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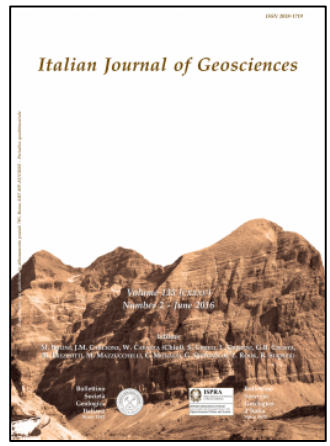

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Understanding seismogenic processes in the Southern Calabrian Arc:a geodynamic perspective

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ABSTRACT

For any scientist working in seismotectonics, the Calabrian Arc represents the most challenging area of Italy. Lying on top of a subduction zone, it is characterised by a complex geological structure largely inherited from the early stages of the collision between the Africa and Eurasia plates. The current and extremely vigorous seismogenic processes, although generated by a mechanism driven by the subduction, are no longer a direct consequence of plate convergence.

About one fourth of the largest Italian earthquakes concentrates in a narrow strip of land (roughly 200x70 km) corresponding to the administrative region of Calabria. The present-day seismicity, both shallow and deep, provides little help in detecting the most insidious seismogenic structures, nor does the available record of GPS-detected strains.

In addition to its fierce seismicity, the Calabrian Arc also experiences uplift at rates that are the largest in Italy, thus suggesting that active tectonic processes are faster here than elsewhere in the country.

Calabrian earthquakes are strong yet inherently elusive, and even the largest of those that have occurred over the past two centuries do not appear to have caused unambiguous surface faulting. The identified active structures are not sufficient to explain in full the historical seismicity record, suggesting that some of the main seismogenic sources still lie unidentified, for instance in the offshore. As a result, the seismogenic processes of Calabria have been the object of a lively debate at least over the past three decades.

In this work we propose to use the current geodynamic framework of the Calabrian Arc as a guidance to resolve the ambiguities that concern the identification of the presumed known seismogenic sources, and to identify those as yet totally unknown. Our proposed scheme is consistent with the location of the largest earthquakes, the recent evolution of the regions affected by seismogenic faulting, and the predictions of current evolutionary models of the crust overlying a W-dipping subduction zone.

Key words: Calabrian Arc, Calabrian earthquakes, Seismotectonics, Seismogenic sources, DISS database

INTRODUCTION

The Calabrian Arc is certainly the most challenging area of Italy's active tectonics map. Calabrian seismicity is perhaps the least understood of the entire country, and proposed models still exhibit a wide range of interpretations. Calabrian earthquakes are among the strongest in Italy's long seismic history (CFTI4Med, Guidoboni et al., 2007; CPTI11, Rovida et al., 2011), yet they are inherently elusive and even the largest of those that have occurred in the XX century do not appear to have caused unambiguous surface faulting (e. g.: Galli et al., 2008). The number of active tectonic structures which have been identified with some confidence and that are large enough to generate potentially damaging earthquakes (M 5.5+) is not sufficient to fully explain the historical seismicity record, suggesting that some of the main seismogenic sources still lie unidentified, for instance in the offshore. Seismogenic processes of Calabria have therefore been the object of a lively debate at least over the past three decades, and none of the current seismogenic models are representative of all seismogenic sources that must exist, starting with those which have caused large earthquakes in very remote times or for which there is no evidence of historical activity (for further details, see "The active faulting" section of this paper).

Aware of these circumstances, we propose to bridge the gap between large-scale geodynamics and more localized seismogenic processes, and use the current understanding of the dynamics of the Calabrian Arc as a guidance to help resolving the ambiguities that concern the identification of its main seismogenic sources. We focus specifically on the southern portion of the Calabrian Arc, from the Catanzaro Straits to the Messina Straits, as this is the region that has experienced the largest earthquakes (CPTI11, Rovida et al., 2011) and that overlies the most active portion of the Ionian subduction (Faccenna et al., 2005). In the first section of the paper we briefly review the tectonic and geodynamic setting and the seismicity of the

region, then move on to the active tectonics and to the alternative models for the distribution of active faulting that can be found in the literature. In the second section we propose a novel scheme that is consistent with the location of the largest earthquakes, with the recent evolution of the regions affected by seismogenic faulting, and with predictions of current evolutionary models for the crust overlying a W-dipping subduction zone. This scheme is largely implemented in Italy's Database of Individual Seismogenic Sources (DISS Working Group, 2015) and as such it is open to discussion and improvements in the future releases of this repository (access the "Sign up as Registered User" section in the database website).

TECTONIC AND GEODYNAMIC SETTING

The complex geological structure of the Calabrian Arc is largely inherited from the early stages of the convergence of the Africa and Eurasia plates (Figure 1). The subduction of oceanic crust that began about 80 Ma along a roughly E-W plate boundary (Faccenna et al., 2001) continues into the present day along a rather small (~150 km) portion of the arc between the Catanzaro Straits (to the north) and the Messina Straits (to the south), which is also the region forming the object of our work. The evolution of this section of the arc is controlled by a roll-back of the subduction that started in the Late Miocene (8-10 Ma; Goes et al., 2004; Faccenna et al., 2005), due to the sinking of the Ionian Mesozoic oceanic crust, the oldest oceanic crust worldwide (Müller et al., 2008; Speranza et al., 2012). The effect of plate convergence upon subduction gradually decreased with the progressive rotation and southeastward migration of the Calabrian Arc due to continental collision in Sicily (e.g. Cifelli et al., 2008). According to current kinematic plate models, Africa and Eurasia converge along a north-northwest to northwest direction at 3 to 8 mm/y (e.g. Nocquet, 2012). Based on interpolated data from the World Stress Map (Heidbach et al., 2008), Carafa & Barba (2013) and Carafa et al. (2015a) have shown that the distribution of stress within the crust exhibits S_{Hmax} striking parallel to the Arc; in this area the interpolation relies upon a limited number of data, however (Figure 1c), and is hence to be considered a preliminary result. In its turn, contraction

perpendicular to the Calabrian Arc proceeds at 2-5 mm/y (D'Agostino & Selvaggi, 2004; Serpelloni et al., 2010; Devoti et al., 2011). Considerations based on geodetic data indicate 5 mm/y as a tentative subduction rate (Devoti et al., 2008), whereas the dynamic model by Carafa et al. (2015a) suggests that the heave component of contraction across the Calabrian Arc is ~ 1 mm/y. Such findings imply that the migration of Calabria is controlled by the subduction process rather than by simple plate convergence. Contraction has led to the formation of a large accretionary wedge currently in the Ionian offshore, obtained by progressive folding of the up to 5.5 km thick sedimentary cover of the oceanic crust (Cernobori et al., 1996; Merlini et al., 2000; Minelli & Faccenna, 2010; Polonia et al., 2011).

The core of the Calabrian Arc is mainly composed of Hercynian metamorphic and intrusive rocks, along with Mesozoic carbonates and terrigenous deposits of Late Oligocene and Early Miocene age (Parotto & Praturlon, 2004). The infill of the overlying Neogene basins consists mainly of regionally extensive mudstones that exhibit significant lateral changes in thickness (e.g. Zecchin et al., 2015), and greatly contribute to the mass-wasting processes affecting the whole region (e.g. Ietto et al., 2008). In addition to that, due to the complex interaction between regional tectonic uplift, fault-related subsidence and Quaternary sea-level fluctuations, mid- to late-Pleistocene marine deposits - mostly sandstones and algal reefs - generally lie several tens or hundreds of meters above present sea level, often lining marine terraces carved within the Pliocene mudstone succession (e.g. Zecchin et al., 2004; Dumas et al., 2005; Cucci & Tertulliani, 2010). Holocene raised shorelines are also found up to 3 m above present sea level at different locations (Pirazzoli et al., 1997; Ferranti et al., 2007), even if most of the known coastal archeological sites seem to have experienced subsidence over the past 3 ky (Stanley & Bernasconi, 2012). The reason for these contrasting vertical motions is as yet unclear.

The Calabrian Arc is also the Italian region that has experienced the fastest uplift over the past 125 ky (> 1 mm/y; Bordoni & Valensise, 1998; Ferranti et al., 2006), thus suggesting that active tectonic processes are faster here than anywhere else in the country. Tectonic and erosion processes, along with the clayey nature of the substratum, give rise to slope instability that in turn favours the development of deep

submarine canyons and turbidite deposits (Morelli et al., 2011; Polonia et al., 2013; Ceramicola et al., 2014; Köng et al., 2016). Large mass movements have also been hypothesised to justify local subsidence and GPS velocity anomalies along the Ionian coast (e.g. the Crotone promontory; Minelli et al., 2013).

THE SEISMICITY RECORD

The seismicity of the Calabrian Arc encompasses a variety of geodynamic settings and a wide depth range. Present-day deep seismicity provides evidence for a well-developed Benioff plane down to a depth of more than 400 km (Chiarabba et al., 2005), in agreement with tomography data (Wortel & Spakman, 2000; Piromallo & Morelli, 2003; Piana Agostinetti et al., 2009). There is no direct evidence of large earthquakes affecting the shallow portion of the plate interface in the subduction zone, however, either in the instrumental or the historical and archeological records (Guidoboni et al., 2000), which locally illuminate a time-window of slightly over 1,000 and 2,000 years, respectively. It is still unclear whether the lack of evidence for large interface earthquakes indicates that the subduction is presently unable to generate them, or that their recurrence interval is ultramillenary, or simply that relevant data are still missing (see the end of this section).

As for crustal seismicity (Figure 1a), over the past five centuries the Southern Calabrian Arc was struck by several M 6+ earthquakes (notice that all magnitude estimates referred to in the text are from either the CFTI4Med catalogue, Guidoboni et al., 2007, or the CPTI11 catalogue, Rovida et al., 2011). The largest events include the main earthquakes belonging to the seismic sequence of February-March 1783, which struck a large region between the southern end of the Gioia Tauro Plain and the region south of the city of Catanzaro (max M_w 7.0); the 16 November 1894 multiple earthquake near the northern end of the Messina Straits (M_w 6.1); the 8 September 1905 earthquake in the Gulf of Sant'Eufemia (M_w 7.0); and the 28 December 1908 earthquake in the Messina Straits (M_w 7.1), that ranks among the most catastrophic events in Italian history. Together these earthquakes ruptured the entire length of the Southern Calabrian Arc, that is to say, the entire region of our investigation, over a time interval of 125 years. In this respect it

may be noteworthy to recall that only limited size earthquakes (M_w <5.5) were recorded over the entire region since 1908 (e.g. the 16 January 1975, M_w 5.2 event in the Messina Straits).

Damaging earthquakes have affected central Calabria on 4 April 1626 (M_w 6.0), 5 November 1659 (M_w 6.5), 7 December 1743 (M_w 5.6), and 13 October 1791 (M_w 6.0). All of these earthquakes struck essentially the same limited area located north of the region struck by the 1783 shocks, inevitably causing a superposition of their effects, which in turn may have caused ambiguities in the correct assessment of their location and magnitude.

Three rather elusive earthquakes struck the eastern piedmont of Aspromonte, a region located east of the Messina Straits, on 14 October 1784 (M_w 5.2), 23 October 1907 (M_w 5.9), and 11 March 1978 (M_w 5.2). Additional significant earthquakes have struck the northeastern end of Sicily, including the 10 March 1786 (M_w 6.2) and 15 April 1978 (M_w 6.1) events, which both hit the northern coast of the island between Patti, Milazzo and the Eolian Islands.

The shallow seismicity recorded in the upper crust of the Ionian offshore is very limited. The largest instrumental earthquake occurred on 26 May 2001 (M_w 4.5; Pondrelli et al., 2006) near the innermost western lobe of the Ionian accretionary wedge (Polonia et al., 2012; Figure 1c). Its focal mechanism is consistent with the compressional tectonic regime that is expected to dominate in the accretionary wedge. The 11 May 1947 earthquake (M_w 5.7) is located on the Ionian coast of central Calabria based on its macroseismic effects, but its instrumental location suggests its epicentre may in fact lie offshore, in the central part of the innermost eastern lobe (Figure 1c); hence, its magnitude could be larger than reported. Other minor tremors reported historically along the Ionian coast could be evidence for more significant earthquakes in the offshore.

Finally, there are hints that a number of earthquakes in the M_w range 5.5 to 6.0 have been misplaced, or have been recorded as one single event being instead of multiple events, or are not listed at all in current catalogues. In addition, the causative faults of at least one out of three of the 30 known

M_w>5.5 earthquakes of the entire Calabria (Rovida et al., 2011) are still unidentified, even if attempts are underway to identify their respective seismogenic sources (Akinci et al., 2015).

In summary, despite the number of damaging earthquakes that struck Calabria in historical times, our degree of knowledge on their effects and our confidence on their causative sources is still limited. This is largely due to one or more of these unfavourable circumstances:

1) the landmass of Calabria is long and narrow, such that the resolving power of felt reports following historical earthquakes is spatially limited and their patterns are potentially misleading;
2) the region is quite mountainous, causing the distribution of the population to be rather inhomogeneous at least until the 18th century. This may have resulted in an undesirable asymmetry in the intensity pattern of the older earthquakes, and hence in their mislocation;
3) as mentioned earlier, the superposition of the effects of earthquakes occurring in close spatial and temporal proximity may have altered the perception of the effects of later shocks, potentially causing their mislocation and causing them to appear larger than they were.

THE ACTIVE FAULTING

GENERALITIES

The active faults of the Calabrian Arc have been investigated by a number of workers and presented in different compilations, including the work done for the *Progetto Finalizzato Geodinamica* (PFG) in the late 1970s and 1980s (Ciaranfi et al., 1983), for the *Gruppo Nazionale Difesa dai Terremoti* (GNDT) project in the late 1990s (Moretti, 1999, 2000; Galadini et al., 2000), by ISPRA (formerly APAT: Michetti et al., 2000), and by INGV workers (Valensise & Pantosti, 2001a). A summary of published active faults from various sources that are relevant to our discussion is shown in Figure 2. In the following three subsections we first summarize and discuss the evidence for normal faulting, then for the thrust faulting seen in the

Ionian offshore in association with the ongoing subduction, and finally for the strike-slip faulting that is believed to accompany the longitudinal fragmentation of the Calabrian Arc.

The main fault system of Calabria runs onshore, parallel to the Tyrrhenian coast. Tortorici et al. (1995), Monaco & Tortorici (2000) and Catalano et al. (2008) referred to it as the Siculo-Calabrian Rift Zone (SCRZ, Figure 2), whereas other workers (Peruzza et al., 1997; Valensise & Pantosti, 2001b, and references therein) simply regarded it as a long, segmented system accommodating extension by gravitational collapse of the ridge-top. Nevertheless, all workers agree that this system extends for the entire length of the Southern Calabrian Arc, from the east-west Catanzaro Straits to the north to the north-northwest-trending Tindari-Letojanni Line to the southwest. Some workers regard these two physiographic boundaries as the surface evidence of major deep-seated shear zones bounding the active portion of the Ionian subduction (e.g. Fabbri et al., 1982; Guarnieri, 2006; Orecchio et al., 2014, 2015).

In summary, while there is wide consensus that the largest Calabrian earthquakes were caused by normal faulting, the extension driving these large faults is traditionally interpreted with reference to two mutually exclusive models: 1) a rifting process that developed at the end of the subduction of the Ionian domain (Ghisetti et al., 1982; Wezel, 1985; Tortorici et al., 1995), or 2) a combination of south-eastward roll-back of the hinge of the subducting Ionian lithosphere (Malinverno & Ryan, 1986), causing extensional collapse of the orogenic belt and the development of back-arc basins (Boccaletti & Guazzone, 1972; Alvarez et al., 1974; Hsü, 1977; Görler & Giese, 1978; Horvath & Berckhemer, 1982; Kastens et al., 1988; Van Dijk, 1994). Over the past 20 years crucial data on the subduction and on the development of the accretionary wedge have become available, leading most of the workers to adopt model 2) and to abandon model 1).

The rest of this section supplies a brief overview of the hypotheses that have been put forward in the literature over the past 40 years concerning the active faulting of our study region. This overview, however, does not comprise a full account of the available evidence, for which the reader is encouraged to

refer to the cited sources. Further details are supplied in the next section, which discusses our preferred seismogenic model.

NORMAL FAULTING

The active extensional basins of the Calabrian back-arc comprise the most inhabited and economically profitable areas of the region. They generally host sedimentary sequences deposited above the crystalline basement since the late Miocene (e.g. Ghisetti & Vezzani, 1980; Patacca et al., 1990), and each one is characterised by a different structural elevation and amount of sediment supply. Although they are thought to be relatively youthful, they all exhibit a structural relief in excess of 1,000 m, suggesting that if they are fault-driven - a fact on which most workers agree on - either the time of inception of such faults is rather old (>> 1 My) or their slip rates are rather fast. Based on evidence from different seismogenic areas of Italy, however, Valensise & Pantosti (2001b) have argued that most of the basins presently undergoing seismogenic extension coincide with troughs created during the construction of the fold-and-thrust belt that comprises most of peninsular Italy. They referred to this process as "mimicking" and warned that this circumstance must be considered when identifying the faults responsible for the creation of such basins, thus assessing their total throw, age of inception, and slip rate.

Whatever their origin and development, all extensional basins lie to the west of the highest peaks and of the regional watershed, greatly affecting the drainage and sediment dispersal patterns. From south to north (Figure 2) they include the Messina Straits (undersea), the Gioia Tauro Plain, the Mesima-Marepotamo Valley, and the Sant'Eufemia basin (undersea). The system continues northward into the Savuto valley and the Crati valley, both of which fall outside our study area. All basins are aligned along a N20°E to north-south trend and exhibit a comparable length, suggesting that they are controlled by similarly long normal faults (≥25 km). We hereby review the main characteristics of each of these basins, from south to north.

Due to the magnificence of the exposed rocks and landforms, the Messina Straits have been the object of intense geological investigations even before the 1908 earthquake. There exist two main interpretations concerning the causative source of this catastrophic event and the recent evolution of the Straits. One view, strictly based on structural geology and geomorphic observations, points to the existence of a graben including three main fault sets trending NE-SW, NW-SE, and E-W (Bottari et al., 1986; Bottari et al., 1992; Tortorici et al., 1995). In this interpretation the causative source of the 1908 earthquake would be a northeast-trending, W-dipping, high-angle fault that intersects the topographic surface on the Calabrian side of the Straits a few km east of Reggio Calabria. This model had lost popularity over the past two decades but has been recently revamped by Aloisi et al. (2013).

The second view proposes that the source of the 1908 earthquake is a low-angle blind fault dipping toward the east or east-southeast (Capuano et al., 1988; Valensise, 1988; Boschi et al., 1989; De Natale & Pingue, 1991; Pino et al., 2009). This source model agrees well with available instrumental data (seismological and geodetic) and the damage pattern (Convertito & Pino, 2014). In addition, according to Valensise & Pantosti (1992) the expected cumulative vertical deformation field caused by sustained slip on this major fault mimics the shape of an asymmetric trough and suits convincingly the overall pattern of long-term deformation revealed by geologic and geomorphic observations.

The ~30 km-long, ~20 km-wide Gioia Tauro Plain is a sedimentary basin hosting a late Miocene-Holocene, marine to continental sequence (Ogniben, 1973; Patacca et al., 1990; Zecchin et al., 2015). It has been interpreted as a graben-like structure (e.g. Cotecchia et al., 1986), having its master fault (Cittanova Fault, CF) running on its eastern flank, i.e. along the mountain slope where the Neogene-Quaternary sediments abut the crystalline rocks forming the backbone of the Aspromonte Massif. This high-angle, W-dipping, westward-concave fault is considered active based on morphotectonic and structural analyses (Tortorici et al., 1995; Monaco et al., 1996), and on contemporary historical reports describing a 20 km-long discontinuous fracture that formed at the base of the mountain slope following the M_w 6.6, 5 February 1783 earthquake (De Dolomieu, 1784; Sarconi, 1784). The fault has been subsequently investigated by

paleoseismological investigation. According to Galli & Bosi (2002) and Galli and Peronace (2015), trenching has supplied evidence for the occurrence of several faulting events during the Holocene.

In contrast, Cucci et al. (1996) propose a rather different solution stemming from the analysis of the long-term landscape evolution of the Gioia Tauro Plain. Their study uses the attitude of recent deposits, the pattern of the drainage network and its behaviour, and the shape and elevation trend of the late Pleistocene paleo-shorelines as markers of the active tectonic deformation. They propose the Gioia Tauro Plain as being tectonically controlled by a relatively young, low-angle, east-dipping blind normal fault (Gioia Tauro Fault, GTF), very similar to the nearby source of the 1908 earthquake in the Messina Straits. This analysis fits well with the geochemical evidence from local spring and well observations (Pizzino et al., 2004).

The upper Mesima Valley is a broad, slightly asymmetrical depression bounded to the east by the westward concave escarpment of the Serre Mts., and to the west by the more rectilinear eastern shoulder of the Capo Vaticano promontory (or Mt. Poro). Morphologically the upper Mesima Valley is connected to the Gioia Tauro Plain and shares with it the same late Miocene-Holocene, marine to continental basin fill (Ogniben, 1973; Patacca et al., 1990; De Rosa et al., 2008). This basin too has been traditionally interpreted as a graben, bounded to the east by the Serre Faults, coincident with the main escarpment, and to the west by a minor antithetic structure; the former was assumed to be the source of the M_w 6.6, 7 February 1783 earthquake (Tortorici et al., 1995; Monaco et al., 1996). An alternative interpretation for the source of the same earthquake was originally invoked by Peruzza et al. (1997) and later incorporated in the first release of the DISS database (Valensise & Pantosti, 2001a); it involves the existence of an east-dipping large normal fault similar to that proposed for the Gioia Tauro Plain.

The Sant'Eufemia undersea basin lies between the northern shore of the Capo Vaticano promontory (to the south) and the western reaches of the Catanzaro Straits (to the north). This area hosts a large portion of the mesoseismal area of the M_w 7.0, 8 September 1905 earthquake, which was followed by a modest tsunami. Several research groups presented alternative hypotheses for the seismogenic source of 1905 earthquake and tsunami. The proposed models fall into three main categories. The first one favours a

low-angle, east-dipping, north-northeast-striking source across the Sant'Eufemia basin, sub-parallel to the extensional axis of western Calabria, derived from a regional segmentation model based on a sequence of large normal faults (Peruzza et al., 1997; Valensise & Pantosti, 2001a, b; Loreto et al., 2013). Models of the second group envision a high-angle, northwest-dipping, northeast-striking normal faults bordering the northern flank of the Capo Vaticano promontory, overall implying an alternative seismotectonic model for the Calabrian Arc and eastern Sicily (Monaco & Tortorici, 2000; Piatanesi & Tinti, 2002). Finally, a third and separate model favours a high-angle, south-dipping, west-northwest-striking normal fault on the southern flank of the Capo Vaticano promontory (Cucci & Tertulliani, 2006, 2010). A further hypothesis was put forward by Galli & Molin (2009), who contend that the 1905 earthquake is a sub-crustal event generated on the subduction plane in the offshore of the Mt. Poro Promontory.

The multibeam and seismic reflection data acquired by Loreto et al. (2013) proved critical for positively identifying a northeast-striking, low-angle, southeast-dipping normal fault. This structure, which these authors named Sant'Eufemia Fault, shows up on the seabed as a brittle feature that can be traced for about 13 km along strike throughout the whole sedimentary stack. Based on their geophysical data, these investigators maintain that the Sant'Eufemia fault is the only seismogenic source in the Sant'Eufemia basin. They also stated that this fault is compatible with the 1905 earthquake based 1) on its size, consistent with macroseismic estimates of the magnitude; 2) on the up-dip prolongation of the fault plane that ruptured the seabed, compatible with the occurrence of the modest tsunami; 3) on its location, which agrees with the damage pattern; and 4) on its geometry, compatible with the seismotectonic setting of the Calabrian back-arc.

THRUST FAULTING IN THE IONIAN ACCRETIONARY WEDGE

Known thrust faults concentrate offshore and have been detected thanks to a number of seismic reflection campaigns run for both commercial and scientific purposes. In fact, in recent years the whole region has

been the object of intense geophysical exploration that allowed the main structural features of the Calabrian offshore to be identified and delineated.

The Calabrian subduction system includes a southeast-verging accretionary wedge that extends for over 200 km into the Ionian Sea. It lies on the subducting African plate and is composed of Mesozoic carbonates, Tertiary clastic sequences, Messinian evaporites and Plio-Peistocene hemipelagic and turbiditic sequences (Polonia et al., 2011; 2015). Mud volcanoes developed since Late Pliocene due to release of overpressured fluids from deep within the accretionary prism (Praeg et al., 2009), thus testifying the sustained compressional tectonic activity of this rather inaccessible region. Interpretations of seismic reflection profiles reveal its internal structure (e.g. Rossi & Sartori, 1981; Cernobori et al., 1996; Merlini et al., 2000; Finetti, 2005; Minelli & Faccenna, 2010; Polonia et al., 2011; Gallais et al., 2012). The sections perpendicular to strike show that the accretionary wedge is formed by two sub-units: a pre-Messinian inner wedge and a post-Messinian outer wedge. Conversely, little is known about the additional internal complexities of the accretionary wedge.

The transition from the inner to the outer wedge is marked by a change of the basal detachment taper angle (Minelli & Faccenna, 2010) from <1.0-1.5° for the outer wedge to >3° for the inner portion (Polonia et al., 2011; Gallais et al., 2012). The basal detachment of the outer wedge lays upon Messinian evaporites (Chaumillon & Mascle, 1997) and is thought to be aseismic (Polonia et al., 2011), whereas the detachment in the inner wedge seems to involve the Tertiary and Mesozoic sediments on top of the oceanic crust (Ryan et al., 1982; Polonia et al., 2011; Gallais et al.2012). The inner wedge hosts large splay faults deemed to be potentially seismogenic (Polonia et al., 2011).

Along-strike, the accretionary wedge is divided into two distinct lobes, the Eastern and the Western ones. The two lobes exhibit a different morphology of the sea-floor, a different depth and dip of the basal detachment, a variable degree of deformation, and probably also different deformation rates (Polonia et al., 2011). The Western lobe is characterised by the presence of high amplitude and large wavelength folds, and by large sedimentary basins (Rossi & Sartori, 1981) and mud diapirs (Praeg et al., 2009). The

maximum horizontal stress (S_{Hmax}; Carafa et al., 2015a; Carafa et al., 2015b) resulting from interpolation of data from the World Stress Map (Heidbach et al., 2008) shows a consistent northwest-southeast orientation for the Western lobe, whereas the orientation of S_{Hmax} is more variable in the Eastern lobe. Such orientations of recent stress show that the northeast-striking thrust faults of the Western lobe are optimally oriented for being active in the current tectonic regime.

Geological estimates of the accretion velocities of the wedge lie in the range 2.0 to 3.0 cm/y (Polonia et al., 2011; Gallais et al., 2012). The accretion velocity cannot be straightforwardly related to the subduction velocity. As mentioned earlier, based on geodetic data Devoti et al. (2008) indicate 5 mm/y as a tentative subduction rate, which should correspond to the rate of contraction across the entire accretionary wedge. Horizontal velocities obtained from geodynamic models by Carafa et al. (2015a) range between 2.0 and 4.0 mm/y, respectively for the Eastern and Western lobe, while finite element geodynamic models by the same investigators predict thrust kinematics with slip rates in the order of 0.9 mm/y for the outer edge of the accretionary system.

No strong historical or instrumentally recorded earthquakes have been directly associated with the thrust faults forming the accretionary wedge. The lack of reported seismicity may be due in part to the offshore location of these faults and to their distance from populated centres, a circumstance that affects the historical portion of any earthquake catalogue. Nevertheless, large active thrusts within accretionary wedges are assumed to be seismogenic in most subduction zones worldwide (e.g. Moore et al., 2007; Shaw et al., 2008).

STRIKE-SLIP FAULTING

Strike-slip faults were originally hypothesised onshore based on geomorphological observations and on lithological discontinuities recognized also through remote sensing interpretation (e.g. Fabbri et al., 1980; Knott & Turco, 1991). These key structural discontinuities seem to cause the longitudinal segmentation of the Calabrian Arc and to act as tracks guiding its drift towards the southeast (Rehault et al., 1987; Knott &

Turco, 1991, among others), or to represent the accommodation of the upper plate to the curved geometry of the subducting slab (Doglioni, 1991).

Their existence as major shear zones seems to have gained further strength following the interpretation of key seismic reflection lines (Finetti, 2005; Del Ben et al., 2008; Polonia et al., 2011; 2012). These structures are recognized in the Ionian Sea, probably extending to the east into the accretionary wedge (Polonia et al., 2011; 2012) and to the west into the Tyrrhenian Sea (e.g. Fabbri, 1974; Fabbri et al., 1982; Loreto et al., 2015).

The southernmost and northernmost shear zones are probably related to boundaries of the active subduction (e.g. Guarnieri, 2006; Orecchio et al., 2014; 2015). The Tindari-Letojanni Line is interpreted as the necessary accommodation zone between the contractional domain of the southern Tyrrhenian and the extensional domain of the Calabrian Arc (Billi et al., 2006). This system seems to continue towards the southeast into a shear zone identified by Polonia et al. (2011; see also Polonia et al., 2012; Gallais et al., 2013), showing the characteristics of a Subduction-Transform Edge Propagator (STEP) fault *sensu* Govers & Wortel (2005), thus bounding the subducting slab to the southeast.

Based on current interpretations of seismic reflection profiles (Finetti, 2005; Del Ben et al., 2008; Polonia et al., 2011; Capozzi et al., 2012), a major shear zone similar to the Tindari-Letojanni Line may exist also in the Squillace Gulf. This tectonic element is thought to have contributed in shaping up the Catanzaro Straits (Guarnieri, 2006; Tansi et al., 2007) and falls in a region where differences in the exposed terrains, in the strike of the mountain belt and in large-scale landscape features mark the transition between a continental collision domain, to the north, and an active subduction domain, to the south.

The Marina di Nicotera-Marina di Gioiosa Ionica Line separates the Serre Mts. to the north from the Gioia Tauro Plain to the south. It is a west-northwest-striking shear zone that is assumed to be characterised by prevalent strike-slip motion. Geomorphological and structural data show that it separates two distinct segments of the Calabrian Arc: the Serre Mts. to the north, where topography is higher and Late Pleistocene uplift is assumed to be faster, and the Gioia Tauro Plain-Aspromonte Massif to the south.

This fault system is supposed to extend offshore in the Tyrrhenian Sea, bordering the Capo Vaticano promontory to the south (Fabbri et al., 1982; De Ritis et al., 2010; Loreto et al., 2015).

More to the south, the Bagnara Calabra-Bovalino Line marks another sharp tectonic and topographic shift from the lowlands of the Gioia Tauro Plain (to the north) to the Aspromonte Massif (to the south). This fault system, originally inferred based on surface geology, geomorphology and structural data as a prevalent normal fault (Fabbri et al., 1982), is currently considered one of the major strike-slip fault that dissect the Calabrian Arc, following the interpretation of seismic reflection data that depict a flower structure off the southwestern coast of Calabria (Del Ben et al., 2008).

The seismogenic nature of these shear zones is still debated, as very few earthquakes can be confidently associated with them. The only exception is the Tindari-Letojanni Line, which is held responsible for the M_w 6.2, 10 March 1786, and the M_w 6.1, 15 April 1978 earthquakes along the Tyrrhenian coast of Sicily, and possibly for the M_w 5.6, 28 March 1780 earthquake, located in the Ionian Sea in front of Taormina.

A COMPREHENSIVE SEISMOGENIC MODEL

DEVELOPING A SEISMOGENIC SOURCE DATABASE

In this section we discuss a seismogenic model of the Southern Calabrian Arc that is already implemented in v. 3.2.0 of the DISS database (DISS Working Group, 2015). Over the past two decades the DISS Working Group, to which the authors of this paper belong, has developed a strategy for identifying, characterising and archiving in a permanent database all seismogenic sources that are believed to be capable of producing M_w 5.5 or larger earthquake in the Italian peninsula and surrounding areas (Valensise & Pantosti, 2001a; Basili et al., 2008). The experience has been recently extended to the rest of Europe

(Basili et al., 2013a) for the compilation of a new seismic hazard map at continental scale (Woessner et al., 2015).

The approach that was employed for compiling the DISS database is based on a combination of geological, geophysical and historical evidence. The DISS Working Group relies on published data and their interpretations, including alternative views, but also on original fieldwork, geomorphologic analyses, and interpretations of seismological and geophysical data (for further details the reader may refer to Basili et al., 2008, Kastelic et al., 2013, and Vannoli et al., 2015).

DISS' cataloguing strategy is currently based on three categories of sources, the former two being described in 3D and fully parameterized geometrically: (i) the Individual Seismogenic Sources (ISS, identified by "ITIS", where IT stands for Italy, followed by a three digit number), which are rectangular fault planes assumed to behave in a "characteristic" fashion with respect to rupture length/width and magnitude; (ii) the Composite Seismogenic Sources (CSS, identified by "ITCS" followed by a three digit number), which are regional fault systems including an unspecified number of seismogenic sources that cannot be singled out; and (iii) the Debated Seismogenic Sources (DSS, identified by "ITDS" followed by a three digit number), unparameterized faults taken from the literature which were considered for a possible inclusion among either the ISS or CSS but have not yet "passed the test" for a number of possible reasons. Notice that an ISS may be responsible for a specific historical or instrumental earthquake, whereas a CSS - and even less so, a DSS - is not associated with a specific earthquake or set of earthquakes.

The current version of the DISS database also contains a simplified and three-dimensional representation of the complex subduction system, identified by the depth contours of the subducted slab (Figures 1, 3-6). Similarly to Composite Seismogenic Sources, DISS' Subduction Zones are not associated with a specific set of earthquakes or earthquake distribution. As this paper deals exclusively with the shallowest portion of the overriding plate the subduction sources are not included in the proposed seismogenic model; nevertheless, the reader is encouraged to consult the DISS website to learn more about their geometry and the relationships with the overlying crustal faults.

Detailed descriptions of the DISS sources and of the multi-step procedure to identify their parameters can be found in Basili et al. (2008, 2009, 2013b), Burrato et al. (2008), Vannoli et al. (2012), Kastelic et al. (2013), Vannoli et al. (2015), and in a specific section of the database website (http://diss.rm.ingv.it/diss/index.php/about).

MAIN CHARACTERISTICS OF THE PROPOSED SEISMOGENIC MODEL

The model described in this paper summarises the fault models that best fit all the available data. In the following we describe how each source was derived and what data and inferences support it. The next section will discuss how this model fits in the geodynamics of the Calabrian Arc.

Our model consists of a series of blind, low-angle normal faults alternated with strike-slip structures that dissect the Calabrian Arc, dividing it into portions characterised by a diverse range of geomorphological features and by different uplift rates. Two major shear zones bound the system to the southwest and to the northeast, respectively, marking the surface projection of the oceanic portion of the African plate beneath the Calabrian Arc. The model is complemented by a series of large thrust faults in the Ionian offshore, which are assumed to be seismogenic.

EXTENSIONAL SEISMOGENIC SOURCES

The extensional seismogenic sources (see also the "Normal faulting" subsection) are broken down into two types: A1 and A2. A1-type faults (Figure 3) are the large east-dipping normal faults underlying the Messina Straits, Gioia Tauro Plain-Mesima River Valley and Sant'Eufemia basins, from south to north. A2-type faults (Figure 4) correspond to the west-dipping faults identified by a number of workers along the eastern boundary of the same basins. In fact, not all geometric and kinematic parameters are available in the literature for A2 faults, and in particular their maximum depth and dip angle are usually undetermined, making it impossible to hypothesise their 3D geometry and the relationships with other nearby faults. Table

1 provides an overview of the data available in the literature for the region of interest of our paper. It is also for this lack of quantitative information that these faults have been included in DISS only as Debated Seismogenic Sources.

Following is a description of each individual A1-type and A2-type fault.

A1-type: The Messina Straits fault

The ITCS016 Aspromonte-Peloritani Composite Source is the southernmost segment of the inner Calabrian extensional fault system, and straddles the marine area between the termination of the Italian peninsula in Calabria and the northeastern tip of Sicily, including the western flank of the Aspromonte Massif (above the city of Reggio Calabria) and the east-facing slope of the Peloritani Mts. (above the city of Messina). It hosts the ITIS013 Messina Straits Individual Source, a 40 km long, east-southeast-dipping low-angle normal fault assumed to be the causative source of the M_w 7.1, 28 December 1908 earthquake (Figure 3). The predicted long-term strain pattern of such a low-angle normal fault describes a slightly asymmetrical syncline, having the western limb steeper, in agreement with the topography and distribution of recent deposits on the two sides of the Straits.

Although there is always room for improvements and refinements, the existence and characteristics of this Composite Source are largely based on the elaboration of data supplied by early seismographic records (Pino et al., 2000; Pino et al., 2009), and on modeling of coseismic elevation changes measured by Loperfido (1909) and by a number of workers (Mulargia & Boschi, 1983, Capuano et al., 1988; Valensise, 1988; Boschi et al., 1989). From the point of view of geological observations the source is supported by a number of independent occurrences: (1) the most recent paleoshorelines, which all exhibit a seaward concavity consistent with the progressive generation of a roughly north-northeast-trending, fault-related syncline; (2) the elevation fluctuations of the 125 ka marine terrace, which appear to be related with the distance from the axis of the syncline; (3) the distribution of recent deposits (the Middle-Late Pleistocene Ghiaie di Messina Fm.), that appears to mimic the subsidence pattern associated with 1908-type

earthquakes; and (4) the local drainage pattern, which exhibits attraction and rotation of streams of all hierarchical levels towards the areas of largest fault-related subsidence (Valensise & Pantosti, 1992). Conversely, various lines of evidence, and particularly (1) the size of the causative fault of a M_w>7.0 earthquake, much larger than any fault mapped in the area, (2) the pattern of coseismic elevation changes measured by Loperfido (1909) not supporting significant shallow faulting on the Calabrian side of the Straits, and (3) the lack of field evidence of coseismic surface faulting (Caciagli, 2008; Comerci et al., 2015), all suggest that the hypothesis of a west-dipping seismogenic fault is unrealistic as a causative source of the 1908 earthquake.

The southern portion of the Aspromonte-Peloritani Composite Source is in part overlapped by the ITDS008 Taormina Debated Fault, a high-angle east-dipping normal fault originally proposed by Stewart et al. (1997).

A1-type: The Gioia Tauro Plain and Mesima Valley faults

The ITCS082 Gioia Tauro Composite Source straddles the southwestern Tyrrhenian shoulder of southern Calabria, just northeast of the Messina Straits. This source shares a similar low-angle, E-dipping geometry with the nearby ITCS016. According to this model, the proposed seismogenic fault progressively generated a syncline having the axis about 5 km inland and roughly parallel to the coast. It hosts the ITIS012 Gioia Tauro Plain Individual Source, a 25 km long, ESE-dipping low-angle normal fault associated with the M_w 6.6, 5 February 1783 earthquake (Figure 3).

The fundamental evidence for the existence and long-term activity of the Gioia Tauro Fault is the present shape and the elevation of the marine terraces encircling the Gioia Tauro Plain, which following Cucci et al. (1996), is best explained by the interplay between regional uplift and more localized synclinal subsidence induced by the activity of the fault. In fact, Valensise & D'Addezio (1994) used the geometry of the sedimentary filling of the basin to discriminate between the east-dipping Gioia Tauro Fault (GTF) and the west-dipping Cittanova Fault (CF) assuming that the sediments must have recorded the cumulative

vertical strains associated with the activity of the main fault: a larger thickness of syn-tectonic deposits is to be found in the area of expected maximum subsidence (i.e., near the mountain slope for the CF and in the middle of the plain for the GTF). As shown by the few published seismic lines (e.g., the AGIP seismic line RC-306-78, available at www.videpi.com) and by InSAR analyses (Raspini et al., 2012), the basin fill and the underlying crystalline bedrock is essentially bowl-shaped, it rises up steeply westward and exhibits a maximum thickness of about 500-800 m a few km east of the present shoreline, i.e several km west of the Aspromonte piedmont. In our opinion this configuration is not compatible with sustained activity of the Cittanova Fault, which instead should have induced a half-graben pattern of sedimentation that is not observed. In particular we find no evidence for the deep basin that should lie in front of a typical range-bounding fault such as the Cittanova Fault. We do acknowledge, however, that more and better data are needed to improve our understanding of the architecture of the sedimentary infilling of the Gioia-Tauro Basin and reconstruct the local fault pattern in full. Other clues supporting the existence of a low-angle, east-dipping fault come from the geochemical anomalies recorded at the northwestern end of the fault, interpreted by Pizzino et al. (2004) as the evidence of the interplay between the Gioia Tauro Fault and the transverse structure known as Nicotera-Gioiosa Ionica Line (ITCS080 Nicotera-Roccella Ionica).

North of the Gioia Tauro Plain, the ITCS053 Serre Composite Source straddles the western flank of the Serre Mts. and the Capo Vaticano promontory. This region has been struck by the M_w 6.6, 7 February 1783 Calabria earthquake, the third mainshock of the 1783 sequence. Very little geological observations are available for the region around this source and no specific paper deals with the 7 February 1783 earthquake. Hence, the parameters of this source were derived from those of the adjacent ITCS082 Composite Source, hypothesizing that they belong to the same system of low-angle, east-dipping, overriding faults that are antithetic with respect to the subduction polarity. The ITCS053 hosts the ITIS011 Upper Mesima Basin Individual Source, a 22 km long, east-southeast-dipping low-angle normal fault that is held responsible for the 7 February 1783 earthquake.

A1-type: The Sant'Eufemia Fault

Moving more to the north, the ITCS110 Sant'Eufemia Composite Source straddles the Sant'Eufemia basin (offshore) and the Sant'Eufemia Plain (onland), roughly extending between Vibo Valentia (to the south) and Lamezia Terme (to the north). This is a low-angle, southeast-dipping, fault located in the southwestern portion of the extensional axis of the southern Apennines. It hosts the ITIS139 Sant'Eufemia Individual Source, a 25 km long, east-southeast-dipping low-angle normal fault associated with the 8 September 1905 earthquake (Figure 3).

Despite its catastrophic effects (including a modest tsunami; Tinti & Maramai, 1996; Guidoboni & Ebel, 2009; Maramai et al., 2014), the 1905 earthquake is poorly documented and even its magnitude estimates exhibit a large variability, from M_w 6.7 based on intensity data (Guidoboni et al., 2007) to a M_s 7.5 based on seismograms (Margottini et al., 1993). Epicentral locations are also uncertain, spanning a large area from the onshore (Rizzo, 1906; Boschi et al., 2000; Guidoboni et al., 2007) to the offshore (Riuscetti & Schick, 1975; Camassi & Stucchi, 1997; Michelini et al., 2006; Rovida et al., 2011).

The identification of the earthquake causative source is equally uncertain. A recent summary by Loreto et al. (2013) includes early hypotheses by Peruzza et al. (1997), who envision an east-dipping, blind normal fault beneath the Sant'Eufemia Gulf, and by Monaco & Tortorici (2000), who favour a steeper northwest-dipping fault on land corresponding with the Vibo Valentia fault of previous investigators. Valensise & Pantosti (2001a, b) further elaborate on the source proposed by Peruzza et al. (1997), while Cucci & Tertulliani (2010) contend that the source of the 1905 earthquake is a segment of a regional transverse structure running along the southwestern flank of the Mt. Poro promontory. Based on new evidence from offshore reflection profiles showing displacement of the seafloor, Loreto et al. (2013) contend that the source of the 1905 earthquake lies beneath the Sant'Eufemia Gulf and is very similar to the east-dipping fault proposed by previous workers.

To sort out these contrasting views Sandron et al. (2015) calculate shaking scenarios for each of the available source models against the damage pattern of the 1905 earthquake, and find that the best-fitting

sources are the Vibo Valentia Fault of Monaco & Tortorici (2000) and the Sant'Eufemia Fault of Loreto et al. (2013). Then based on the post-Miocene stratigraphic sequence of the Sant'Eufemia basin imaged by Loreto et al. (2013) they conclude that the Sant'Eufemia Fault is the most likely candidate as the source of the 1905 earthquake.

A2-type: Steep west-dipping faults

As we mentioned earlier, our model includes also a number of Debated Seismogenic Sources, i.e. faults either poorly or not parameterized at all, which we refer to as A2-type faults (Table 1 and Figure 4) and that were considered for a possible inclusion among either the ISS or CSS or both. Some of them have already been mentioned in the discussion on the A1-type faults.

The ITDS007 Reggio Calabria and ITDS065 Armo are normal faults that lie east of Reggio Calabria and have been in the literature for many years. They have been identified based on structural-geomorphic evidence similarly to the ITDS022 Scilla Fault (Ghisetti, 1992). The ITDS005 Cittanova Fault is first proposed by Tapponnier et al. (1987) based on geomorphic evidence and on the already mentioned historical reports on the 5 February 1783 earthquake. The ITDS006 Serre Fault is introduced by Tortorici et al. (1995) as the northeastward prolongation of the Cittanova Fault, based on combined structural and geomorphic data. The ITDS023 Capo Vaticano and ITDS024 Vibo faults are proposed by Monaco & Tortorici (2000), also based on geological and geomorphic evidence.

Table 2 shows an attempt to estimate the depth at which these faults should intercept the E-dipping, A1-type faults, based on the geometry derived for the corresponding Individual Seismogenic Sources and on assumptions on the missing parameters of the A2-type faults. Assuming that the fault dip is constant and falls in the range 40° and 70°, we obtained interception depths in the range 4.3 to 12.1 km, corresponding to a fault width bracketed in the range 3.5 to 17.3 km under the assumption that dynamic slip occurs only below 1.0 km. Based on the relationships proposed by Wells and Coppersmith (1994) for the regression between fault width and moment-magnitude this range converts into a M_w range of 5.3 to 6.5. Notice,

however, that the inferred depth must be regarded as an absolute maximum for the bottom depth of seismogenic faulting. Also, it should be considered as theoretical, due to the very mechanism of fault inception in crestal collapse settings (for an overview: Nemčok, 2016) . Nevertheless, even the upper bound of this range is smaller than the maximum magnitude assigned to the largest Calabrian earthquakes (see the relevant table in Figure 3).

CONTRACTIONAL SEISMOGENIC SOURCES

Among the several thrust faults that are known to be part of the Calabrian accretionary wedge we identified five potential Composite Seismogenic Sources (Figure 5: see also the "Thrust faulting in the Ionian accretionary wedge" subsection). They all dip landwards (northwestward) and lie within the inner (pre-Messinian) accretionary wedge. The ITCS095, ITCS096 and ITCS097 lie in the Western lobe, while the ITCS098 and ITCS099 are located in the Eastern lobe.

The ITCS095 and ITCS098 represent the outermost faults of the wedge system. We consider them seismogenic between 4-9 km depth and assign them a dip angle between 10° and 25°.

The Western lobe is assumed to host two additional seismogenic sources in its more internal portions. The innermost of them, the ITCS097, is marked by a major topographic scarp producing a 600-700 m offset in the seafloor (Polonia et al., 2011). These are thrust faults extending between 4 and 12 km depth. In the lack of more precise constraints, we estimated their slip rate by subdividing the expected regional shortening velocity among the three of them, which yields 0.5-1.3 mm/y for each individual system.

In the Eastern lobe we identified one additional thrust fault - the ITCS099 - which lies landwards with respect the more external ITCS098 source. We consider it seismogenic in the depth range 3-12 km with a dip angle that varies between 10° and 40°. The 0.8 to 2.0 mm/y slip rate, the same hypothesised also for the ITCS098, has been estimated in the same way described for the sources of the Eastern lobe.

No Individual Seismogenic Sources have been hypothesised in this area yet, nor is any large earthquake known for it; nevertheless, the size and the geometry of accretionary wedge thrust faults are fully consistent with an expected maximum magnitude of ≥ 7.0 for all corresponding seismogenic sources.

STRIKE-SLIP SEISMOGENIC SOURCES

Four main strike-slip faults break through the thrust belt, dissecting the extensional axis of the Calabrian Arc into three major portions (Figure 6; see also the "Shear zones and strike-slip faulting" subsection).

The ITCS042 Composite Seismogenic Source is a near-vertical, right-lateral strike-slip fault that is part of the Tindari-Letojanni Line, an important NNW-trending dextral - or moderately oblique - system inferred from stratigraphic and structural data (Ghisetti & Vezzani, 1979). A segment of the ITCS042 source has been associated with the M_w 6.1, 15 April 1978 earthquake (ITIS045 source, see Figure 6). The location of this earthquake falls at sea between the Island of Vulcano and the northern coast of Sicily. The area that experienced the largest effects includes a 30 km-long stretch of the coastline of northern Sicily, centred near the on-land portion of the Tindari-Letojanni Line (Barbano et al., 1979). The first focal mechanism obtained for the mainshock shows prevalent strike-slip motion with planes striking northwest, right-lateral, and northeast, left-lateral (Del Pezzo & Martini, 1982). The right-lateral solution is in agreement with the strike of the Tindari-Letojanni Line, and with the orientation of present-day stress field (e.g. Fabbri et al., 1980). Later work by Gasparini et al. (1985) estimated a hypocentral depth of 10 km and confirmed the prevalently strike-slip motion.

The ITCS068 Composite Seismogenic Source lies at the northern end of the investigated region. It is a near-vertical left-lateral strike-slip fault that stretches E-W between the Sila massif to north and the Serre Mts. to the south.

Two additional Composite Seismogenic Sources lying between the ITCS042 and ITCS068 are responsible for the along-strike segmentation of the Calabrian Arc. The ITCS080 Composite Seismogenic

Source is the onshore portion of the northernmost of these two lineaments, marking a sharp transition from the uplands of the Serre Mts. to the Gioia Tauro basin, and is thought to act as a transverse feature bounding the Gioia Tauro Fault to the north (see Section on Extensional Seismogenic Sources). The ITCS055 Composite Seismogenic Source is modelled as a high-angle transtensional fault representing the onshore portion of the southernmost lineament. A segment of the ITCS055 has been associated with the 6 February earthquake (ITIS040 source: its magnitude is poorly defined). This source separates two Individual Seismogenic Sources that are thought to have ruptured during the 16 November 1894 complex earthquake sequence, the ITIS041 and ITIS042. The southeasternmost segment of the ITCS055 has been associated with the M_w 5.9, 23 October 1907 earthquake (ITIS043) that struck the Ionian coast of southern Calabria and the northeastern flank of the Aspromonte Massif. Based on the results presented in this paper, however, the 1907 earthquake could be interpreted as having been generated by an A2-type fault belonging to a system of west-dipping faults that we postulate to lie on the Ionian side of the Aspromonte-Serre range (see sub-section "Filling in the knowledge gaps based on geodynamics").

DISCUSSION

The investigations on the seismotectonics of the Calabrian Arc have often neglected its recent geodynamics and the hierarchy implied in the relationships between the ongoing subduction and the evolution of the overlying shallow crust. As the active faulting is nothing but a surface manifestation of the mantle dynamics of this unique area of the central Mediterranean, we believe it is appropriate to step back from shallow seismogenic sources and put the evolution of the Calabrian Arc into a broader geodynamic perspective.

ALTERNATIVE MODELS

As we mentioned earlier, current interpretations of the seismicity and the seismotectonics of the Calabrian Arc mainly refer to two alternative – and, apparently, mutually exclusive - views. The first, originally described by Tortorici et al. (1995) and Monaco & Tortorici (2000), among others, postulates the existence of a "Siculo-Calabrian Rift Zone" (Figure 2). In the portion of the Calabrian Arc that we are analysing the SCRZ envisions a series of large, west-dipping normal faults running along the Tyrrhenian coast and bordering to the east its main depositional basins (with the sole exception of the Taormina Fault, which dips to the east), that would also be responsible for fast uplift and subsequent erosion of the chain (see also Jacques et al., 2001; Galli & Bosi, 2002; Tortorici et al., 2003; Catalano et al., 2008; Ferranti et al., 2008). According to this model, which we refer to as the "Rifting model", such faults have been active at least since the Early Pleistocene, causing the inception of the longitudinal basins along the Calabrian Arc, and are responsible for the largest historical earthquakes. The Rifting model, however, is broadly incompatible with the growing evidence for active thrusting in the Ionian Sea and with the well documented regional-scale uplift affecting the entire region, not just the fault footwall areas. An additional limitation of the Rifting model is that it does not take into account the transversal elements presented in the literature (e.g. Knott & Turco, 1991; van Dijk, 1992; Del Ben et al., 2008). These transverse faults break down the extensional and contractional belts, thus affecting the length of the large normal or thrust fault systems, and may also be responsible for significant earthquakes (Fabbri et al., 1980), similarly to other regions in the Mediterranean Area. For instance, in a recent paper based on high-resolution 3D seismic imaging of the Hellenic Arc subduction, Sachpazi et al. (2016) revealed segmentation of the slab by transverse, predominantly strike-slip faults causing significant lower crustal or even subcrustal earthquakes. The transverse structures affecting the Northern Apennines and the Southern Alps compressional belts were recently interpreted as the brittle response of the upper lithosphere to the lateral changes in the geometry of the subducted slab; subduction in the northern Apennines is more mature than in the Calabrian Arc, yet the main transverse lineaments are held responsible for a number of small to mid-size earthquakes (Vannoli et al., 2015).

The second alternative view, which is that presented in this work, is referred to as the "Subduction-top model". It postulates the existence of a series of large, east-dipping normal faults along the Tyrrhenian side of the Calabrian Arc, dissected at right angles by strike-slip faults crossing the whole region. To the east, in the offshore, a set of thrust faults characterises the accretionary wedge that lies above the plate interface. This view is supported by all the potentially seismogenic sources that we elucidated in detail in the previous section and that are model-independent: rather they rest on the elaboration of instrumental data from the 1908 earthquake (Capuano et al., 1988; Valensise, 1988; Pino et al., 2000; Pino et al., 2009), on direct evidence for active faulting in the Sant'Eufemia Gulf (Loreto et al., 2013), on robust geomorphic evidence (Cucci et al., 1996) and geochemical data (Pizzino et al., 2004) from the Gioia Tauro Plain, and on good quality industrial seismic reflection profiles in the Ionian offshore (e.g. Rossi & Sartori, 1981; Cernobori et al., 1996; Merlini et al., 2000; Finetti, 2005; Minelli & Faccenna, 2010; Polonia et al., 2011; Gallais et al., 2012).

The seismotectonic diversity implied in the "Subduction-top model" in fact captures the much larger variety of occurrences that is necessary to explain the location and characteristics of the most significant Calabrian earthquakes. In contrast, the "Rifting model" attempts to explain only the fault activity seen along the main trend of the Calabrian Arc, thus failing to explain equally active structural features such as the strike-slip and thrust faults documented in the offshore.

MATCHING THE GEODYNAMIC EXPECTATIONS

Figure 7 is an idealized cross-section showing the pattern of faults that are expected to lie within the overriding plate in a W-directed subduction (Doglioni, 1999), superimposed on the fault configuration comprising the "Subduction-top model". The good match between the geometry of the two fault patterns suggests that the "Subduction-top model" is a direct consequence of the south-eastward roll-back of the hinge of the subducting Ionian lithosphere being the main local geodynamic engine (Malinverno & Ryan, 1986). This process would cause extensional collapse of the orogenic belt, the development of the back-arc

basins on the Tyrrhenian side of Calabria, and the creation of a big accretionary wedge accompanied by large thrust faults on its Ionian side, just as observed along the Southern Calabrian Arc. More specifically, this view assumes an eastward-migrating mantle flow, which generates and controls shear stress at the base of the overlying brittle crust (Doglioni et al., 1999; Baccheschi et al., 2007; Barba et al., 2008). In turn this process triggers a sort of "differential drag" affecting the deeper portion of the crust, thus causing the nucleation of low-angle normal faults dipping towards the east and southeast (Doglioni et al. 1999). These large faults affecting the overriding plate lie antithetic to the subduction plane (e.g. Charvet & Ogawa, 1994), along with a number of associated, high-angle normal faults at a lower hierarchical level, in their turn synthetic with respect to the subduction plane (Figure 7). This configuration matches the observation that the dominant – albeit rather subdued – geomorphic signal is that associated with the east-dipping faults (A1-type, Figure 3), which are also larger and deeper than their west-dipping counterparts (A2-type, Figure 4 and Table 2), thus justifying the occurrence of larger earthquakes.

The cross-section in Figure 7 also shows that *per se* the faults belonging to the Rifting model and those belonging to the "Subduction-top" model are not mutually exclusive; rather, they may coexist – at least partially. Analogue modelling carried out by Bonini et al. (2011) to reproduce the active faulting in the Messina Straits shows that the west-dipping normal faults (A2-type) may well represent the only surface expression of a deeper, larger, east-dipping blind normal fault (A1-type). Petricca et al. (2015) analyse the seismogenic role of normal faults at the back of an orogen, concluding that east-dipping and west-dipping fault systems are both capable of releasing earthquakes, depending on local conditions. Hence, while we maintain that the east-dipping faults release large earthquakes, we cannot rule out that also these seemingly secondary faults hold a sizable seismogenic potential, especially those located more to the east as they could approach the master fault more at depth (see Table 2 and discussion in the section "A2-type: Steep west-dipping faults").

We thus acknowledge that neither model is able to fully explain the puzzling seismicity of Calabria. Recent literature shows that other potential seismogenic faults still lie unmapped, such as the

Alfeo Fault and other thrust faults within the accretionary wedge (Polonia et al., 2011, 2012; Gallais et al., 2012; Gutscher et al., 2016). Also, no large historical or instrumental earthquake has been yet associated with the plate interface at crustal depths. Subduction interfaces are known to be the site of large or very large earthquakes in most subduction zones worldwide, as recently shown for example by the M_w 8.8, 2010 Maule, Chile (Lorito et al., 2011) and the M_w 9.0, 2011 Tōhoku-Oki, Japan earthquakes (Ozawa et al., 2011), though their frequency may be extremely variable due to the large diversity in plate size and convergence rates (e.g., Lay & Bilek, 2007).

EXPLORING THE GEODYNAMIC COMPLEXITY

Different kinematic models have been postulated during the '70s and '80s to describe the origin of the Calabrian Arc and to explain the processes that contributed to shaping it: this wealth of models is remarkably well summarised in Van Dijk & Okkes (1991) (Figure 8). These investigators provided a long-standing, clear breakdown of the numerous views into four main sets of models, each set being based on a preferential tectonic interpretative key:

- Models#1 (Translation) focus on the existence of south-eastward-trending shear zones that accompanied the progressive shift of independent portions of the arc to their present position;
- Models#2 (Sphenochasm) invoke a counterclockwise rotation of the arc coupled with north-eastward migration;
- Models#3a (Bending) concentrate on the arc geometry and on the folds and faults associated with it in the fore-arc and back-arc; and finally
- Models#4 (Radial Drift) imply the 'break-up' of the arc in a number of wedges migrating in different directions.

Each of these rather diverse models inevitably tends to highlight only a few of all the elements comprising the Calabrian tectonic puzzle. For instance, the "Translation models" point to the transverse lineaments, assumed to exhibit strike-slip kinematics, as the main structural elements guiding the

progressive deformation of the Calabrian Arc. In their turn the "Bending" and "Radial drift" models stress the role of the normal/thrust fault pairs that propagate jointly towards the foreland. More recently, new data and further syntheses in the literature have shown a preference for models 1) and 3), while models 2) and 4) have been abandoned (Knott and Turco, 1991; Martini et al., 2001; Marshack, 2004; Rosenbaum and Lister, 2004; Schellart and Lister, 2004; Weil and Sussman, 2004; Edwards and Grasemann, 2009; Polonia et al., 2011, 2012). Other investigators have highlighted the role of subduction in controlling the topography and tectonics of the upper plate in the Calabrian Arc, focusing on the geodynamic processes (Faccenna et al., 2011 and references therein; Neri et al., 2012; among others) but without investigating in detail the relationships between subduction and crustal seismogenic process.

Despite being based only on shallow crustal data, the "Subduction-top model" fits convincingly the expectations based on the understanding of the recent geodynamic evolution of the Southern Calabrian Arc arising from the most recent works. It also ideally draws some elements from the "Translation" and "Bending" kinematic models discussed above, since it includes (i) length-wise normal fault segmentation in the back-arc, (ii) portions of thrust fronts forwarding in the fore-arc, and (iii) strike-slip transverse faults dissecting the remains of the thrust-belt onshore, possibly as a consequence (in the upper plate) of lateral discontinuities of the subduction interface (in the lower plate).

FILLING IN THE KNOWLEDGE GAPS BASED ON GEODYNAMICS

As we mentioned earlier, our seismotectonic model implemented in the DISS database is still incomplete, some crucial questions are still unanswered and, as a result, some large seismogenic faults are still undetected. Some of the largest historical earthquakes are still not associated with a causative fault (e.g.: the M_w 7.0, 28 March 1783 event) or, when they are, the association shows a high score of uncertainty. Can the geodynamic framework delineated in this paper be exploited to identify these missing sources? We believe that the location and parameters of the missing faults can be hypothesised based on the "Subduction-top model", taking the scheme of Figure 7 as a guidance.

Figure 9 suggests that this exercise is interesting and potentially fruitful, showing a number of distinctive features:

- as stated earlier, in a subduction domain the main normal faults lie antithetic to the subduction plane (Figure 7), and it is reasonable to assume that they may host the largest earthquakes;
- between 1783 and 1908 five large earthquakes ruptured the section of the western extensional domain of the Southern Calabrian Arc, fully encompassing the ~130 km distance between the Tindari-Letojanni Line and the unnamed lineament bordering the Catanzaro Straits to the north (see also Figures 3, 6);
- more specifically, three major shocks of the 1783 earthquake sequence (5 February, M_w 6.6; 7 February, M_w 6.6; 1 March, M_w 5.9) ruptured the central portion of the Arc within less than a month, while the 1905 (M_w 7.0) and 1908 (M_w 7.1) earthquakes ruptured the extreme portions of the Arc within a three year time interval;
- according to Pino et al. (2000, 2009) and Convertito & Pino (2014) the 1908 earthquake ruptured with south-to-north directivity, while the combined evidence supplied by Loreto et al. (2013) and Sandron et al. (2015) suggests that the 1905 may have ruptured with north-to-south directivity.

We can argue that these five earthquakes caused the complete rupture of the western shoulder of the Southern Calabrian Arc seismogenic backbone between 1783 and 1908. Based on the same assumptions, we can consequently argue that other smaller earthquakes, such as the 14 October 1784 (M_w 5.2), the 23 October 1907 (M_w 5.9) and the 11 March 1978 (M_w 5.2), all of which appear to have occurred east of the main drainage divide of southern Calabria, may have been generated by a system of west-dipping normal faults (A2-type: Figure 7). This system may continue for the entire length of the Southern Calabrian Arc – and possibly also along the Northern Calabrian Arc. Akinci et al. (2015) propose that even the much larger 28 March 1783 earthquake (M_w 7.0) may have occurred on a west-dipping fault; this event, however, may have been overestimated due to its being the last major shock of a long and destructive

sequence. Though rather speculative – it will require some careful field work in a geologically complex area – this hypothesis would:

- fit the predictions based on the geodynamic considerations delineated above;
- supply a tentative model for locating the sources of the 1784, 1907 and 1978 earthquakes;
- highlight that between the north-eastern flank of the Aspromonte Massif and the core of the Serre Mts. may still lie a considerable seismogenic potential.

We may remark that most if not all of the "anomalies" that characterise the Southern Calabrian Arc with respect to the rest of the Italian peninsula, such as faster uplift rates, faster tectonic rates, larger earthquake rates, and larger magnitude earthquakes, are different aspects of the same process: our conclusion is that subduction explains them all.

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Table 1 – Summary of the characteristics of large seismogenic faults discussed in the literature. Notice that most of these faults are shown at small or very small scale, and that only in a few cases the relevant geometric parameters are explicitly supplied. SCRZ: Siculo-Calabrian Rift Zone.

Original reference	Fault/ fault zone	Scale of regional map	Scale of individual segments	Fault parameters										Method(s) of investigation	Long-term displacement (m)
				Len	Wid	Z_{min}	Z_{max}	Strike	Dip	Rake	D_{avg}	SR	M_w		
Ghisetti, 1979	Serre	--	1/385,000	--	--	Yes	--	Yes	Yes	Yes	--	--	--	S	--
Ghisetti & Vezzani, 1981	Calabrian Arc/Sicily	1/5,500,000	--	--	--	Yes	--	--	--	--	--	--	--	G, M, S	--
Ghisetti & Vezzani, 1982	Calabrian Arc	1/16,000,000	--	--	--	Yes	--	--	--	--	--	--	--	G, M, S	--
Ghisetti, 1984	Messina	1/18,000,000 1/8,600,000 [1]	1/1,725,000 [2]	--	--	Yes	--	--	--	--	--	--	--	G, M, S	--
Ghisetti, 1992	Messina	--	1/137,000 [2]	Yes	--	Yes	--	Yes	Yes	Yes	Yes	Yes [a]	--	S, SS	Yes
Tortorici et al., 1995	All of SCRZ	1/1,175,000	1/180,000 [3, 4, 5]	Yes	--	Yes	--	Yes	--	Yes	--	Yes [b, c]	--	M, S	Yes [a, b]
Monaco et al., 1996	Southern Calabria	1/1,000,000	1/200,000 [2]	--	--	Yes	--	--	--	--	--	--	--	S, SS, M	--
Monaco & Tortorici, 2000	All of SCRZ	1/1,850,000	--	Yes	--	Yes	--	--	--	Yes	Yes	Yes [b]	Yes	G, M	Yes [a]
Jacques et al., 2001	Sant'Eufemia	1/1,670,000	--	--	--	Yes	Yes [a]	--	Yes	Yes	--	--	Yes	S, G	Yes [a]
Jacques et al., 2001	Galatro	1/1,670,000	--	--	--	Yes	Yes [a]	--	Yes	Yes	--	--	Yes	S, G	Yes [a]
Jacques et al., 2001	Cittanova	1/1,670,000	1/290,000 [3]	--	--	Yes	Yes [a]	Yes	Yes	Yes	--	--	Yes	S, G	Yes [a]
Catalano et al., 2008	All of SCRZ	1/1,250,000	1/270,000 [2]	Yes	--	Yes	--	--	--	--	--	Yes [a]	Yes	P, G, M	Yes [a]
Ferranti et al., 2008	Scilla	1/667,000	1/77,000 [6]	Yes	--	Yes	--	--	Yes	Yes	Yes	Yes [d]	Yes	G	Yes
Galli & Peronace, 2015	Cittanova	1/3,333,333	1/167,000 [3]	Yes	--	Yes	--	Yes	Yes	--	--	Yes [e]	--	P, G	Yes [a]
Pirrotta et al., 2016	Southern Calabria	1/1,000,000	1/400,000 [1]	--	--	--	--	--	--	--	--	--	--	M	--

Scale of regional maps and individual segments, Key to fault names: 1: Southern Calabria; 2: Messina Straits; 3: Cittanova; 4: Sant'Eufemia; 5: Reggio Calabria; 6: Scilla.

Fault parameters: Len: Length; Wid: Width (km); Z_{min}: Minimum Depth; Z_{max}: Maximum Depth; D_{avg}: Average displacement; SR: slip rate. The dip angle is estimated at the surface.

Z_{min}: all the faults are assumed to be surface breaking;

Z_{max}: a: inferred from regional seismogenic thickness;

SR: a: vertical component, unspecified time interval; b: vertical component during past 700 ka; c: vertical component during past 125 ka; d: vertical component during the Holocene; e: vertical component during past 28 ka.

Method of investigation: P: Paleoseismology; G: Geomorphology; M: basic geological Mapping; S: Structural geology; SS: Sedimentology/Stratigraphy.

Long-term displacement: a: height of mountain front/triangular facets; b: displacement of Late Pliocene-Lower Pleistocene beach deposits.

Table 2 - Theoretical depth of intersection between the four main A1-type faults (Figure 3) and the overlying A2-type faults (Figure 4). As the dip angle of the fault is generally not supplied, we calculated the range of intersections using dip=40° and dip=70° as two end members. Notice that in most cases the faulted volume is shallower than 8.1 km, implying a fault width in the range 7 to 12 km. Standard empirical relationships between rupture width and M_w for normal faulting (Wells and Coppersmith, 1994) indicate that the seismogenic potential of A2-type faults should not exceed M_w 6.0 for closer faults (Cittanova, Reggio Calabria, Serre, Vibo) and M_w 6.5 for farther faults (Armo, Serre).

Source name (A1-type)	Fault name 1 (A2-type-closer)	Depth of intersection (km)	Fault name 2 (A2-type-farther)	Depth of intersection (km)
Sant'Eufemia	Vibo	4.3-6.4	Serre	8.1-12.1*
Upper Mesima Basin	Serre	5.2-7.2	--	--
Gioia Tauro Plain	Cittanova	5.5-8.1	--	--
Messina Straits	Reggio Calabria	5.2-7.2	Armo	7.5-10.4

* Depth of hypothetical intersection (A2-type fault intersects only the downward prolongation of the A1-type fault).

FIGURE CAPTIONS

Figure 1 - Key structural, seismicity and geodynamic characteristics of the broader region surrounding the Calabrian Arc. a) seismicity, historical earthquakes, focal mechanism solutions and recorded tsunami effects; b) main structural elements and active faults; c) velocity and stress vectors, respectively from GPS observations and worldwide tectonic stress compilations.

Figure 2 - Overview of active fault systems affecting the Calabrian Arc as reported in the literature. These systems, which are mostly extensional, include the Siculo-Calabrian Rift Zone (after Tortorici et al., 1995; Monaco and Tortorici, 2000; Jacques et al., 2001) and were named after the fault/basin/valley they are centered on (red labels). Hachured lines: normal faults; sawteeth lines: thrust faults; simple line: strike-slip faults. Geographic features are labeled in black.

Figure 3 - Summary of the characteristics of the seismogenic sources in the Southern Calabrian Arc from the DISS database: the east-dipping normal faults (A1-type). Top left: Summary table of most important characteristics (earthquake data from Rovida et al., 2011; tsunami data from NOAA/WDC Tsunami Event Database). Above right: Map of the seismogenic sources. The A1-type sources are highlighted and labelled (DISS Working Group, 2015). Below: Lists of the main parameters of the Individual, Composite and Debated Sources belonging to the A1-type. M: magnitude; I: Intensity. ITXS###: univocal code for each Italian source, where: IT is the official code for Italy; XS identifies the category of source (IS: Individual, CS: Composite, DS: Debated); and ### is a unique number selected for each source. EQ, EQS stand for earthquake(s).

Figure 4 – Same as in Figure 3 for the west-dipping normal faults (A2-type).

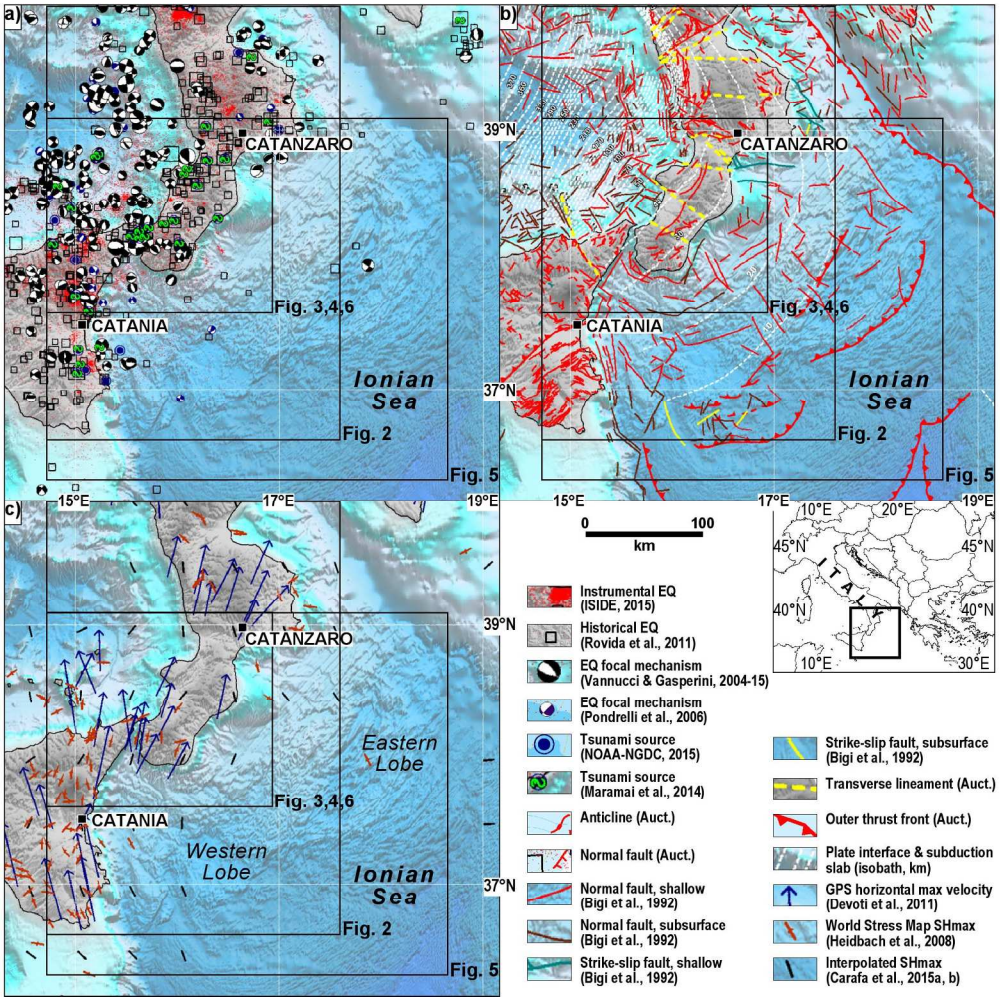
Figure 5 – Same as in Figure3 for the thrust faults (B-type).

Figure 6– Same as in Figure 3 for the strike-slip faults (C-type).

Figure 7 - Above: Schematic section showing an active and retreating W-dipping subduction, as the Calabrian Arc is assumed to be, and the main tectonic and structural elements related to the system (redrawn from Doglioni et al., 1999). In this conceptual model the inner (westernmost) compartment of the overriding plate is deformed by low-angle, overriding normal faults antithetic to the subduction plane and by their high-angle conjugate systems (Source types A1 and A2, respectively: Figures 3 and 4). Conversely, in the external (easternmost) compartment the accretionary wedge is deformed by thrust splays synthetic to the subduction plane (Source type B, Figure 5).. Below: Schematic view of the geometrical relationships between DISS' fault types A1, A2 and B, shown in the general context of the Calabrian subduction (no vertical exaggeration). The geometry and location of each category of faults appears to fit well the model predictions. Topography and bathymetry are from the GEBCO global 30 arc-second interval grid (The General Bathymetric Chart of the Oceans, available at http://www.gebco.net/). The top of the Moho is taken from the compilation of the EUCOR-URGENT Project (https://comp1.geol.unibas.ch/).

Figure 8 - Synoptic view of the four main groups of earlier kinematic models proposed in the literature to explain the emplacement of the Calabrian Arc (after van Dijk and Okkes, 1991, redrawn and modified). The two columns to the left assembles each group, listing the papers where each model was first presented. The central column graphically synthesises the key elements of each group. The column on the right, not present in the original figure by van Dijk and Okkes (1991), shows the superposition of the main features of each model upon the main structural trends shown in Figures 1 and 2 (i.e the Siculo-Calabrian Rift Zone by Tortorici et al., 1995, and the 2D features associated with the Composite Sources of DISS Working Group, 2015, and references therein). Notice that groups #1 and #3 exhibit a good fit with the geological syntheses, whereas models #2 and #4 are more difficult to reconcile with the tectonic evidence.

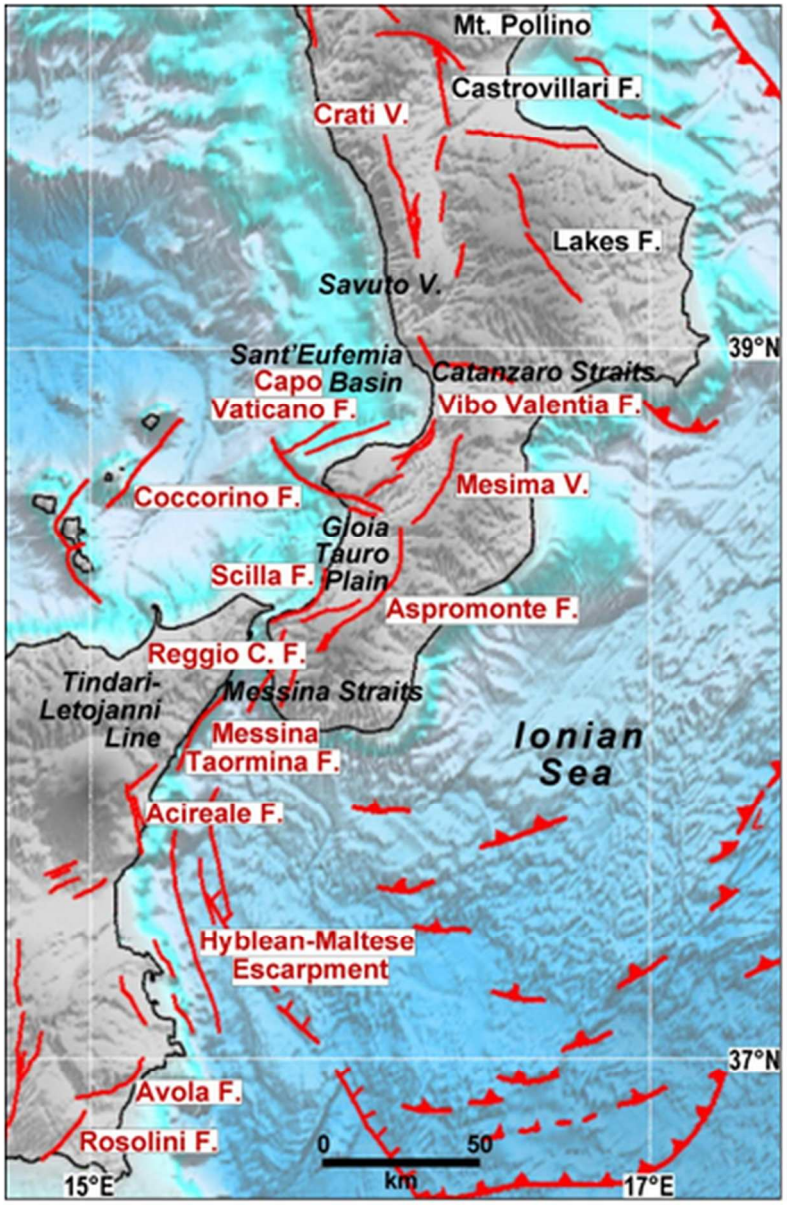
Figure 9 – Overview of the extensional Composite Sources associated (from south to north) respectively with the 1908 Messina Straits earthquake, with the second, first, third and fourth mainshocks of the 1783 sequence (6 February, 5 February, 7 February and 1 March, respectively), and with the 1905 Sant'Eufemia earthquake. Notice that the first and third 1783 mainshocks were caused by large normal faults, while the second event is thought to have occurred on a segment of the strike-slip transverse structure that separates the Messina Straits from the Gioia Tauro plain – and hence separates the associated large normal faults. Seismological data in Pino et al. (2000) show evidence of northward directivity for the source of the 1908 Messina earthquake, whereas the modeling proposed by Sandron et al. (2015) may be used to infer a southward directivity for the source of the 1905 Sant'Eufemia earthquake. No source as been proposed yet for the fifth destructive mainshock of the 1783 sequence (28 March).



Key structural, seismicity and geodynamic characteristics of the broader region surrounding the Calabrian Arc. a) seismicity, historical earthquakes, focal mechanism solutions and recorded tsunami effects; b) main structural elements and active faults; c) velocity and stress vectors, respectively from GPS observations and worldwide tectonic stress compilations.

Figure 1

187x185mm (300 x 300 DPI)

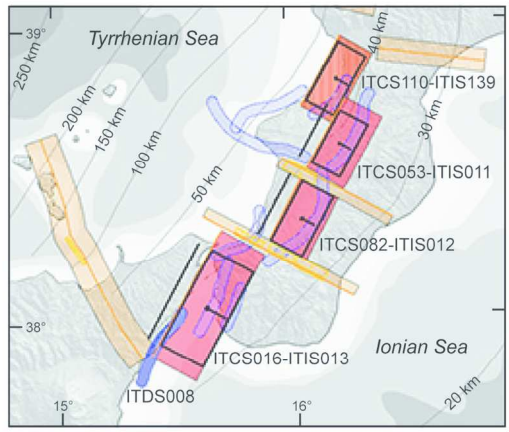


Overview of active fault systems affecting the Calabrian Arc as reported in the literature. These systems, which are mostly extensional, include the Siculo-Calabrian Rift Zone (after Tortorici et al., 1995; Monaco and Tortorici, 2000; Jacques et al., 2001) and were named after the fault/basin/valley they are centered on (red labels). Hachured lines: normal faults; sawteeth lines: thrust faults; simple line: strike-slip faults. Geographic features are labeled in black.

Figure 2

90x137mm (300 x 300 DPI)

Source Type	A1
Structural setting	Back-arc
Structural type	Overriding antithetic
Faulting style	Normal faulting
Dip	Low-angle
Benioff plane depth	~ 45-35 km
Largest associated EQ	28.12.1908 M_w 7.1
Largest associated tsunami	28.12.1908 I 5
Remarks	Sources responsible for the largest known historical EQS



Individual Seismogenic Sources

ID	Name	Length (km)	Width (km)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip (m)	Slip Rate (mm/y)	M	Latest EQ
ITIS139	Sant'Eufemia	25.0	14.4	0.5-9.4	31	38	270	2.00	0.11-0.3	6.8	8 Sep 1905
ITIS011	Upper Mesima Basin	22.0	13.5	3.0-9.8	30	30	270	1.09	0.1-1.0	6.6	7 Feb 1783
ITIS012	Gioia Tauro Plain	25.0	15.0	3.0-10.5	30	30	270	0.86	0.1-1.0	6.6	5 Feb 1783
ITIS013	Messina Straits	40.0	20.0	3.0-12.7	30	29	270	1.42	0.93-2.0	7.0	28 Dec 1908

Composite Seismogenic Sources

ID	Name	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip rate (mm/y)	Max M
ITCS110	Sant'Eufemia	0.5-12.0	25-35	35-45	260-280	0.11-0.3	6.8
ITCS053	Serre	3.0-11-0	20-40	20-40	260-280	0.1-1.0	6.6
ITCS082	Gioia Tauro	3.0-11-0	20-40	20-40	260-280	0.1-1.0	6.6
ITCS016	Aspromonte-Peloritani	2.0-13.0	20-40	25-40	250-280	0.9-2.0	7.0

Debated Seismogenic Sources

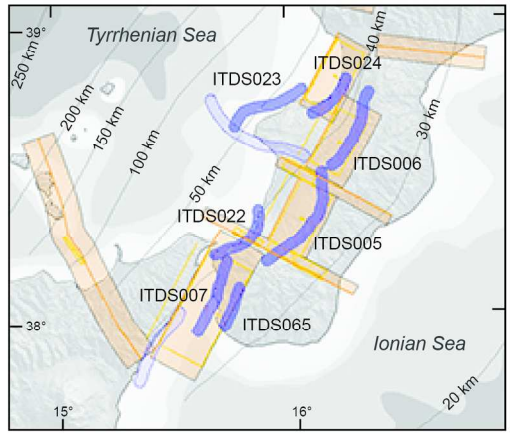
ID	Name	References
ITDS008	Taormina	Stewart et al., 1997

Summary of the characteristics of the seismogenic sources in the Southern Calabrian Arc from the DISS database: the east-dipping normal faults (A1-type). Top left: Summary table of most important characteristics (earthquake data from Rovida et al., 2011; tsunami data from NOAA/WDC Tsunami Event Database). Above right: Map of the seismogenic sources. The A1-type sources are highlighted and labelled (DISS Working Group, 2015). Below: Lists of the main parameters of the Individual, Composite and Debated Sources belonging to the A1-type. M: magnitude; I: Intensity. ITXS###: univocal code for each Italian source, where: IT is the official code for Italy; XS identifies the category of source (IS: Individual, CS: Composite, DS: Debated); and ### is a unique number selected for each source. EQ, EQS stand for earthquake(s).

Figure 3

181x160mm (250 x 250 DPI)

Source Type	A2
Structural setting	Back-arc
Structural type	Overriding conjugate
Faulting style	Normal faulting
Dip	High-angle
Benioff plane depth	~ 40-30 km
Largest associated EQ	Unknown
Largest associated tsunami	Unknown
Remarks	Root on A1 Type faults

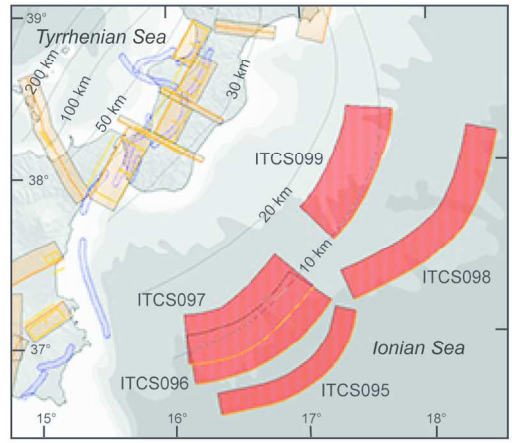


No Individual Seismogenic Sources
No Composite Seismogenic Sources
Debated Seismogenic Sources

ID	Name	References
ITDS023	Capo Vaticano	Monaco and Tortorici, 2000
ITDS024	Vibo	Monaco and Tortorici, 2000
ITDS006	Serre	Tortorici et al., 1995
ITDS005	Cittanova	Tapponier et al., 1987
ITDS022	Scilla	Ghisetti, 1992
ITDS007	Reggio Calabria	Ghisetti, 1992
ITDS065	Armo	Ghisetti, 1992

Same as in Figure 3 for the west-dipping normal faults (A2-type).
Figure 4
181x117mm (300 x 300 DPI)

Source Type	B
Structural setting	Accretionary wedge
Structural type	Synthetic splays
Faulting style	Thrusting
Dip	Low-angle
Benioff plane depth	NA
Largest associated EQ	Unknown
Largest associated tsunami	Unknown
Remarks	Mapped from seismic profiles



No Individual Seismogenic Sources

Composite Seismogenic Sources

ID	Name	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip rate (mm/y)	Max M
ITCS099	Calabria offshore NW	3.0-12.0	180-250	10-40	80-100	0.8-2.0	7.1
ITCS098	Calabria offshore NE	4.0-9.0	180-260	10-20	80-100	0.8-2.0	7.1
ITCS097	Calabria offshore SW	4.0-12.0	180-280	10-20	80-100	0-5-1.3	7.1
ITCS096	Calabria offshore S	4.0-12.0	190-270	10-20	80-100	0-5-1.3	7.1
ITCS095	Calabria offshore SE	4.0-9.0	190-270	15-25	80-100	0-5-1.3	7.1

No Debated Seismogenic Sources

Same as in Figure3 for the thrust faults (B-type).
Figure 5
181x119mm (250 x 250 DPI)

Source Type	C
Structural setting	Subduction linked
Structural type	Shear zone
Faulting style	Strike slip
Dip	Sub-vertical
Benioff plane depth	~ 25-200 km
Largest associated EQ	16.11.1894 M_w 6.1
Largest associated tsunami	23.10.1907 I 3
Remarks	Related to boundaries of the Subduction (ITCS068 and ITCS042) or/and dissects the back-arc extensional axis (ITCS068, ITCS080, ITCS055 and ITCS042)

Individual Seismogenic Sources

ID	Name	Length (km)	Width (km)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip (m)	Slip Rate (mm/y)	M	Latest EQ
ITIS044	Nicotera-Rosarno	12.5	8.8	3.0-11.3	120	70	315	0.37	0.1-0.5	6.0	7 Mar 1928
ITIS041	Scilla offshore	5.0	4.5	3.0-7.2	300	70	225	0.16	0.1-0.5	5.3	16 Nov 1894 (1/2)
ITIS040	Aspromonte Northwest	5.0	4.5	3.0-7.2	300	70	225	0.16	0.1-0.5	5.3	6 Feb 1783
ITIS042	Aspromonte Northeast	10.0	7.5	3.0-10.0	300	70	225	0.27	0.1-0.5	5.8	16 Nov 1894 (2/2)
ITIS043	Aspromonte East	12.5	8.8	3.0-11.3	300	70	225	0.37	0.1-0.5	6.0	23 Oct 1907
ITIS045	Patti Gulf	12.1	8.6	1.5-10.0	147	83	180	0.6	0.1-0.5	6.1	15 Apr 1978

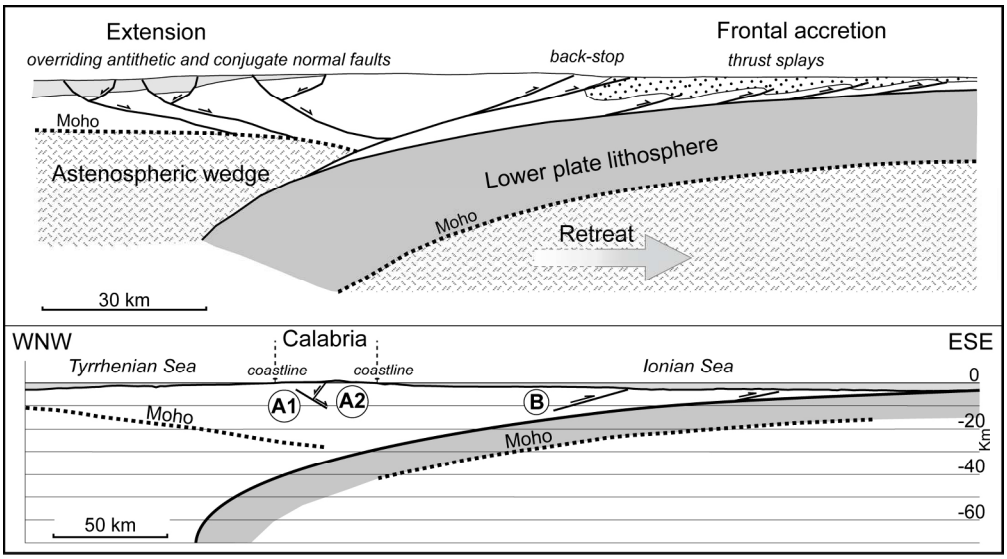
Composite Seismogenic Sources

ID	Name	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip rate (mm/y)	Max M
ITCS068	Caraffa-Squillace Gulf	3.0-20.0	90-110	70-90	330-10	0.1-0.5	6.9
ITCS080	Nicotera-Roccella Ionica	3.0-12.0	110-130	60-80	300-330	0.1-0.5	6.0
ITCS055	Bagnara-Bovalino	3.0-12.0	290-310	60-80	210-240	0.1-0.5	6.0
ITCS042	Patti-Eolie	1.0-25.0	140-170	70-90	180-220	0.1-0.5	6.1

Debated Seismogenic Sources

ID	Name	References
ITDS025	Coccorino	Monaco and Tortorici, 2000

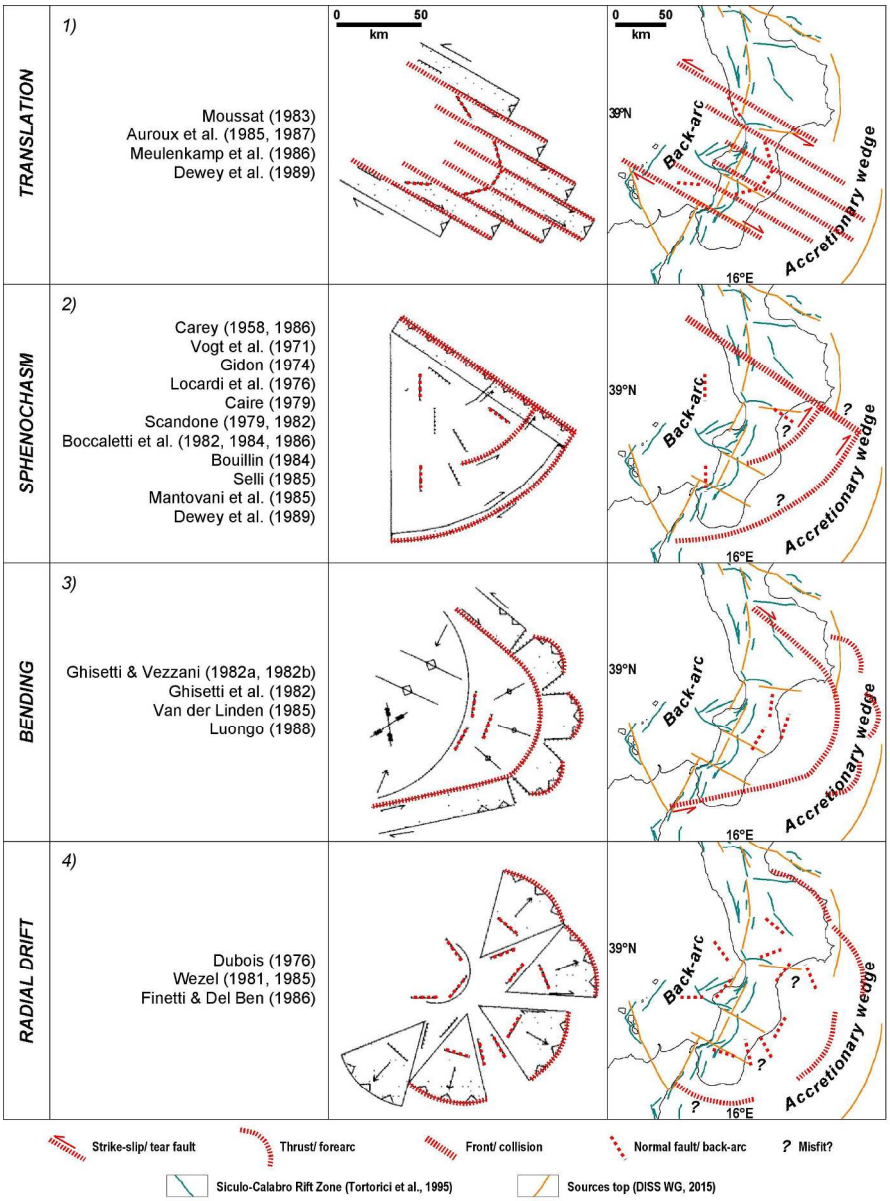
Same as in Figure 3 for the strike-slip faults (C-type).
Figure 6
181x167mm (250 x 250 DPI)



Above: Schematic section showing an active and retreating W-dipping subduction, as the Calabrian Arc is assumed to be, and the main tectonic and structural elements related to the system (redrawn from Doglioni et al., 1999). In this conceptual model the inner (westernmost) compartment of the overriding plate is deformed by low-angle, overriding normal faults antithetic to the subduction plane and by their high-angle conjugate systems (Source types A1 and A2, respectively: Figures 3 and 4). Conversely, in the external (easternmost) compartment the accretionary wedge is deformed by thrust splays synthetic to the subduction plane (Source type B, Figure 5).. Below: Schematic view of the geometrical relationships between DISS' fault types A1, A2 and B, shown in the general context of the Calabrian subduction (no vertical exaggeration). The geometry and location of each category of faults appears to fit well the model predictions. Topography and bathymetry are from the GEBCO global 30 arc-second interval grid (The General Bathymetric Chart of the Oceans, available at http://www.gebco.net/). The top of the Moho is taken from the compilation of the EUCOR-URGENT Project (https://comp1.geol.unibas.ch/).

Figure 7

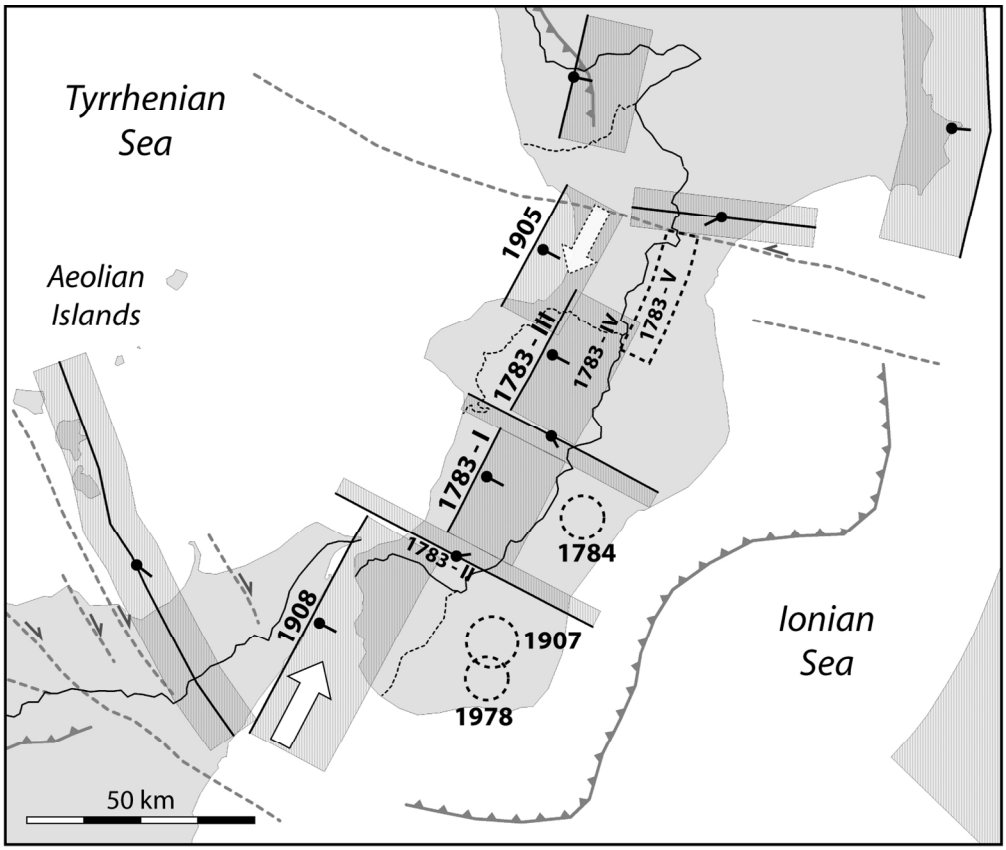
185x101mm (300 x 300 DPI)



Synoptic view of the four main groups of earlier kinematic models proposed in the literature to explain the emplacement of the Calabrian Arc (after van Dijk and Okkes, 1991, redrawn and modified). The two columns to the left assembles each group, listing the papers where each model was first presented. The central column graphically synthesises the key elements of each group. The column on the right, not present in the original figure by van Dijk and Okkes (1991), shows the superposition of the main features of each model upon the main structural trends shown in Figures 1 and 2 (i.e the Siculo-Calabrian Rift Zone by Tortorici et al., 1995, and the 2D features associated with the Composite Sources of DISS Working Group, 2015, and references therein). Notice that groups #1 and #3 exhibit a good fit with the geological syntheses, whereas models #2 and #4 are more difficult to reconcile with the tectonic evidence.

Figure 8

191x258mm (300 x 300 DPI)



Overview of the extensional Composite Sources associated (from south to north) respectively with the 1908 Messina Straits earthquake, with the second, first, third and fourth mainshocks of the 1783 sequence (6 February, 5 February, 7 February and 1 March, respectively), and with the 1905 Sant'Eufemia earthquake. Notice that the first and third 1783 mainshocks were caused by large normal faults, while the second event is thought to have occurred on a segment of the strike-slip transverse structure that separates the Messina Straits from the Gioia Tauro plain – and hence separates the associated large normal faults. Seismological data in Pino et al. (2000) show evidence of northward directivity for the source of the 1908 Messina earthquake, whereas the modeling proposed by Sandron et al. (2015) may be used to infer a southward directivity for the source of the 1905 Sant'Eufemia earthquake. No source as been proposed yet for the fifth destructive mainshock of the 1783 sequence (28 March).

Figure 9

131x110mm (300 x 300 DPI)