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

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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.

Keywords : slab tear, subduction, Mediterranean, bathymetry, seismics, active faults

### 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 (~5mm/yr) (D'Agostino et al., 2011) and where narrow slabs sink down into the upper mantle causing roll-back and back-arc extension (Wortel and Spakman, 2000; Faccenna et al., 2004). Slab roll back can only occur if the small oceanic basin detaches itself from the adjacent (commonly continental) lithosphere along sub-vertical 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 towards the foreland due to slab roll back. Many consider the

50 Calabrian arc of southern Italy (Fig. 1) as the type example of a narrow, retreating slab 51 (Faccenna et al., 2004; Rosenbaum et al., 2002; 2008).

52 The geodynamic evolution of the Western Mediterranean and Italy was largely 53 controlled by a NW dipping subduction zone beneath southern France and Iberia, which 54 began around 35 Ma (Malinverno and Rvan, 1986; Jolivet and Faccenna, 2000). As the slab 55 of Tethys oceanic lithosphere between Africa and Europe retreated to the SE, it opened a 56 series of back-arc basins and left several small continental blocks in its wake (e.g. Corsica-57 Sardinia) (Faccenna et al., 2001; 2004; Rosenbaum et al., 2002). Tomographic studies of the 58 upper mantle image a steeply NW dipping slab descending beneath Calabria and the SE 59 Tyrrhenian Sea to depths of >500km and with a sharp SW boundary at depth below Mt. Etna 60 (Wortel and Spakman, 2000; Neri et al., 2009). Several workers have proposed a causal effect 61 between the lateral slab tear, creating an asthenospheric window and enhancing toroidal flow 62 in the upper mantle and the presence of Mount Etna in northeastern Sicily (Gvirtzman and 63 Nur, 1999; Faccenna et al., 2011). Today most of the oceanic lithosphere has been consumed 64 and there remains at most a narrow corridor (150 km to 300 km wide) connecting the oceanic 65 domain of the Ionian Sea to the slab observed beneath the SE Tyrrhenian Sea (Wortel and 66 Spakman, 2000; Neri et al., 2009; Giacomuzzi et al., 2012).

67 The combination of NW-directed subduction and the SE-ward advance of the 68 Calabrian-Peloritan block drove shortening and thusting in the thick layers of marine 69 sediments within the Ionian Sea, leading to the construction of a large accretionary wedge 70 imaged by deep seismic reflection lines (Finetti, 1982; Cernobori et al., 1996; Nicolich et al., 71 2000; Minelli and Faccenna, 2010). A broad belt of undulating seafloor occupies a gentle 72 slope down to the Ionian abyssal plain and is characterized by anticlinal ridges as seen in 73 high-resolution seismic profiles and bathymetry (Hieke et al., 2005; Gutscher et al., 2006; 74 Loubrieu et al., 2007). Some researchers interpreted this compressional deformation as caused 75 by regional gravitational sliding (Chamot-Rooke et al., 2005). However, more recent studies 76 have concluded that deformation in this outer Calabrian arc is caused by large-scale 77 compression affecting the Plio-Quaternary and Messinian sediments above a decollement at 78 the base of the Messinian (Polonia et al., 2011; Gallais et al., 2012). While the position of the 79 outer deformation front in the Ionian abyssal plain is well documented by seismic profiles and 80 existing bathymetric compilations (Loubrieu et al., 2007; Polonia et al., 2011; Gallais et al., 81 2012), the position of the lateral ramp offshore eastern Sicily is largely uncertain and has been 82 interpreted in a wide range of locations by different workers (Chamot-Rooke et al., 2005; 83 Minelli and Faccenna, 2010; Polonia et al., 2011; Gallais et al., 2012; 2013).

84 According to available geodetic data, there is slow, but significant convergence ( $\geq 3$ 85 mm/yr) occurring between the Hyblean platform (SE Sicily) and NE Sicily (the Peloritan 86 Mountains domain) and slow (3-5 mm/yr) SE-ward motion of the Calabrian block with 87 respect to the Apulian and Hyblean domains (D'Agostino et al., 2011; Devoti et al., 2011; 88 Palano et al., 2012). These authors attribute most of this motion to the Calabria subduction, 89 with roll-back of the Ionian slab inducing SE-ward motion of the Calabria - Peloritan block. 90 However, Sicily itself and the neighboring regions appear to be composed of a mosaic of 91 micro-blocks with slow moving, but complex kinematics (Serpelloni et al., 2010).

92 Researchers have been seeking for the lithospheric scale tear fault associated with 93 subduction roll-back, presumably located offshore eastern Sicily, since it was first suggested 94 (Gvirtzman and Nur, 1999; Orecchio et al., 2014). Many have proposed the Malta Escarpment 95 to be the active tear fault, primarily due to its striking morphological expression as a 3 - 4 km 96 high step on the seafloor (Argnani and Bonazzi, 2005; Govers and Wortel, 2005; Argnani, 97 2009; Argnani et al., 2012). The Malta Escarpment is widely considered to be an ancient 98 Tethyan passive margin formed by rifting in the Mesozoic (or earlier) (Catalano et al., 2000; 99 Nicolich et al., 2000; Frizon de Lamotte et al., 2011; Gallais et al., 2013). Several studies

100 have reported active normal faulting on the northern portion of this escarpment (Argnani and 101 Bonazzi, 2005; Argnani, 2009; Argnani et al., 2012). Other researchers have identified major 102 normal faults imaged in seismic profiles further east and interpreted these as the tear fault 103 (Cernobori et al., 1996; Nicolich et al., 2000; Polonia, et al., 2011; Gallais, et al., 2013) (Fig. 104 1). The exact geometry and degree of activity of the network of faults offshore Sicily in the 105 Ionian Sea remain uncertain and highly controversial (Argnani 2014; Gallais et al., 2014; 106 Orecchio et al., 2014). These faults pose a significant seismic and tsunami hazard in this 107 region where nearly 200,000 deaths have occurred over the past 5 centuries (Jenny et al., 108 2006). However, the sources of many of these earthquakes and tsunamis remain unknown or 109 disputed to this day (Piatanesi and Tinti, 1998; Gutscher et al., 2006; Argnani et al., 2012; 110 Aloisi et al., 2013), with some workers arguing for a contribution from submarine landslides 111 in some cases (Billi et al., 2008; 2010). There is no consensus on the surface expression of the 112 STEP fault and its trace through eastern and northern Sicily is uncertain (Fig. 1) (Orecchio et 113 al., 2014). The objective of this study is to map active faults offshore eastern Sicily which 114 may pose a seismic hazard and to identify the tectonic expression of the lateral slab tear or 115 STEP in the Ionian Sea.

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117 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 450m long, 72-channel Sercel seismic streamer with an average geophone spacing of 6.25m and towed 150m behind the vessel. The seismic source was a 6 GI airgun array with a total volume of 111 cubic inches fired at a cadence of once every 6 sec, for an average shot spacing of 16 m and a 24-fold coverage for each Common Mid Point. 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 (Fig. 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 - 30m. The Simrad echosounder software automatically performs an initial quality control, which flags doubtful data. Thereafter, swaths of pings are re-processed 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 seconds (about 60m).

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137 Results

The seismic and bathymetric data were used to probe several morpho-tectonic 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 (Figs. 2, 3).

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# 143 Morpho-bathymetry

The most striking feature in the bathymetry is the >150 km long, Malta-Hyblean Escarpment (Figs. 2, 3), which over a lateral distance of 20-30 km marks the transition from the Hyblean continental platform (with shallow water carbonates) on the west to a deep marine environment to the east with water depths of 3000 - 4000m. The slopes here are 10 -20° on average and can locally reach 30° (Fig. 2). The escarpment is deeply incised by submarine canyons, commonly running orthogonal to the escarpment and locally joining together to form large amphitheatre like structures (e.g. at  $36^{\circ}48^{\circ}N$ ). This incision may be in large part due to erosion during the Messinian salinity crisis when sea level was approximately 1500m lower than today (Lofi et al., 2011). Offshore SE Sicily (south of  $36^{\circ}30^{\circ}N$ ) the escarpment is highest (nearly 4000m) and most rugged. To the north between Syracuse ( $37^{\circ}$  00' N) and Augusta ( $37^{\circ}$  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 (Fig. 2).

156 At the foot of the Malta Escarpment is a 10 - 20 km wide, curvi-linear trough running 157 gently downslope to the south (Figs. 2, 3). This broad valley is marked by abundant sinusoidal 158 ridges and troughs, oriented roughly orthogonal to the downslope direction. They have a 159 characteristic spacing of 2 - 3 km and an average height of about 30m and represent deep-160 water sedimentary structures known as sediment waves (bedforms created either by 161 downslope-flowing turbidity currents or alongslope-flowing bottom currents in deep water 162 settings) (Wynn and Stow, 2002). Originating from gently sloping regions further east, some 163 smaller tributary channels and broad valleys (locally marked by sediment waves) join this 164 main N-S trending trough known hereafter as the "broad turbidite valley".

165 The morphology east of the broad turbidite valley is irregular and rugose in general, 166 but has certain clearly identifiable structural patterns. The region immediately east is mostly 167 dominated by N170° to N140° trending subparallel ridges, typically spaced 0.5 - 2 km apart. 168 and which locally curve into a lobe-like pattern (e.g. at 36° 45'N and between 36°20'N and 169 36°30'N) (Fig. 2). A small but striking feature which emerges from this gently folded pattern 170 is a morphologic high named Alfeo Seamount and known from Italian dredging work in the 171 1970's to contain shallow platform carbonate rocks, which suggest a continental affinity 172 (Argnani and Bonazzi, 2005). Steep, linear scarps bound Alfeo Seamount on three out of four 173 sides, the steepest located on its W side where a narrow linear graben feature is observed. 174 Beginning directly east of Alfeo Seamount and extending to the SSE is an elongate basin, 60 175 km long, 5 km wide, oriented N150° which ends abruptly at 36° 24'N. East of this elongate 176 basin a series of sub-parallel NE-SW trending ridges, spaced about 2 - 3 km apart is observed 177 and extend to the eastern limit of our mapped area. The narrowly spaced (~1km) N160° 178 trending ridges and troughs, as well as the 2 - 3 km spaced NE-SW oriented ridges are located 179 within the tectonic domain known as the Calabrian accretionary wedge (Polonia et al., 2011; 180 Gallais et al., 2012) and have a structural pattern consistent with compressional folding. Two 181 zones of tightly spaced folds seem to wrap around Alfeo Seamount and form two distinct 182 lobes. The structural pattern at the northern and eastern limit of our mapped area, within the 183 accretionary wedge is generally rugged and chaotic, though local basins (including a roughly 184 5 x 8 km sub-circular basin) and submarine channels are present. East of the elongate basin 185 fold axes are oriented primarily NE-SW, nearly orthogonal to fold axes west of the basin.

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## 187 High-resolution multichannel seismic profiles

188 Five multi-channel seismic profiles, oriented ENE-WSW and crossing the morpho-189 structural domains described above are presented here (Figs. 4, 5, 6). They allow a better 190 understanding of the tectonic and sedimentary processes that shaped the morpho-tectonic 191 provinces. The southernmost profile, CIR-03 (Fig. 4) begins on the Hyblean platform, where 192 well-laminated, undeformed reflectors are observed. The rugged 3.5 km high drop of the 193 Malta Escarpment is crossed in two half-steps, with a prominent mid-slope valley overlain by 194 0.5 - 0.8 s TWT of slope sediments. Three enigmatic diapiric structures are observed here, 195 which may be serpentine diapirs related to the transform margin origin of the Malta 196 Escarpment. Nearby, in outcrops onshore in SE Sicily, serpentine-rich mud diapirs have been 197 reported (Barreca 2014). At the foot of the Malta Escarpment three separate seismic units can 198 be identified. The shallowest unit consists of 0.4 s TWT thick, finely laminated, horizontal to 199 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, sub-horizontal, 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).

204 On its eastern side, the broad turbidite valley ends, where tightly spaced sinusoidal 205 folds appear affecting the top Messinian reflector and the Plio-Quaternary strata above (Fig. 206 4). The boundary between the folded and unfolded strata forms the lateral ramp of the 207 accretionary wedge. Although this fault appears as a blind-thrust (not directly cutting through 208 to the seafloor), it affects even the most recently deposited turbidite sediments and thus 209 appears to be active. The central part of the profile is dominated by these evenly spaced salt-210 cored anticlines, comprising the external (evaporitic) part of the Calabrian accretionary wedge 211 as described previously (Finetti, 1982; Polonia et al., 2011; Gallais et al. 2012; 2013).

212 In the eastern portion of the profile, a remarkable deep narrow basin is observed (Fig. 213 4). Well-laminated and gently W dipping reflectors are observed providing evidence of syn-214 tectonic sedimentation (tilting and fanning of the strata) with a thickness of about 500 m (0.6 215 s TWT). The basin is bounded by a master normal fault on the WSW side, though at a very 216 fine scale, steeply dipping sub-faults can be observed on both sides of this half-graben. The 217 sense of motion appears to be predominantly normal, though some strike-slip component 218 (transtensional deformation) cannot be excluded. The eastern end of the profile ends in a 219 much more gently undulating domain, consistent with folding in the main Calabrian 220 accretionary wedge. Here the mean fold spacing appears much larger (10km) though the 221 anticlinal ridges are cut rather obliquely and the true spacing is closer to 2 or 3 km.

The northernmost seismic line CIR-01 (Fig. 5 and Suppl. Fig. S1) 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 mid-slope and at the base of the Malta Escarpment, where the observed sediment thickness increases slightly to 0.8 s TWT, the strata are cross-cut and slightly tilted by a network of two major and several minor faults. These faults all show a predominantly normal sense of motion. Further east (Fig. 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 5 lines roughly orthogonal to the East Sicily Margin. All lines are displayed together as line drawings below (Fig. 6) and are shown individually as seismic sections in the supplemental materials (Figs. S1-S5). Taken together, these profiles illustrate nicely the juxtaposition of the morpho-tectonic domains and the major bounding faults in the study area and how several structures converge in the north (Fig. 6).

237 The southern seismic reflection profiles (CIR-03, and CIR-04) distinctly image three 238 tectonic elements separated by distances of 10 - 40 km: the base of the Malta Escarpment, the 239 lateral ramp of the accretionary wedge, and the deep, narrow (5 km wide) basin marked by 240 normal faults (Fig. 4 and Suppl. Figs. S4, S5). Further north these three structures become 241 progressively more tightly spaced and nearly overlap (profiles CIR-05 and CIR-07, Fig. 6 and 242 Suppl. Figs. S2, S3). The deep narrow basin, with syn-tectonic sedimentation thickens from 243 about 500 m (0.6 s TWT) in the south, to 800 m (1.0 s TWT) in the north. The seismic 244 profiles commonly show one or two closely spaced master normal faults on the WSW side, 245 that control the generally WSW dip of the growth strata (Fig. 4 and zoom at bottom right). 246 This deep, narrow basin imaged in the three southern profiles (CIR-03, 04 and 05) coincides spatially with the 60km N150° trending elongate basin, and for the next profile north (CIR-247 248 07) with the circular basin (Fig. 3 and Fig. 6). Earlier seismic studies had already mapped 249 normal faulting here (Cernobori et al., 1996; Nicolich et al., 2000; Polonia et al., 2011;

Gallais et al., 2013). However, the associated elongate syn-tectonic basin imaged by our new bathymetric data (Fig. 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 (Fig. 5 and Suppl. Fig. 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 (Fig. 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 0.3-0.5s TWT thick, highly reflective, wellstratified Plio-Quaternary turbiditic series, with some internal sedimentary structure.

262 These seismic profiles and the morpho-bathymetry of the seafloor reveal two 263 kinematically distinct fault segments: an 80 km long southern segment, the South Alfeo Fault 264 (SAF) with primarily down-to the east normal faulting and a set of previously unmapped, en-265 echelon strike-slip faults extending from a circular basin in a roughly N50°W direction 266 towards Mt. Etna, the North Alfeo Fault (NAF) system (Fig. 3) with a cumulative length of 267 about 60 km. This latter fault system appears to connect to a 15 km long strike-slip fault on 268 the continental slope offshore east Sicily, which in turn links to a system of dextral strike-slip 269 faults on the SE flank of Mt. Etna (Chiocci et al., 2011).

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271 Discussion

272 Malta Escarpment

The activity of the Malta Escarpment has long been a subject of debate (Argnani and Bonazzi, 2005; Argnani et al., 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.

280 In the southern part of our study area, the top Messinian reflector, the chaotic facies 281 layer, and the overlying turbiditic sediments are perfectly horizontal and undisturbed (profiles 282 CIR-03, and CIR-04), implying no significant reactivation of the Malta Escarpment here since 283 the late Messinian (5.2 Ma) (Fig. 4). In the northernmost profile (CIR-01) there are two major 284 and a set of minor normal faults bounding and crosscutting the sedimentary basin at the foot 285 of the escarpment in agreement with earlier interpretations of normal faulting here (Argnani 286 and Bonazzi, 2005; Argnani et al., 2009; Argnani et al., 2012) (Fig. 5 and Supppl. Fig. S1). 287 The Malta Escarpment is not currently active along its entire length, but only shows signs of 288 recent normal faulting north of Syracuse.

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290 Lateral ramp and lateral lobe of the accretionary wedge

291 As noted in the introduction, the lateral ramp of the accretionary wedge was poorly 292 described until now. This work clearly images the lateral ramp in the three southern seismic 293 profiles and somewhat less clearly in line CIR-07 (the second-most northerly profile) (Fig. 6). 294 The lateral ramp forms the eastern boundary of the broad turbidite valley, which is filled with 295 abundant sediment waves (Figs. 2, 3). To the west of Alfeo Seamount there is a V-shaped 296 domain about 50km (N-S) by 15-30 km wide (E-W) (Fig. 3) and marked by more than a 297 dozen anticlinal folds, as imaged on seismic profiles CIR-05 and CIR-07 (Fig. 6). This 298 structural domain has all the same characteristics as the outer (evaporitic) Calabrian 299 accretionary and we interpret it as a lateral lobe of the evaporitic accretionary wedge that has

300 been isolated from the rest of the accretionary wedge. This has been achieved via two 301 processes: first the insertion into a formerly sheltered domain between Alfeo Seamount and 302 the Malta Escarpment, and second the isolation and separation by translation of the remaining 303 part of the accretionary wedge along the NAF dextral strike-slip fault (see also below). This 304 isolated lobe of the accretionary wedge (Fig. 3) has not been previously described, and 305 represents an important structural element in this portion of the East Sicily margin that is 306 distinct from the Malta Escarpment. The clear expression of the lateral ramp in the 307 bathymetry (as a long sharp lineament with up to 10° slopes) suggests recent activity, since it 308 would otherwise be rapidly buried by the sediment waves filling the turbidite valley (Fig. 2, 309 3).

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# 311 Surface expressions of the STEP fault

312 We interpret the two-part fault system (NAF and SAF) described above, as surface 313 expressions of the STEP fault (Fig. 7). These two fault systems are distinct from the Malta 314 Escarpment, passing 10 - 50 km further east over the majority of our mapped area (Figs. 3, 5). 315 Southeast of Mt. Etna the NAF intersects the Malta escarpment and here normal faulting is 316 observed. The strike-slip NAF system has a length of about 60 km (as mapped by our new 317 data) with a possible prolongation of 30 km, 15 km mapped offshore (Chiocci et al., 2011) 318 and 15 km flank-faults on Mt. Etna (Bonforte et al., 2011). The dextral sense of motion we 319 interpret for the NAF system is based partly on focal mechanisms of earthquakes for the 320 offshore portion (Palano et al., 2012; Musumeci et al., 2014) (Fig. 3). It is also based on 321 structural interpretation of linear fault strands linked to transtensional (pull-apart) basins 322 indicating dextral strike-slip kinematics (Fig. 8). These detailed images show the fault strands 323 crossing the broad turbidite valley, which serves as a channel for downslope transport of 324 turbidity currents like the one triggered by the 1908 Messina (M7.2) earthquake, with 325 associated submarine cable rupture (Ryan and Heezen, 1965). The clear morphological 326 expression of faults here testifies to ongoing tectonic activity. Further to the NW, along the 327 coast and in shallow water, field mapping and scuba diving studies have shown dextral offsets 328 in young basalt flows (Chiocci et al., 2011). Finally, a set of NW-SE trending dextral strike-329 slip faults on the SE flank of Mount Etna are known from InSAR studies and may represent 330 the NW termination of this segment (Bonforte et al., 2011).

331 Previous workers have proposed a variety of fault traces in the study area and offered 332 contrasting interpretations for the surface expression of the lithospheric tear or STEP fault. 333 The two most common interpretations are along the Malta Escarpment (Argnani and Bonazzi, 334 2005; Argnani et al., 2012; Argnani 2014) or faults located further east in the vicinity of our 335 NAF system (Chamot-Rooke et al., 2005; Polonia et al., 2011; Gallais et al., 2013). The fault 336 maps proposed by these previous studies have been compiled in order to compare to our new 337 structural interpretation (Fig. 9). As can be seen, in all these previous publications, the 338 interpreted faults and the proposed surface expression of the STEP fault were normal faults. 339 Our results show 3 parallel, N160°E striking normal faults reactivating the base of the Malta 340 Escarpment north of Syracuse, in good agreement with the active faults mapped here by 341 earlier studies (Nicolich et al., 2000 - their faults F3, F4 and F5) (Fig. 9 C) (Argnani and 342 Bonazzi, 2005; Argnani et al., 2009; Argnani et al., 2012) (Minelli and Faccenna, 2010) (Fig. 343 9D), though our detailed bathymetry allows the fault traces to be followed more accurately 344 towards the south where they merge. Our newly mapped and roughly N130°E oriented, 345 dextral strike-slip NAF system was not reported previously. All prior work had one or several 346 N150°E trending normal faults in this area, most commonly following the fault F6 (Fig. 9C) 347 (Nicolich et al., 2000). Our N150°E trending SAF system is located close to previously 348 identified normal faults (Nicolich et al., 2000; Minelli and Faccenna, 2010; Polonia et al., 349 2011; 2012; Gallais et al., 2013), though there are commonly 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 (Fig. 9).

356

357 Seismic hazard

358 Considering the length of the two identified fault systems offshore eastern Sicily (60 359 km long NAF and 80 km SAF), empirical scaling relationships suggest that each of these 360 could be capable of generating magnitude 6.5 - 7 earthquakes (Wells and Coppersmith, 1994). 361 This corresponds well to the estimated magnitudes of several large historical earthquakes in 362 eastern Sicily; 1693 (M7.4), 1542 (M6.6) 1169 (M6.6) (Jenny et al., 2006). Given that the 363 1693 earthquake produced a major tsunami with 5 - 10 m high waves, a strike-slip origin 364 seems unlikely and indeed some workers argue in favor of a major normal fault along the 365 Malta Escarpment (Piatanesi and Tinti, 1998). It has also been suggested that this powerful 366 M7.4 earthquake occurred on the subduction fault plane (Gutscher et al., 2006), which would 367 be consistent with historical reports of an extremely long shaking duration of 4 mins 368 (Bonajutus and Malpighius, 1694). Interestingly, on 9 January 1693, two days before the 369 M7.4 event, a magnitude 6.2 earthquake struck causing damage in eastern Sicily, apparently a 370 foreshock. An intriguing hypothesis proposed here, is that the M6.2 earthquake may have 371 occurred on one segment of the lateral slab tear, thereby liberating the subduction fault plane 372 to slip a few days later. Unfortunately, our knowledge of historical earthquakes is seriously 373 hampered by the lack of instrumental observations and thus it is difficult to impossible to 374 reconstruct focal mechanisms. Given the slow fault-slip rates (a few mm/yr) and long 375 characteristic return intervals (several centuries) for earthquakes in southern Italy additional 376 observations are necessary to improve the regional hazard assessment. These could include 377 paleoseismological work to extend the earthquake record back in time and more detailed 378 geodetic work, to better constrain the current strain field and to clarify the regional 379 kinematics.

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# 381 Kinematics of the Calabrian arc system

382 Until now, while there was wide disagreement on the exact location of the STEP fault 383 offshore eastern Sicily (Orecchio et al., 2014), most authors agreed that the surface expression 384 would be one or several major normal faults (Polonia et al., 2011; Argnani et al., 2012; 385 Gallais et al., 2013; Argnani 2014). A major strike-slip fault, as reported here (the NAF 386 system) was not expected. However, kinematically, large-scale strike-slip movements are 387 predicted along a STEP fault between the advancing upper plate block and the adjacent upper 388 plate (Govers and Wortel, 2005). There is a broad concensus that the Tyrrhenian Sea basin 389 formed mostly after 6 Ma and that the southeastern Tyrrhenian Sea formed primarily during 390 the Pleistocene, when the Upper Miocene-Pliocene rifting migrated from the central 391 Tyrrhenian Sea (Vavilov basin) towards the SE (Marsili basin) as confirmed by deep-sea 392 drilling (Sartori, 1990) and dating of basalts (Marani and Trua, 2002). Thus, the Calabrian-393 Peloritan block must have been displaced by several hundred kilometers as indicated in most 394 plate kinematic reconstructions (Faccenna et al., 2001; 2004; Rosenbaum et al., 2002; Jolivet 395 et al., 2006). On the basis of our newly mapped faults, we propose here a kinematic 396 reconstruction of the Sicily - Calabria - Ionian Sea region since 6 Ma (Fig. 10). This 397 reconstruction offers a plausible explanation for the abrupt change in strike direction of 398 compressional anticline fold axes east and west of the elongate basin. The accretionary wedge 399 west of the elongate basin consists of the external evaporitic post-Messinian wedge, with fold 400 axes aligned generally parallel to the external deformation front (green lines in Fig. 10 C,D). 401 On the other hand, the portion of the accretionary wedge east of the elongate basin represents 402 the internal clastic pre-Messinian wedge (tightly spaced brown lines in Fig. 10, see also Fig. 403 3). While the exact limit between the external evaporitic and internal clastic wedges is not 404 perfectly well constrained, there is general agreement that it is located here as mapped by 405 previous authors (Minelli and Faccenna, 2010 their Figure 4 and Figure 11 inset; Polonia et 406 al., 2011 their Figure 13; Ceramicola et al., 2014 their Figure 1 inset). An industry seismic 407 profile images this boundary between the clastic and evaporitic wedges coinciding to the edge 408 of the elongate basin (Minelli and Faccenna, 2010). This limit is also confirmed by velocity 409 analysis of seismic reflection profiles crossing this boundary (Gallais et al., 2013). The 410 resulting large dextral displacement of the internal clastic wedge allows us to reconcile the 411 conflicting orientations of fold axes east and west of the elongate basin (the SAF) and offers a 412 simple, elegant explanation why the evaporitic post Messinian wedge ends abruptly along this 413 structure. It does, however, require large dextral displacement, which is not directly observed 414 in the seismic profiles, though the long narrow trough (elongate basin) bounded by normal (or 415 transtensional) faults on both sides is a characteristic feature of strike-slip environments.

416

417

# 418 Conclusions

New, high-resolution seismic profiles and detailed morpho-bathymetry 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 80km 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
Mt. Etna. These active offshore faults are mechanically capable of generating magnitude 6 - 7
earthquakes and may be responsible for some enigmatic historical earthquakes.

428

429 Acknowledgments:

We thank the captain Jean-René Glehen and the crew of the R/V Le Suroît, whose excellent work was crucial to acquire these data. We acknowledge INSU for cruise related funding and the European Union FP7 project ASTARTE for post-cruise financial support. AM was funded by Marie Curie Career Integration Grant PCIG13-GA-2013 618149 within the 7<sup>th</sup> European Community Framework Programme. Seismic and bathymetric data are archived and available upon request in the French national oceanographic data center -SISMER (Ifremer, Plouzané) http://www.ifremer.fr/sismer/index\_UK.htm.

437

# 438 Figure Captions:

439 Figure 1: Simplified tectonic map of southern Italy region, showing; seismicity (red circles) 440 from PDE-NEIC earthquake catalog (1973-2014,  $M \ge 2.5$ ), accretionary wedge thrust 441 structures (green lines, with black teeth at the deformation front) (Polonia et al., 2011; Gallais 442 et al., 2012); active volcanoes (yellow triangles); normal faults proposed as likely surface 443 expressions of the STEP fault (red lines with barbs); possible prolongations of the STEP fault, 444 north of Mt. Etna in NE Sicily (Jenny et al., 2006; Palano et al., 2012) (black dashed lines) 445 Lip. - Tind. line = Lipari - Tindari Line, Taorm. line = The Taormina Line, forming the SW 446 boundary of the Variscan crystalline basement of Calabria and the Peloritan Mountains 447 (Pel.Mts.) shown in magenta. Inset shows the study area located in southern Italy and the 448 Central Mediterranean Sea (Ionian Sea).

449

Figure 2: High-resolution swath bathymetry (color slope map) acquired with R/V Suroit and a
Simrad EM302 echosounder (90m grid, NW illumination) superposed on the gray shaded
relief from MediMap bathymetric compilation (Mascle and Loubrieu, 2010) (500m grid).
Inset - Color shaded relief of new swath data and existing compilation (Mascle and Loubrieu
2010), (NW illumination).

455

456 Figure 3: Morpho-bathymetric interpretation showing: position of seismic profiles (straight 457 black lines), sediment waves (alternating green and blue lines), accretionary wedge anticlines 458 and synclines (black and green lines), likely faults (red lines), the upper and lower limits of 459 the Malta Escarpment (orange lines), flat lying sedimentary basins (yellow shading) and 460 earthquake focal mechanisms, taking a representative subset (20 out of 80) of the earthquakes 461 at sea and along the coast from a published study (Musumeci et al., 2014). Inset - Simplified 462 morpho-tectonic interpretation. Symbols: minor thrust faults in the accretionary wedge (green 463 lines); sedimentary structures, (blue lines); basin boundaries and other tectonic lineaments 464 (black lines); major faults (red lines) with kinematics indicated (barbs for normal faults, 465 arrows for strike-slip faults, teeth for thrust faults) NAF = North Alfeo Fault system and SAF 466 = South Alfeo Fault system; position of seismic profiles (straight magenta lines), Faults on the 467 SE flank of Mt. Etna are from mapping and InSAR studies (Bonforte et al., 2011; Chiocci et 468 al., 2011; Barreca et al., 2013) and show dextral strike-slip motion.

469

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; major interpreted faults (red lines with sense of motion). Boxes show zooms of the original 72-channel seismic data.

474

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

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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; major interpreted faults (red lines with sense of motion).

484

485 Figure 7: schematic block diagram (view looking SW) of the Sicily - Calabria area showing 486 the regional kinematics and fault activity related to the STEP. Slab-rollback induces a SE 487 advance of the Calabrian-Peloritan block driving shortening in the external Calabrian 488 accretionary wedge (light green shading). The Ionian oceanic slab progressively detaches 489 from the adjacent Malta - Sicily (Hyblean) continental lithosphere. An isolated lobe of the 490 accretionary prism has been inserted between a small continental horst (AS - Alfeo 491 Seamount) and the Malta escarpment. Note the mostly normal faulting SAF = South Alfeo492 Fault system which veers (at the red dashed circle - representing the circular basin) into the 493 strike-slip NAF (North Alfeo Fault system) extending directly to Mount Etna. The volcano 494 sits atop the lithospheric tear fault and asthenospheric window (Gvirtzman and Nur, 1999). 495 The continuation of the STEP fault north of Mount Etna is uncertain and three possible 496 prolongations are shown schematically here.

497

Figure 8. Zoom of bathymetry at the northern end of the NAF system. Left - slope map (in
black & white), Right - residual bathymetric map (after filtering and removing a regional
trend for long wavelength relief). Several of the NAF strands connect to small transtensional

- 501 (pull-apart) basins indicating dextral strike-slip kinematics. Note that the NAF crosses the
- 502 broad turbidite channel and offsets a submarine canyon (see white arrows).
- 503
- 504 Figure 9. Compilation of all major published fault maps for the East Sicily margin. A -
- 505 Simplified morpholological interpretation and tectonic map from this study (same color code
- as inset to Fig. 3), with primary interpreted active faults shown in red (the dashed line in the
- 507 remaining three panels marks the base of the Malta Escarpment); B gray lines (Polonia et al.,
- 508 2011; 2012) NB lines without symbols are described as "normal faults from Chamot-Rooke
- 509 et al., 2005", red lines faults from this study. C black lines (Nicolich et al., 2000), dark blue
- 510 lines (Chiocci et al., 2011), dark green line shows an interpreted trace of the STEP fault
- 511 (Gallais et al., 2013), red lines faults from this study. D pink lines (Argnani & Bonazzi,
- 512 2005; Argnani et al., 2009; Argnani et al., 2012), light blue lines (Minelli and Faccenna,
- 513 2010) with the outer deformation front shown as a dashed line, red lines faults from this
- 514 study.
- 515
- 516 Figure 10. Kinematic reconstruction of the Sicily Calabria Ionian Sea region since 6 Ma517 showing:
- 518 A) at 6.0 Ma - the pre-Messinian (clastic) accretionary wedge developed in front of the 519 advancing Calabro-Peloritan block, B) at 5.2 Ma - at the end of the Messinian salinity crisis a 520 thick layer of evaporites was deposited in the large Ionian abyssal plain, C) at 4.0 Ma - the 521 construction of a large evaporitic accretionary wedge in front of the internal pre-Messinian 522 (clastic) wedge, the evaporite wedge is wrapping around Alfeo Seamount (AS) which acts as 523 an indenter, note the Ionian abyssal plain is diminishing in size and the West Mediterranean 524 Ridge appears (moving to the W and SW), D) at 0 Ma - the present day situation, with a large 525 scale dextral offset between the internal (clastic) wedge and lateral (western) portions of the 526 evaporitic wedge stranded between Alfeo Seamount and the Malta Escarpment. The Ionian 527 abyssal plain is greatly reduced in size as the Calabrian and West Mediterranean Ridge 528 accretionary wedges collide and intersect.
- 529

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