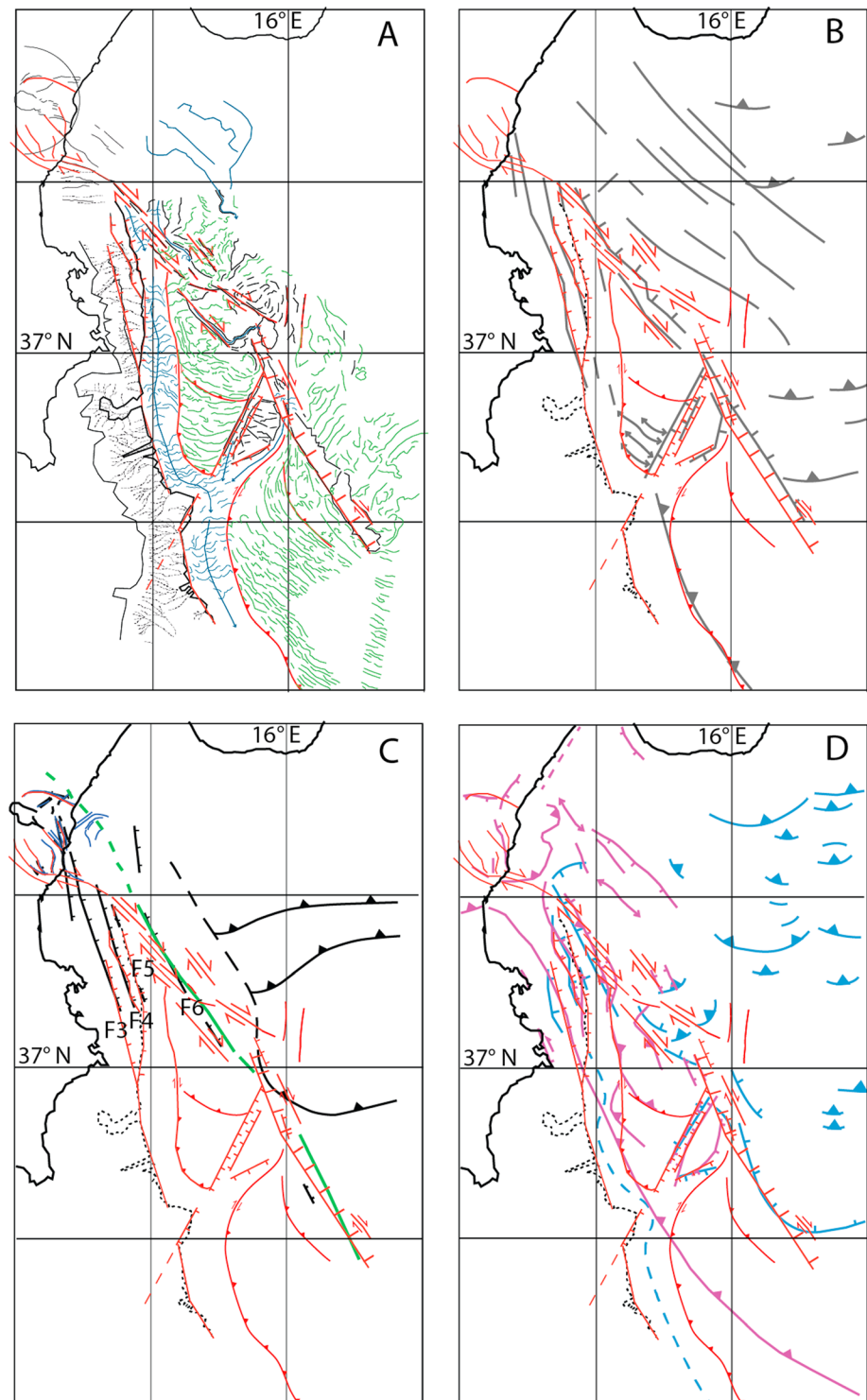


**Figure 8.** Zoom of bathymetry at the northern end of the NAF system. (left) Slope map (in black and white), (right) Residual bathymetric map (after filtering and removing a regional trend for long wavelength relief). Several of the NAF strands connect to small transensional (pull-apart) basins indicating dextral strike-slip kinematics. Note that the NAF crosses the broad turbidite channel and offsets a submarine canyon (see white arrows).

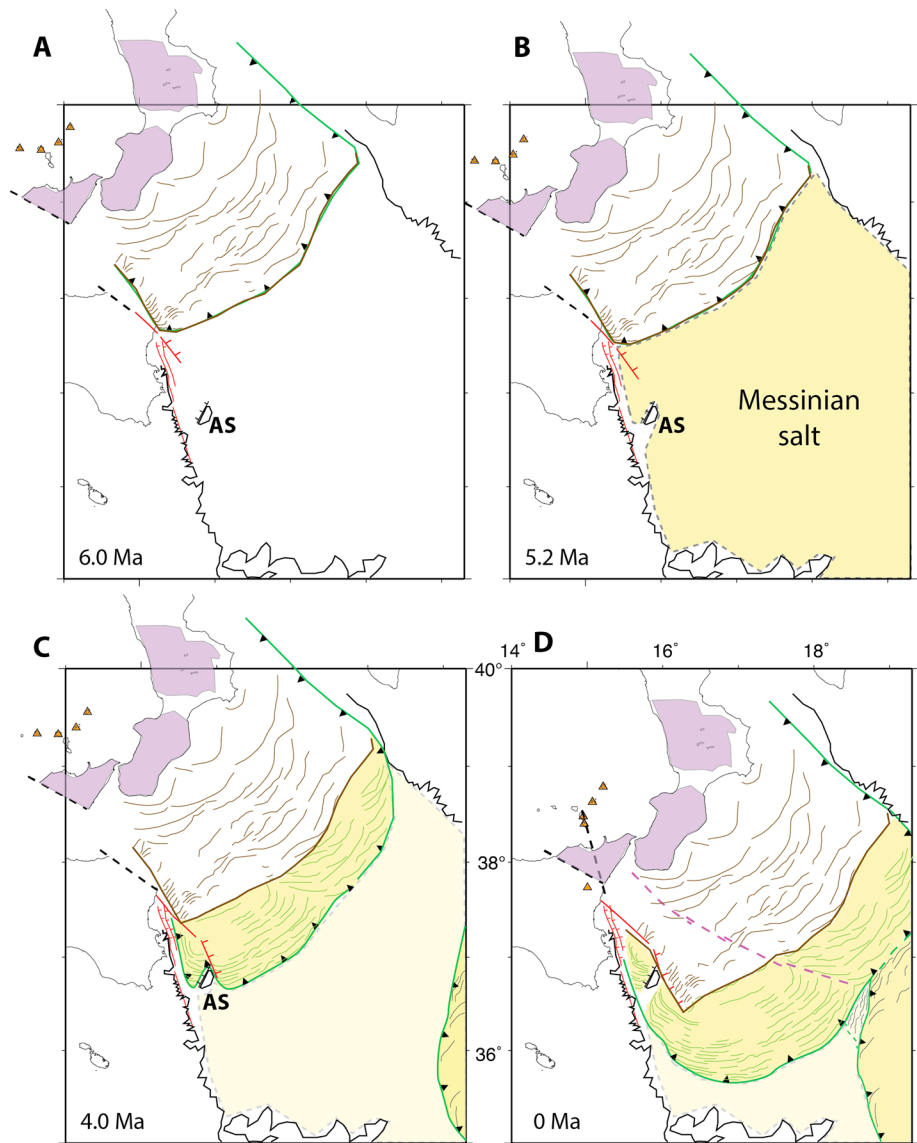
one segment of the lateral slab tear, thereby liberating the subduction fault plane to slip a few days later. Unfortunately, our knowledge of historical earthquakes is seriously hampered by the lack of instrumental observations and thus it is difficult to impossible to reconstruct focal mechanisms. Given the slow fault slip rates (a few mm/yr) and long characteristic return intervals (several centuries) for earthquakes in southern Italy, additional observations are necessary to improve the regional hazard assessment. These could include paleoseismological work to extend the earthquake record back in time and more detailed geodetic work to better constrain the current strain field and to clarify the regional kinematics.

#### 4.2.1. Kinematics of the Calabrian Arc System

Until now, while there was wide disagreement on the exact location of the STEP fault offshore eastern Sicily [Orecchio *et al.*, 2014], most authors agreed that the surface expression would be one or several major normal faults [Polonia *et al.*, 2011; Argnani *et al.*, 2012; Gallais *et al.*, 2013; Argnani, 2014]. A major strike-slip fault, as reported here (the NAF system) was not expected. However, kinematically, large-scale strike-slip movements are predicted along a STEP fault between the advancing upper plate block and the adjacent upper plate [Govers and Wortel, 2005]. There is a broad consensus that the Tyrrhenian Sea basin formed mostly after 6 Ma and that the southeastern Tyrrhenian Sea formed primarily during the Pleistocene, when the Upper Miocene-Pliocene rifting migrated from the central Tyrrhenian Sea (Vavilov basin) toward the SE (Marsili basin) as confirmed by deep-sea drilling [Sartori, 1990] and dating of basalts [Marani and Trua, 2002]. Thus, the Calabrian-Peloritan block must have been displaced by several hundred kilometers as indicated in most plate kinematic reconstructions [Faccenna *et al.*, 2001, 2004; Rosenbaum *et al.*, 2002; Jolivet *et al.*, 2006]. On the basis of our newly mapped faults, we propose here a kinematic reconstruction of the Sicily-Calabria-Ionian Sea region since 6 Ma (Figure 10). This reconstruction offers a plausible explanation for the abrupt change in strike direction of compressional anticline fold axes east and west of the elongate basin. The accretionary wedge west of the elongate basin consists of the external evaporitic post-Messinian wedge, with fold axes aligned generally parallel to the external deformation front (green lines in Figures 10c and 10d). On the other hand, the portion of the accretionary wedge east of the elongate basin represents the internal clastic pre-Messinian wedge



**Figure 9.** Compilation of all major published fault maps for the East Sicily margin. (a) Simplified morphological interpretation and tectonic map from this study (same color code as inset to Figure 3), with primary interpreted active faults shown in red (the dashed line in the remaining three panels marks the base of the Malta Escarpment); (b) gray lines [Polonia *et al.*, 2011, 2012] NB, lines without symbols are described as “normal faults from Chamot-Rooke *et al.* [2005]”, red lines, faults from this study. (c) Black lines [Nicolich *et al.*, 2000], dark blue lines [Chiocci *et al.*, 2011], and dark green line show an interpreted trace of the STEP fault [Gallais *et al.*, 2013]; red lines, faults from this study. (d) pink lines [Argnani and Bonazzi, 2005; Argnani, 2009; Argnani *et al.*, 2012] and light blue lines [Minelli and Faccenna, 2010] with the outer deformation front shown as a dashed line, red lines, faults from this study.



**Figure 10.** Kinematic reconstruction of the Sicily-Calabria-Ionian Sea region since 6 Ma showing (a) at 6.0 Ma, the pre-Messinian (clastic) accretionary wedge developed in front of the advancing Calabro-Peloritan block, (b) at 5.2 Ma, at the end of the Messinian salinity crisis a thick layer of evaporites was deposited in the large Ionian abyssal plain, (c) at 4.0 Ma, the construction of a large evaporitic accretionary wedge in front of the internal pre-Messinian (clastic) wedge, the evaporite wedge is wrapping around Alfeo Seamount (AS) which acts as an indenter; note that the Ionian abyssal plain is diminishing in size and the West Mediterranean Ridge appears (moving to the west and SW), (d) at 0 Ma, the present day situation, with a large-scale dextral offset between the internal (clastic) wedge and lateral (western) portions of the evaporitic wedge stranded between Alfeo Seamount and the Malta Escarpment. The Ionian abyssal plain is greatly reduced in size as the Calabrian and West Mediterranean Ridge accretionary wedges collide and intersect.

(tightly spaced brown lines in Figure 10, see also Figure 3). While the exact limit between the external evaporitic and internal clastic wedges is not perfectly well constrained, there is general agreement that it is located here as mapped by previous authors [Minelli and Faccenna, 2010, Figure 4 and Figure 11, inset; Polonia *et al.*, 2011, Figure 13; Ceramicola *et al.*, 2014, Figure 1 inset]. An industry seismic profile images this boundary between the clastic and evaporitic wedges coinciding to the edge of the elongate basin [Minelli and Faccenna, 2010]. This limit is also confirmed by velocity analysis of seismic reflection profiles crossing this boundary [Gallais *et al.*, 2013]. The resulting large dextral displacement of the internal clastic wedge allows us to reconcile the conflicting orientations of fold axes east and west of the elongate basin (the SAF) and offers a simple, elegant explanation why the evaporitic post-Messinian wedge ends abruptly along this structure. It does,



however, require large dextral displacement, which is not directly observed in the seismic profiles, though the long narrow trough (elongate basin) bounded by normal (or transtensional) faults on both sides is a characteristic feature of strike-slip environments.

## 5. Conclusions

New, high-resolution seismic profiles and detailed morphobathymetry of the seafloor reveal a two-part fault system, interpreted as the shallow tectonic expression of a lithospheric scale lateral slab tear (STEP fault); the 80 km long South Alfeo Fault (SAF) system with primarily down-to-the-east normal faulting (and possibly large dextral strike-slip displacement) and the 60+ km long, previously unknown North Alfeo Fault (NAF) system, striking N130°E and showing strike-slip kinematics. The NAF merges with known dextral strike-slip faults on the shallow continental slope offshore east Sicily and on the SE flank of Mount Etna. These active offshore faults are mechanically capable of generating magnitude 6–7 earthquakes and may be responsible for some enigmatic historical earthquakes.

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