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Structure and morphology of an active conjugate relay zone, Messina Strait, southern Italy

Rebecca J. Dorsey[1] | **Sergio G. Longhitano**[2] | **Domenico Chiarella**[3]

[1]Department of Earth Sciences, University of Oregon, Eugene, Oregon, USA

[2]Department of Sciences, University of Basilicata, Potenza, Italy

[3]Department of Earth Sciences, Royal Holloway University of London, Egham, UK

Correspondence
Rebecca J. Dorsey, Department of Earth Sciences, University of Oregon, Eugene, OR, USA.
Email: rdorsey@uoregon.edu

Abstract

Messina Strait is a narrow fault-bounded marine basin that separates the Calabrian peninsula from Sicily in southern Italy. It sits in a seismically active region where normal fault scarps and raised Quaternary marine terraces record ongoing extension driven by southeastward rollback of the Calabrian subduction zone. A review of published studies and new data shows that normal faults in the Messina Strait region define a conjugate relay zone where displacement is transferred along strike from NW-dipping normal faults in the northeast (southern Calabria) to the SE-dipping Messina-Taormina normal fault in the southwest (offshore eastern Sicily). The narrow marine strait is a graben undergoing active subsidence within the relay zone, where pronounced curvature of normal faults results from large strain gradients and clockwise rotations related to fault interactions. Based on regional fault geometries and published age constraints, we infer that normal faults in southern Calabria migrated northwest while normal faults in NE Sicily migrated southeast during the past ca. 2–2.5 Myr. This pattern has resulted in tectonic narrowing of the strait through time by inward migration of facing normal faults and rapid mantle-driven uplift.

KEYWORDS

extension, Messina Strait, normal faults, Pleistocene, relay zone

1 | INTRODUCTION

Accommodation zones are a common feature of rift systems where offset is transferred along strike between adjacent normal faults (Childs et al., 1995; Gawthorpe & Hurst, 1993; McClay et al., 2002; Morley, 1995; Morley et al., 1990; Peacock & Sanderson, 1994; Rosendahl, 1987). They comprise of two main types: (1) synthetic accommodation zones, or relay ramps, where overlapping normal faults dip in the same direction; and (2) conjugate relay zones where faults have opposing dip direction. Conjugate relay zones are divided into graben-type, where normal faults dip towards each other to form a subsiding graben in the zone of fault overlap (Figure 1), and horst-type relay zones where crust is uplifted between normal faults that dip away from each other (Childs et al., 2019). Graben-type and horst-type relay zones are also designated with terms 'convergent' and 'divergent' respectively (Childs et al., 2019). Conjugate relay zones commonly display high lateral strain gradients and vertical-axis rotations related to slow lateral propagation of overlapping faults (Acocella et al., 1999, 2000; Childs et al., 2019; Ferrill & Morris, 2001; Imber et al., 2004).

The Messina Strait (Southern Italy) sits in a seismically active region where ongoing NW-SE extension is driven by southeastward rollback and retreat of the Ionian subduction zone and Calabrian forearc crust (Figure 2) (Faccenna et al., 2003; Gutscher et al., 2016; Rosenbaum & Lister, 2004). The Strait forms a narrow hook-shaped constriction where daily exchange of water masses between the Ionian and Tyrrhenian seas produces strong tidal currents that erode, mobilize and deposit sediment (e.g. Longhitano, 2018a; Martorelli et al., 2023). Numerous studies have documented active faults, earthquakes, tsunamis, sedimentation and uplift in this region (Aloisi et al., 2013; Antonioli et al., 2021; Barreca et al., 2021; Doglioni et al., 2012; Fu et al., 2017; Gallen et al., 2023; Ghisetti, 1981, 1992; Longhitano, 2018a, 2018b; Longhitano & Chiarella, 2020; Meschis, Roberts, et al., 2022; Meschis, Teza, et al., 2022; Monaco & Tortorici, 2000; Ridente et al., 2014), but uncertainty persists regarding the long-term evolution of active faults over the past 2–3 Myr, vertical crustal motions, growth of topography and seafloor bathymetry in this region.

This article integrates information from previous studies with new data to examine active extensional kinematics and structural controls on topography, bathymetry and sedimentation in the modern Messina Strait. We find that normal faults in this area define a conjugate relay zone (c.f. Childs et al., 2019), where displacement on opposed-dipping normal faults is transferred through a zone of overlap near the fault tips. The distinctive plan-view hook shape and strong curvature of basin-bounding normal faults reflect large strain gradients and clockwise rotations near the interacting faults. These fault interactions are part of a rapidly evolving 4D strain field related to ongoing extensional breakup of the Calabrian forearc region, as tear faults in the subducting Ionian slab propagate into the overlying forearc lithosphere.

Highlights

- Normal faults in the Messina Strait define an active extensional conjugate relay zone.
- Strain is transferred between opposed-dipping normal faults in southern Calabria and northeast Sicily.
- Plan-view fault curvature results from large strain gradients and rotations related to fault-tip interactions.
- Messina Strait has narrowed in the past ~2.5 Myr by inward migration of facing normal faults.

2 | TECTONIC AND GEOLOGIC SETTING

2.1 | Regional geology and tectonic stratigraphy

The central Mediterranean region has a complex history of Cenozoic thrusting and mountain building related to subduction at the Iberian margin, followed by rifting and opening of the Tyrrhenian Sea during rapid rollback

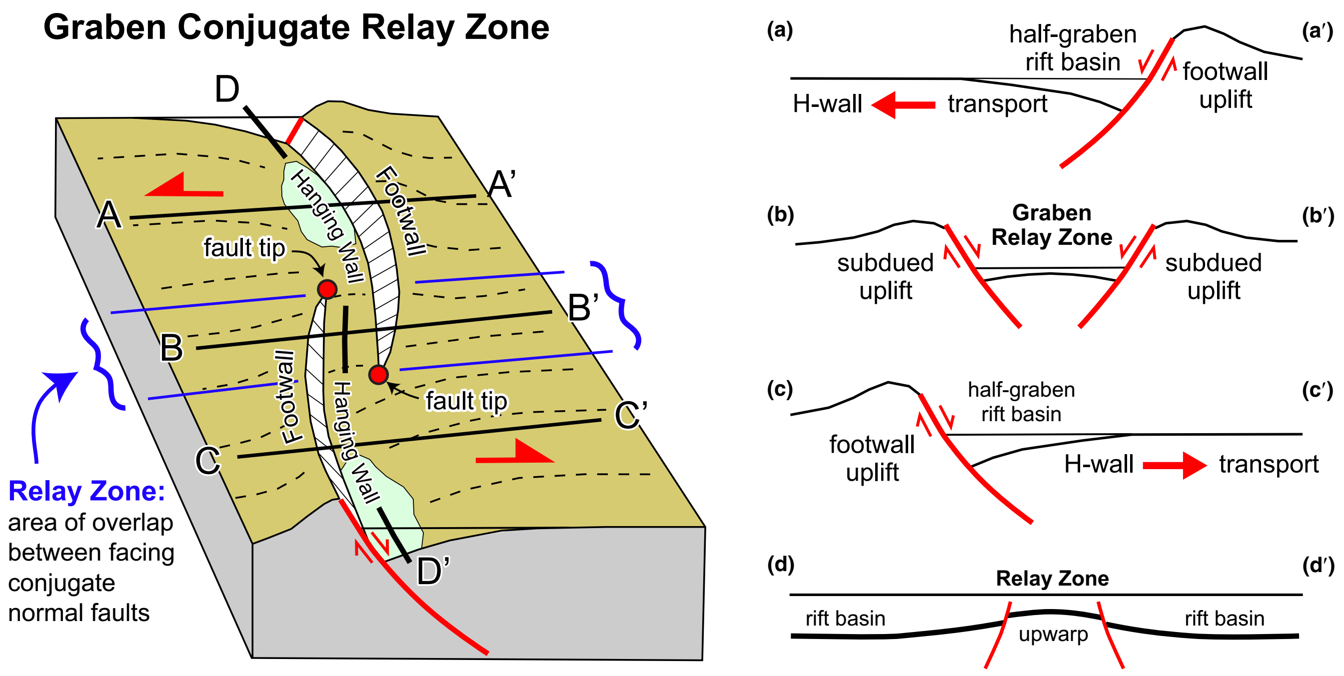


FIGURE 1 Major 3D geometries, idealized cross-sections and kinematics of interacting normal faults in a graben conjugate relay zone. Large strain gradients are commonly observed in the area of overlap (relay zone) where offset decreases along strike towards the fault tips.

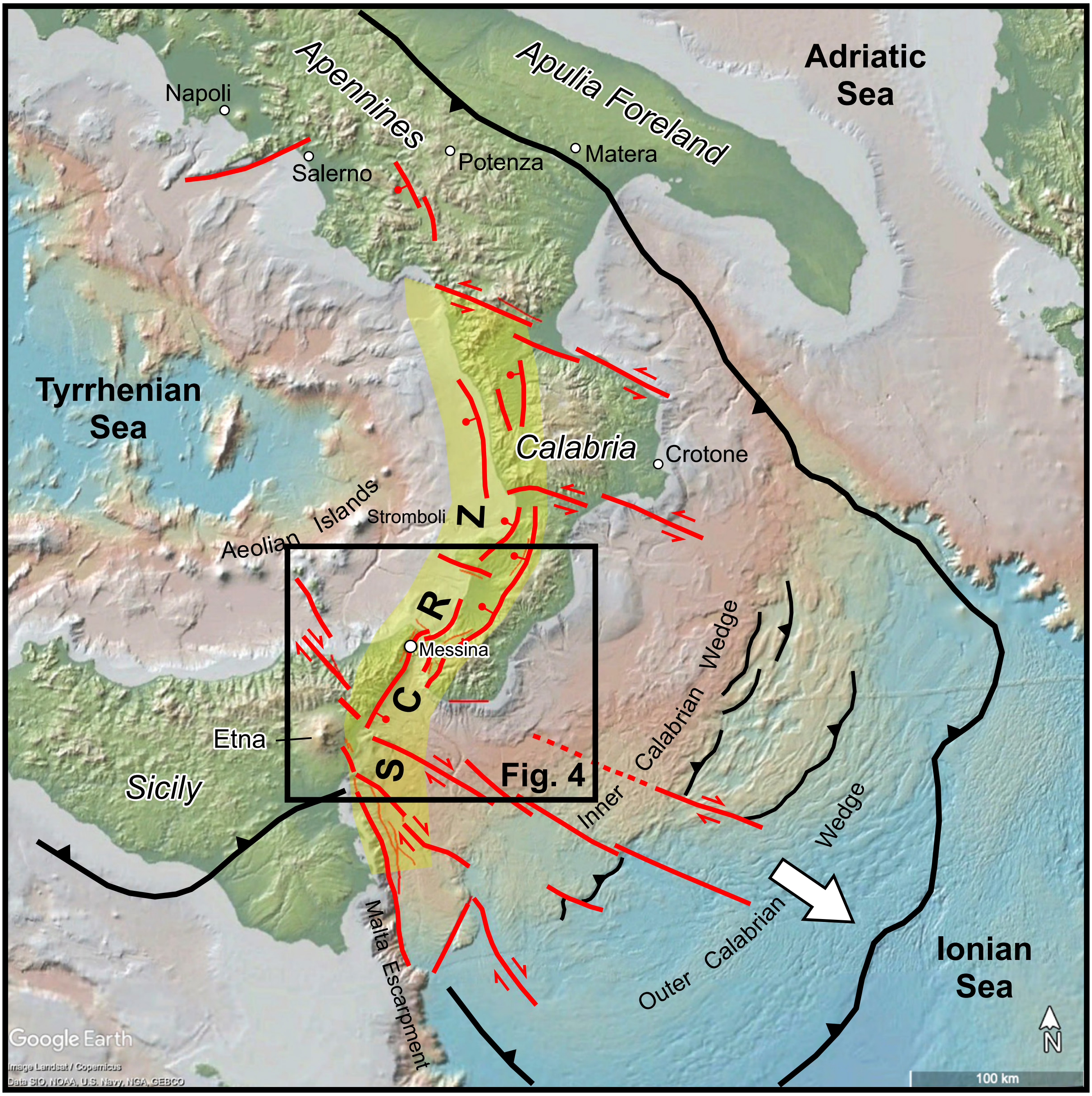


FIGURE 2 Regional tectonics of southern Italy showing major subduction zones and faults (compiled from Polonia et al., 2011; Gutscher et al., 2016; Scarfì et al., 2018; Maesano et al., 2020). SCRZ is the Siculo-Calabrian Rift Zone. Topography and bathymetry from GeoMap App.

and retreat of the Ionian subduction zone (Rosenbaum & Lister, 2004; Rosenbaum et al., 2002; Wortel & Spakman, 2000). Forearc crust in Calabria and NE Sicily has translated ca. 800 km to the southeast over the past ca. 30 Myr in response to rollback of the highly arcuate Ionian subduction zone (Figure 2) (Faccenna et al., 2003, 2004; Gutscher et al., 2016; Loreto et al., 2021; Romagny et al., 2020; van Hinsbergen et al., 2020). The Calabria-Peloritani terrane is a belt of Palaeozoic to Mesozoic plutonic and metamorphic rocks in southern Calabria and NE Sicily that form a stack of thrust nappes and ophiolite-bearing tectonic units of the Alpine internal zone (Cirrincione et al., 2015; Rossetti et al., 2001; Vitale & Ciarcia, 2013). Irregular retreat of the subduction zone has produced tear faults in the subducting slab that promote mantle upwelling, decompression melting, basaltic volcanism and NW-striking strike-slip faults that partition the crust into zones of upper-plate extension and oblique transtensional deformation (Figure 2) (Faccenna et al., 2004, 2011; Gallais et al., 2013; Jolivet et al., 2021; Maesano et al., 2020; Pirrotta et al., 2021, 2022; Scarfì et al., 2018; Sgroi et al., 2021).

Crystalline rocks of the Calabria-Peloritani terrane are unconformably overlain by Cenozoic sedimentary deposits that record a change from subduction-related compression and shortening to crustal extension, rifting and strike-slip faulting due to rollback and retreat of the Ionian subduction zone (Cavazza et al., 1997; Monaco et al., 1996; Tripodi et al., 2013; Van Dijk et al., 2000). Late Oligocene to middle Miocene shallow-marine deposits of the Stilo-Capo D'Orlando Formation, olistostrome deposits of the Argille Varicolori and intra slope deposits of the Motta San Giovanni Formation accumulated in thrust-bounded accretionary trench-slope and wedge-top basins and along a transform margin (Cavazza & Ingersoll, 2005; Critelli & Martín-Martín, 2022; Critelli et al., 2017; Rohais et al., 2021). Middle to late Miocene normal faults and rift basins were initiated by the onset of extension in western Calabria at the southeast margin of the Tyrrhenian Sea, while subduction-related shortening and sedimentation continued in eastern Calabria. By late Miocene time, the entire Calabrian forearc terrane was affected by extension and opening of NE-striking rift basins cut by coeval NW-striking strike-slip faults (del Ben et al., 2008; Tripodi et al., 2013). Strike-slip faults in this region represent the upper crustal expression of tears in the subducting Ionian slab (e.g. Jolivet et al., 2021; Sgroi et al., 2021), which have segmented the upper plate of the retreating Ionian subduction zone since middle to late Miocene time (Civile et al., 2022; and references therein). NW-striking strike-slip faults display right-lateral offset in the southwest and left-lateral offset in the northeast (Brutto et al., 2016; del Ben et al., 2008; Longhitano et al., 2014; Tansi et al., 2007), consistent with microplate kinematics predicted for southeastward extrusion of the subduction zone and highly arcuate offshore accretionary wedge (Figure 2) (Serpelloni et al., 2010; Viti et al., 2021; Zecchin et al., 2015).

Pliocene-Pleistocene deposits of southern Calabria and NE Sicily are divided into four tectono-sedimentary sequences (P1 to P4; Figure 3) that record fault-controlled phases of subsidence and uplift related to retreat and fragmentation of the Ionian subduction zone (Di Stefano et al., 2007; Tripodi et al., 2018; Zecchin et al., 2015). Sequence P1 overlies Messinian evaporites and consists of lower Pliocene coccolith-foraminiferal marls and marly rhythmites of the Trubi Formation that accumulated in low-energy offshore marine basins. Sequence P2 includes upper Pliocene fine-grained marine sandstones, marls and mudstones of the Monte Narbone Formation and correlative units (Bonardi et al., 2001; Cavazza et al., 1997; Di Stefano et al., 2007), which record continued offshore marine deposition with increasing input of fine-grained siliciclastic sediment from distal sources (Cavazza & Ingersoll, 2005). Sequence P3 is composed of early Pleistocene mixed bioclastic-siliciclastic cross-bedded sandstones and calcarenites of the Calcareniti di Vinco Formation (Vinco Calcarenites) and

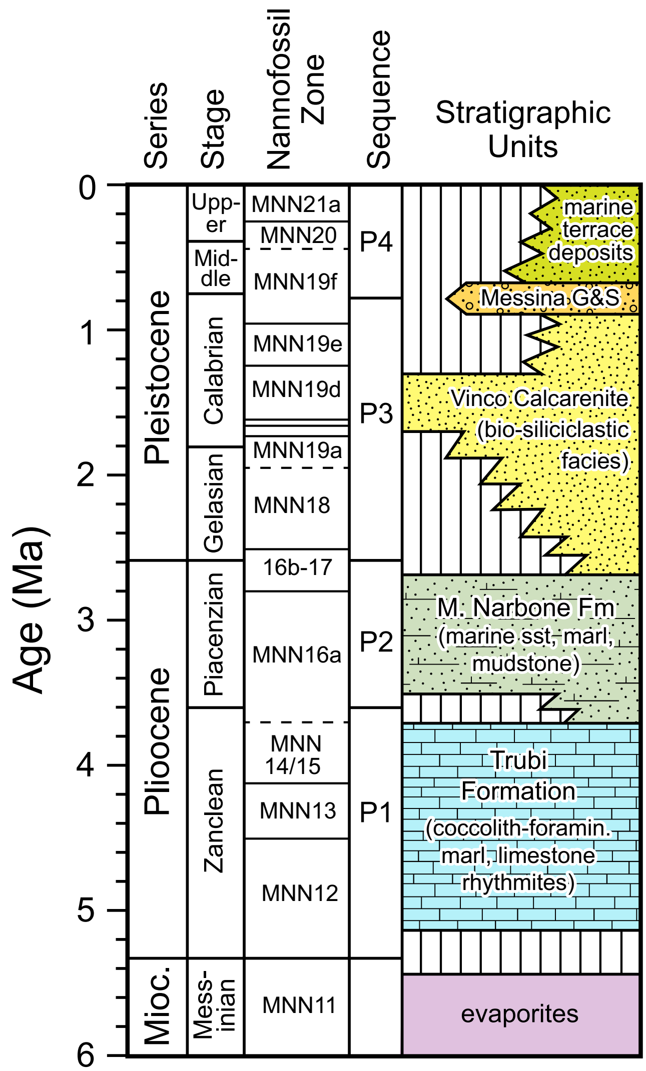


FIGURE 3 Generalized Pliocene—Pleistocene stratigraphy of the Messina Strait region (compiled from Di Stefano et al., 2007; Longhitano et al., 2012; Zecchin et al., 2015). P1 to P4 are tectono-stratigraphic sequences of Zecchin et al. (2015). MNN, Mediterranean Neogene Nannoplankton zone (Rio et al., 1990).

equivalent mudstones and conglomerates that accumulated in tidal straits during early development of the modern fault system (Chiarella et al., 2021; di Stefano & Longhitano, 2009; Longhitano, 2011, 2018b; Longhitano et al., 2012, 2021; Rossi et al., 2017; Zecchin et al., 2015). The Pellaro paleo-high is a fault-bounded horst in the footwall of the southern Armo fault, east of the Messina Strait (Figure 4), that underwent uplift during deposition of the Early Pleistocene (Gelasian) Vinco Calcarenites (Chiarella et al., 2021; Longhitano, 2018b). Paleocurrent data record transport north and south, away from the Pellaro paleo-high, indicating that the horst formed a structural high on the flank of the paleo-Messina Strait during deposition (Longhitano, 2018b). Tidal deposits north of the paleo-high display stratal wedge geometries and fanning dips produced by syn-tectonic tilting away

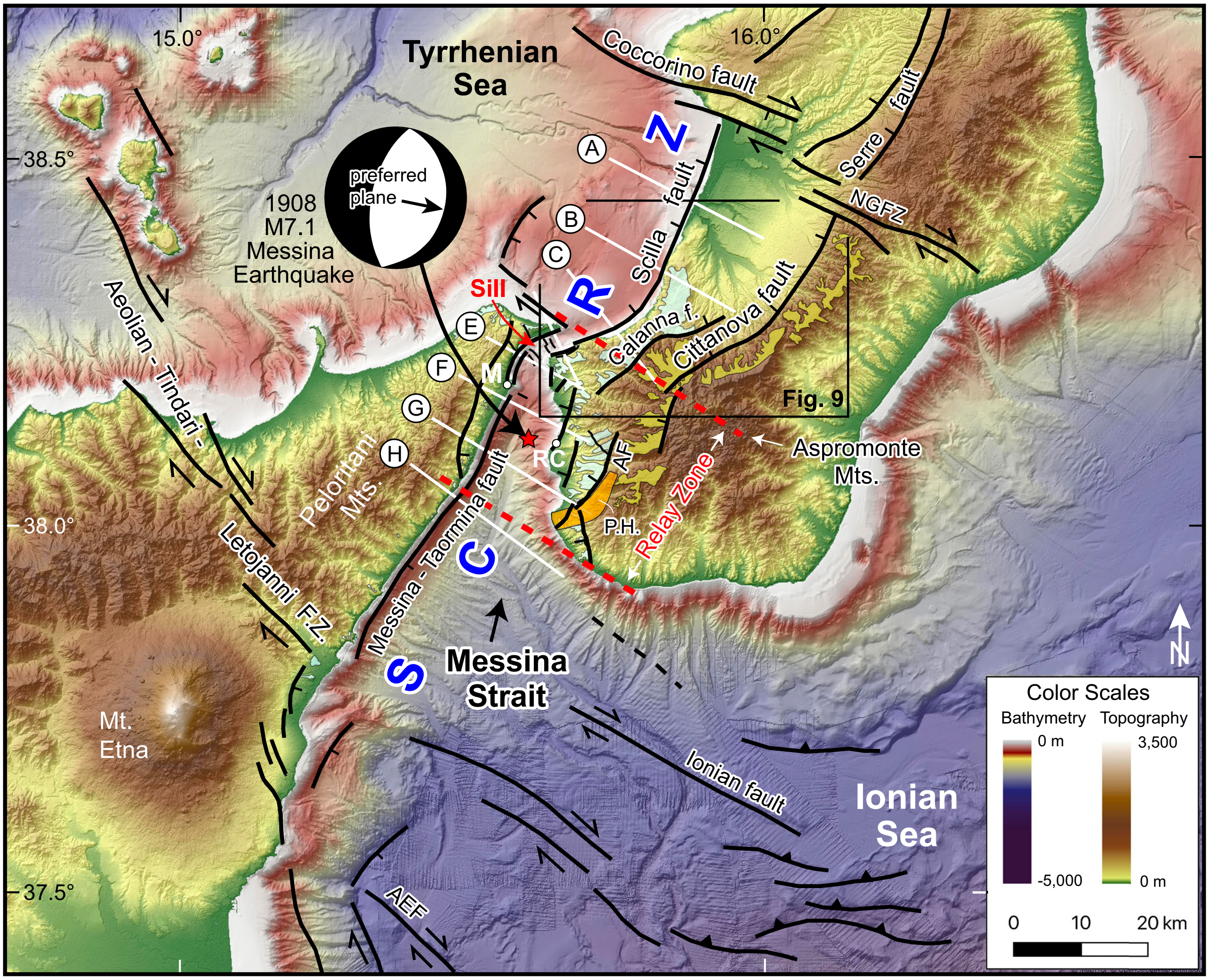


FIGURE 4 Topographic and bathymetric map showing major faults, location of profile transects in Figure 5 (white lines with letters) and uplifted marine terraces (from Catalano & De Guidi, 2003; Roda-Boluda & Whittaker, 2017; Monaco et al., 2017; Antonioli et al., 2021) (faults compiled from Antonioli et al., 2006; Doglioni et al., 2012; Ridente et al., 2014; Pavano et al., 2016; Tripodi et al., 2018; Sgroi et al., 2021). Yellow surfaces are early Pleistocene marine terraces at elevations of ca. 1.0–1.2 km; light blue surfaces are ≤730 ka at lower elevations. The Messina Strait conjugate relay zone is the area of overlap between opposite-dipping normal faults between the red dashed lines, where strain is transferred from SE-dipping faults in the southwest to NW-dipping faults in the northeast. Fault plane solution for the 1908 M7.1 Messina earthquake is from Boschi et al. (1989), epicentre of Gasparini et al. (1982). AEF, Alfeo–Etna fault; AF, Armo fault; M, Messina; NGFZ, Nicotera-Gioiosa fault zone; P.H. Pellaro paleo-high; RC, Reggio Calabria; and SCRZ, Siculo-Calabrian Rift Zone. Topography is SRTM 1 arc-second DEM downloaded from USGS website (https://earthexplorer.usgs.gov/), bathymetry is 1/16 arc-minute data from EMODnet (https://portal.emodnet-bathymetry.eu/) displayed in QGIS version 3.24.

from the uplifting horst during early stages of fault growth (Chiarella et al., 2021; Longhitano et al., 2021).

The Pleistocene Messina Gravels and Sands Formation formed by progradation of Gilbert deltas away from emerging topography on both sides of the Messina Strait (Barrier, 1986; Barrier et al., 1986; di Stefano & Longhitano, 2009; Lentini et al., 2000; Longhitano, 2018b; Longhitano et al., 2021). Messina Gravels and Sands are capped by thin red soils that record the onset of uplift and abandonment of the terrace surface. Sequence P4 is a sequence of middle to late Pleistocene marine and fluvial terrace deposits in southern Calabria and NE Sicily that have been uplifted to elevations up to 1.0–1.2 km in the past ca. 1.0–2.5 Myr (Figures 3 and 4) (Antonioli et al., 2006, 2021; Roda-Boluda & Whittaker, 2017).

2.2 | Active tectonics of the Messina Strait region

The Siculo-Calabrian Rift Zone is a ca. 350-km long belt of seismically active, north to NE-striking normal faults

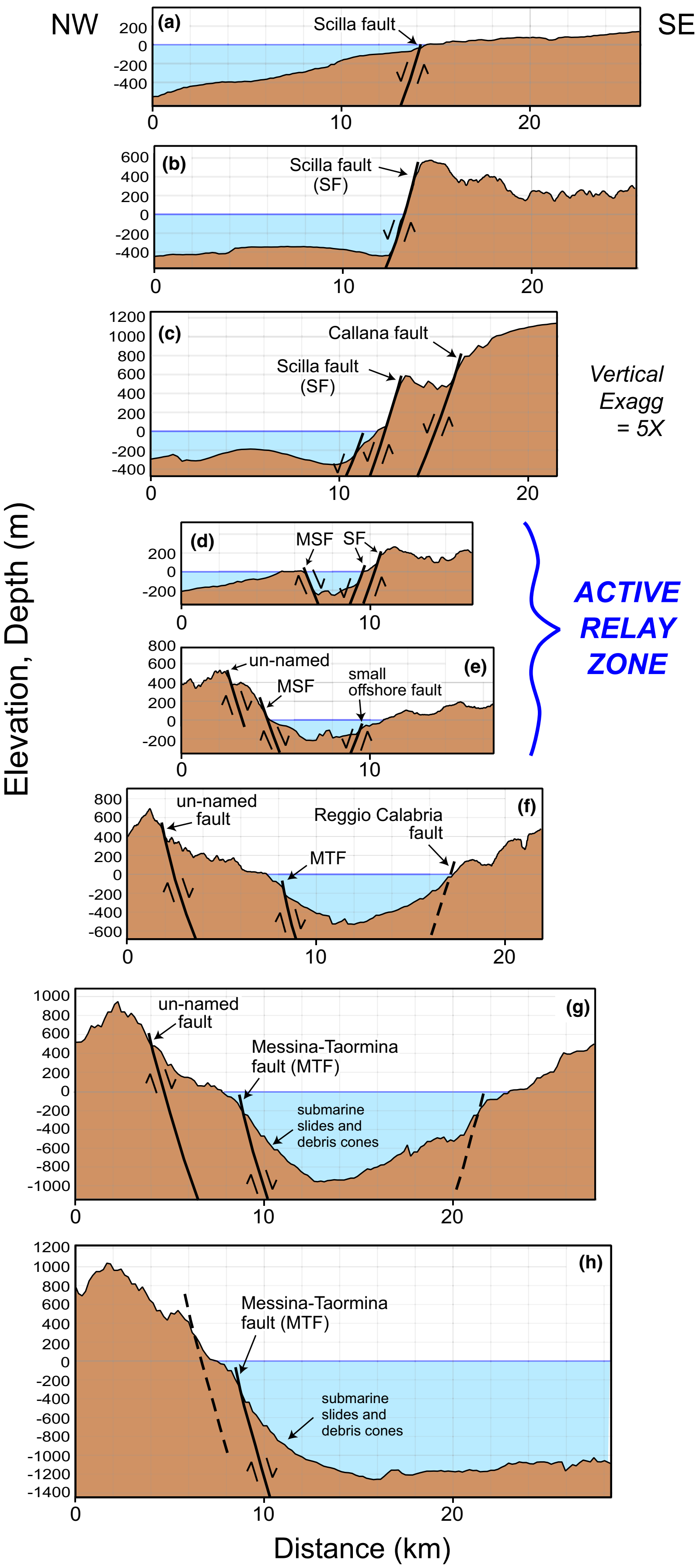


FIGURE 5 Fault-perpendicular topographic-bathymetric profiles showing major faults and related onshore–offshore morphology. Location of profiles in Figure 4. MTF is Messina-Taormina fault.

in Calabria and eastern Sicily that accommodate NW-SE extension in the upper plate of the Ionian subduction zone (Figures 2 and 4) (Brutto et al., 2016; Catalano et al., 2003, 2008; Jacques et al., 2001; Monaco et al., 1997; Monaco & Tortorici, 2000; Palano et al., 2012, 2017; Pirrotta et al., 2021, 2022; Presti et al., 2019; Tortorici et al., 1995, 2003; Valensise & Pantosti, 1992; Westaway, 1993). Well-preserved normal fault scarps, marine terraces, river channel profiles and low-temperature thermochronology record Pleistocene footwall uplift at rates of ca. 0.2–2 mm/year in Sicily (Catalano & De Guidi, 2003; Catalano et al., 2008; Meschis, Roberts, et al., 2022; Pavano et al., 2016; Tortorici et al., 1995) and southern Calabria (Antonioli et al., 2006, 2021; Catalano et al., 2003; Gallen et al., 2023; Meschis, Roberts, et al., 2022; Miyauchi et al., 1994; Monaco et al., 1997; Montenat et al., 1991; Quye-Sawyer et al., 2021; Roberts et al., 2013; Roda-Boluda & Whittaker, 2017). The Cittanova, Calanna, Scilla and Armo faults dip northwest and terminate to the northeast at the Coccorino and Nicotera-Gioiosa fault zones (Figure 4). An en-echelon array of north- to NNE-striking faults in southwest Calabria bound the eastern margin of the Messina Strait (Figure 4). In NE Sicily, NW-SE extension is accommodated primarily on the 50 km long offshore Messina-Taormina fault, which dips SE towards the Ionian Sea and terminates in the southwest against strands of the Aeolian-Tindari-Letojanni right-lateral strike-slip fault zone.

The Messina-Taormina fault is an enigmatic structure that may have ruptured during the catastrophic 1908 M7.1 Messina earthquake. Some studies conclude that this fault was the source of the earthquake (e.g. Meschis et al., 2019; Pino et al., 2000, 2009; Serpelloni et al., 2010), while others place the rupture on farther offshore SE-dipping normal faults (Barreca et al., 2021) or west-dipping normal faults in Calabria (Aloisi et al., 2013; Argnani, 2021, 2022). Submarine slope failures, slides and slumps are common at the steep western margin of the Strait, in the immediate hanging wall of the fault and may have contributed to production of tsunamis during the 1908 earthquake (Billi et al., 2008; Goswami et al., 2014, 2017; Schambach et al., 2020). Although the Messina-Taormina fault is implicated as a major active normal fault based on a narrow linear shelf, steep seafloor bathymetry and regional patterns of uplift and erosion in northeast Sicily (Catalano & De Guidi, 2003; Catalano et al., 2003, 2008; De Guidi et al., 2003; Monaco & Tortorici, 2000; Pavano et al., 2016), to date, the fault has not been clearly imaged with marine seismic data causing some workers to question the existence of an active SE-dipping normal fault in this position (Argnani, 2021, 2022; Argnani et al., 2009; Argnani & Pino, 2023). However, published offshore seismic lines in Messina Strait (Argnani et al., 2009) stop just short of the likely trace of the fault, located at the top of a steep slope with abundant submarine slides and debris cones (Figure 4), and thus do not provide a definitive test of this fault. Moreover, GPS data and modelling point to the Messina-Taormina fault as a major structure bounding the west side of the Strait that accommodates rapid NW-SE extension (Serpelloni et al., 2010). We therefore treat this as a large active normal fault that remains poorly imaged and requires more work to assess its role in the 1908 earthquake (e.g. Argnani & Pino, 2023).

GPS velocities reveal NW-SE extension across the Siculo-Calabrian Rift Zone at rates of 3–4 mm/year (Palano et al., 2012; Serpelloni et al., 2010). The NNW-trending Malta Escarpment and related strike-slip faults east of Sicily connect north to a system of right-stepping dextral faults in the Aeolian-Tindari-Letojanni fault zone (Figures 2 and 4) (Gutscher et al., 2016, 2017; Maesano et al., 2020; Palano et al., 2015; Scarfì et al., 2018). This fault system represents a diffuse lithospheric boundary located above a tear in the Ionian slab that accommodates differential motion between the Ionian and Sicily microplates, providing a conduit for mantle-derived magmas of Mount Etna (e.g. Faccenna et al., 2011; Goes et al., 2004). The Peloritani Mountains in northeast Sicily represent a semi-independent crustal block east of the Aeolian-Tindari-Letojanni fault zone, and northwest of the Messina-Taormina normal fault, that accommodates northwest motion away from southern Calabria (Figure 4) (Catalano et al., 2003; Pavano et al., 2015, 2016). Slip on the Messina-Taormina fault produces hanging-wall subsidence in the Strait and footwall uplift in the Peloritani Mountains that may be enhanced by mantle doming in the upper plate of the Ionian subduction zone (Barreca et al., 2021; Meschis et al., 2019; Serpelloni et al., 2010).

2.3 | Modern Messina Strait

The present-day Messina Strait is a marine connection between the Tyrrhenian Sea in the north and the Ionian Sea in the south (Figure 4) (Doglioni et al., 2012; Longhitano, 2018a; Martorelli et al., 2023). The sill is a shallow narrow constriction, 3–5 km wide and <100 m deep, which formed a narrow land bridge for several thousand years during the last glacial maximum sea-level lowstand ca. 25–20 ka (Antonioli et al., 2016). A tidal elevation difference of ca. 35 cm between the two marine basins produces a water surface gradient and consequent gravity-driven water mass transfers every 6 h per day (Defant, 1940; Vercelli, 1925). This tidal difference stimulates collinear tidal currents moving axially along the Strait that accelerate up to velocities of >3 m s^{-1} as they traverse the shallow constriction across the strait sill

(Brandt et al., 1999). Although waves are present in the Strait, tidal currents represent the major element controlling net sediment transport along two principal directions away from the strait centre (Longhitano, 2018a; Martorelli et al., 2023). Because of high shear stresses exerted by strong tidal currents, the sill is a by-pass zone where most of the sediment load is transported in suspension and coarse-grained deposits are locally entrapped within topographic lows of the sill (Longhitano, 2013, 2018a). Fast current velocities maintain a rocky marine substrate at the sill, and sediment is swept into wider, deeper depositional zones to the north and south where it accumulates in large-scale tidal dune fields (Santoro et al., 2004).

3 | FAULT ZONE ANALYSIS

3.1 | Conjugate relay zone

The Messina Strait conjugate relay zone (c.f. Childs et al., 2019) is defined here as the zone of overlap and strain transfer between two sets of opposed-dipping normal faults: (1) NW-dipping faults in southwest Calabria; and (2) the SE-dipping Messina-Taormina fault and associated normal faults in NE Sicily (Figure 4). Both fault sets are present within the relay zone and dip towards each other to form a graben where subsidence maintains the basin floor below sea level. The width of the strait decreases to ca. 3 km and water shallows to <100 m depth in the narrow constriction at the sill. Closely spaced normal faults strike perpendicular to the major strait-bounding faults across the sill in a zone of broad doming relative to deeper offshore basins to the south and north (Figure 4), similar to the along strike pattern of subtle uplift see in classic conjugate relay zones (Figure 1d).

The morphological expression of normal faults in the Messina Strait is revealed in a series of fault-perpendicular (Figure 5) and fault-parallel (Figure 6) profiles that were constructed from topographic and bathymetric data and integrated with published fault maps (Figure 4) (Antonioli et al., 2006; Critelli et al., 2016; Doglioni et al., 2012; Ferranti et al., 2008; Pavano et al., 2016; Ridente et al., 2014; Tripodi et al., 2018, 2022). Fault-perpendicular profiles (Figure 5) show large displacements with structural relief up to ca. 1200 m on individual normal faults. The Scilla fault forms a precipitous NW-facing escarpment with ca. 1000 m of vertical relief northeast of the constriction (Figures 4 and 5b,c). Fault-parallel profiles (Figure 6) reveal systematic along-strike decrease in footwall elevation and hanging-wall water depth, which collectively represent fault throw, in the zone of fault overlap where strain is transferred from the NW-dipping Scilla fault to the SE-dipping Messina-Taormina fault. The Messina-Taormina fault reveals ca. 1100 m of throw (Figure 6b) and up to 2200 m of combined

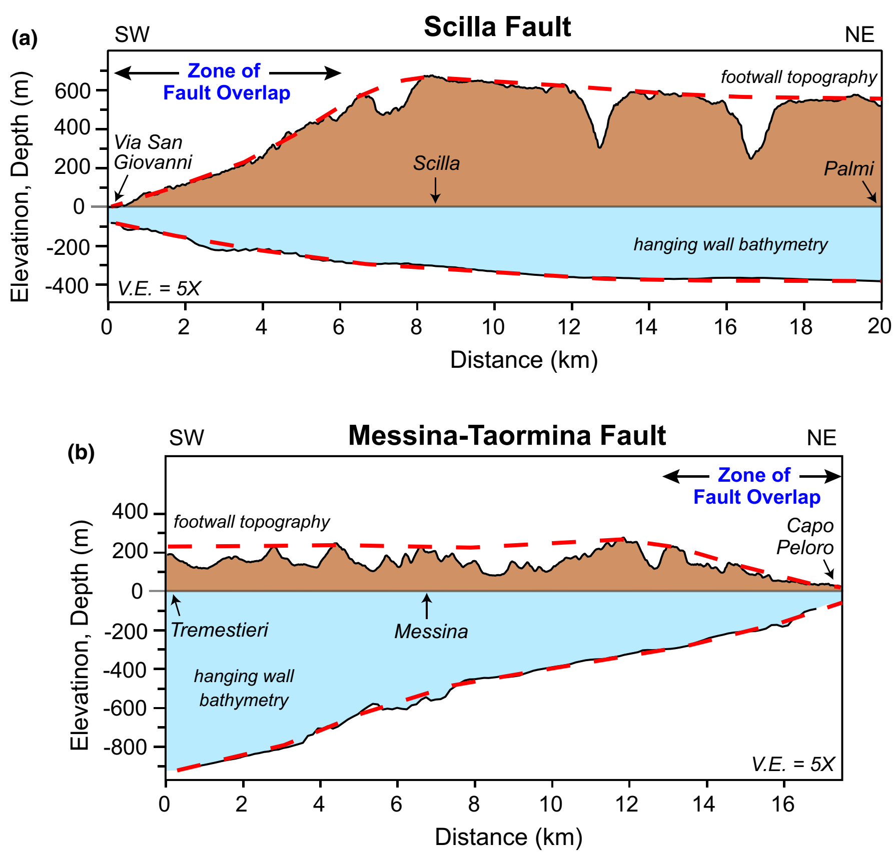


FIGURE 6 Longitudinal, strike-parallel profiles of footwall topography and hanging-wall bathymetry for the two major facing normal faults of the Messina Strait conjugate relay zone. (a) Scilla fault. (b) Messina-Taormina fault. Vertical separation between smoothed footwall elevation and hanging-wall water depth (red dashed lines) represents approximate fault throw, which likely are minimum values due to footwall erosion and hanging-wall sedimentation. Throw decreases along strike in the zone of fault overlap and strain transfer near the fault tips. Reference locations shown in Figure 7a.

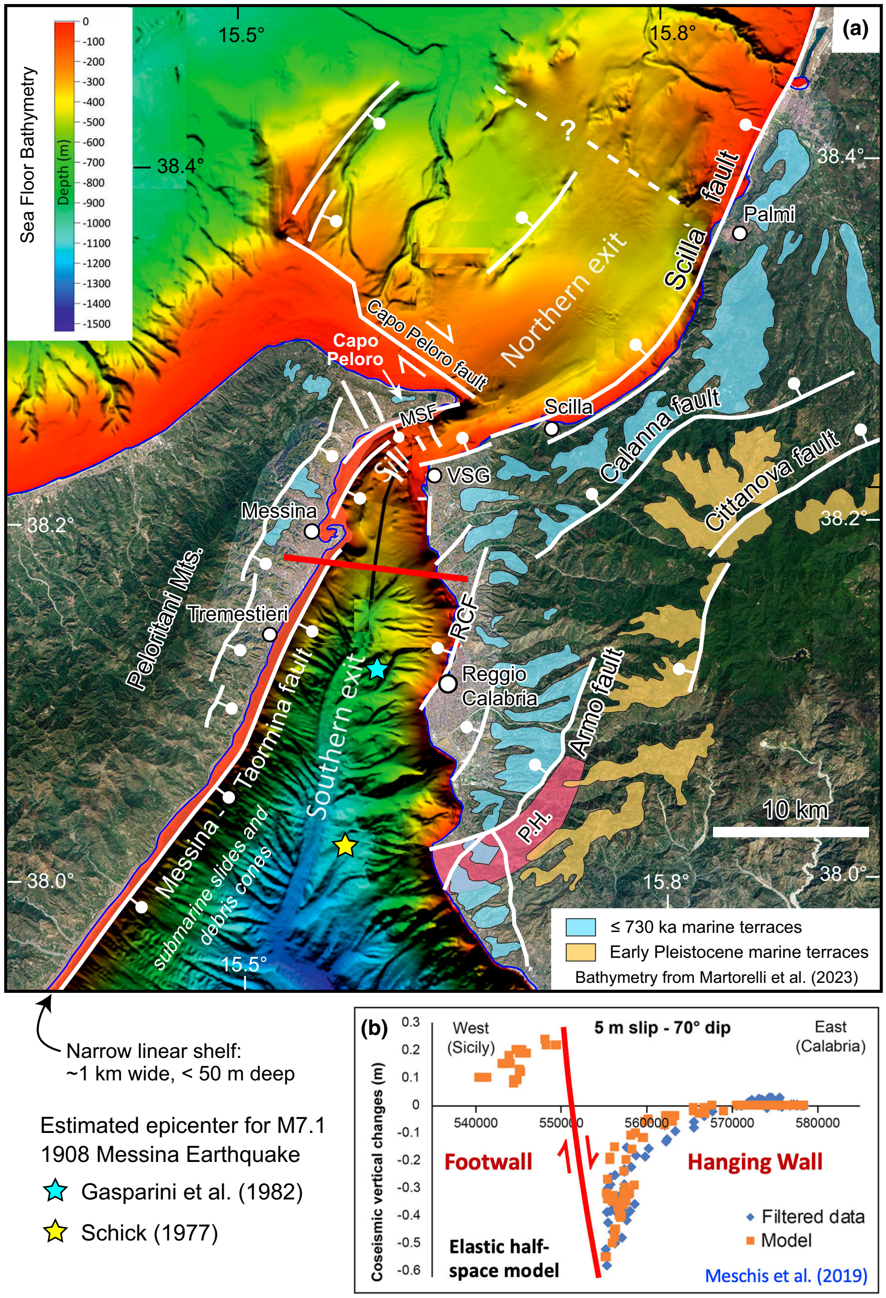


FIGURE 7 Faults and bathymetry of Messina Strait. (a) Map of sea floor bathymetry (modified from Martorelli et al., 2023) and active faults. Red line is approximate position of transect in part B. P.H. is Pellaro paleo-high; RCF is the Reggio Calabria fault. (b) Profile view of surface displacements associated with the 1908 M7.1 Messina earthquake, showing close agreement between observed surface motions (filtered data) and modelled geometry of flexural slip on a normal fault with hanging-wall subsidence greater than footwall uplift (Meschis et al., 2019). Submarine slides and debris cones fill the proximal hanging wall of the Messina-Taormina fault.

total offset on the master fault and adjacent smaller normal faults in NE Sicily (Figure 5h). Transfer of fault displacement is also reflected in elevations of Quaternary marine terraces on both sides of the relay zone:in addition to stepped profiles that reveal older terraces at higher elevations due to regional uplift, individual terraces in the footwall of normal faults in southern Calabria and NE Sicily dip gently towards fault tips in the zone of fault overlap (Barreca et al., 2021; Monaco et al., 2017), mimicking the overall decrease of elevation seen in longitudinal profiles of footwall topography (Figure 6).

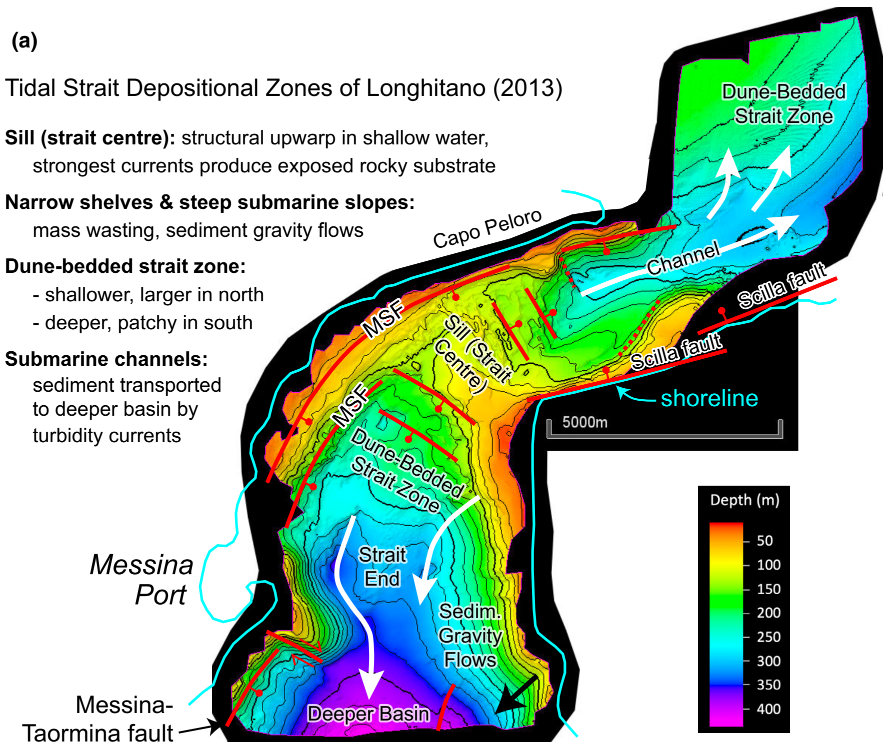
Figure 7a shows the distribution of major active faults, Pleistocene deposits and modern seafloor bathymetry of the Messina Strait region. The linear coastline of northeast Sicily is controlled by uplift in the footwall of the Messina-Taormina fault along a strike distance of ca. 50 km (see also Figure 4). Co-seismic surface displacements during the 1908 earthquake form a characteristic pattern of footwall uplift and hanging wall subsidence produced by slip on an active normal fault (Figure 7b) (Meschis et al., 2019). In contrast to the linear western margin, the irregular eastern margin of the strait hosts a north-trending en-echelon array of shorter active NNE-striking faults and fault segments that control the shape of the coastline. West-facing promontories are produced by footwall uplift near southern fault terminations, and scallop-shaped bays form in areas of hanging-wall subsidence (Figure 7a). The oldest fault in this en-echelon set is the Armo fault, which formed the active margin of the paleo-constriction during deposition of early

Pleistocene tidal strait deposits (Chiarella et al., 2021; Longhitano, 2011, 2018b).

A distinctive feature of the conjugate relay zone is pronounced plan-view curvature of normal faults adjacent to the central sill (Figures 4 and 7). Outside of the relay zone, the regional strike of normal faults is 030°–035°. Faults curve progressively along strike into the relay zone where strike values increase to 070°–075°, deviating from the regional fault strike by 40°–45° (Figure 7). The area of greatest strike deviation coincides with minimum fault offset and subdued footwall topography near the tips of the overlapping faults (Figures 5d,e and 6). The offshore Capo Peloro fault (Figure 7) is marked by a prominent NW-striking bathymetric lineament and truncated Plio-Pleistocene deposits with growth strata in the subsurface (Doglioni et al., 2012). Figure 8 shows seafloor bathymetry and an aerial view of Messina Strait, illustrating the influence of active faulting on local topography, submarine morphology and sedimentary processes. The Messina Strait relay zone is thus characterized by strong fault curvature where fault offset, footwall elevation and water depth all decrease along strike towards the tips of facing normal faults in the area of extensional strain transfer and maximum reorientation of fault strike.

3.2 | Normal fault initiation and migration

Figure 9 depicts the evolution of topography and migrating shorelines in response to initiation and migration of normal faults in southwest Calabria (Pirrotta et al., 2016)



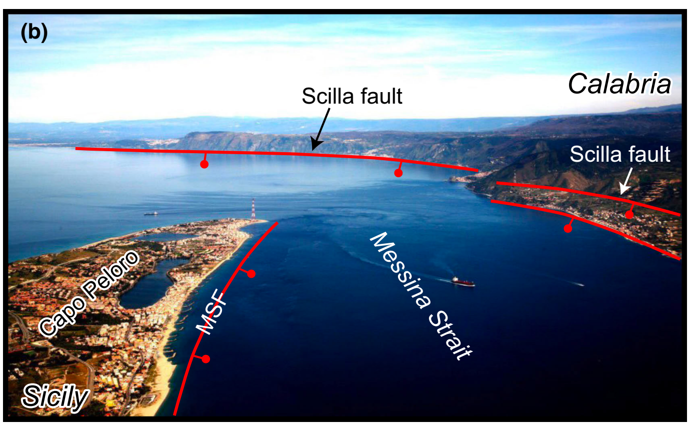


FIGURE 8 (a) Detailed multibeam bathymetric map of Messina Strait showing active fault controls on seafloor bathymetry and sediment transport processes, with depositional zones of Longhitano (2013). MSF is Messina Strait fault. (b) Oblique aerial photo looking east at Messina Strait and bounding normal faults of the conjugate relay zone. Photo Credit: Longhitano et al. (2020), Field Trip Guide FT1, Tidalites Conference 2022.

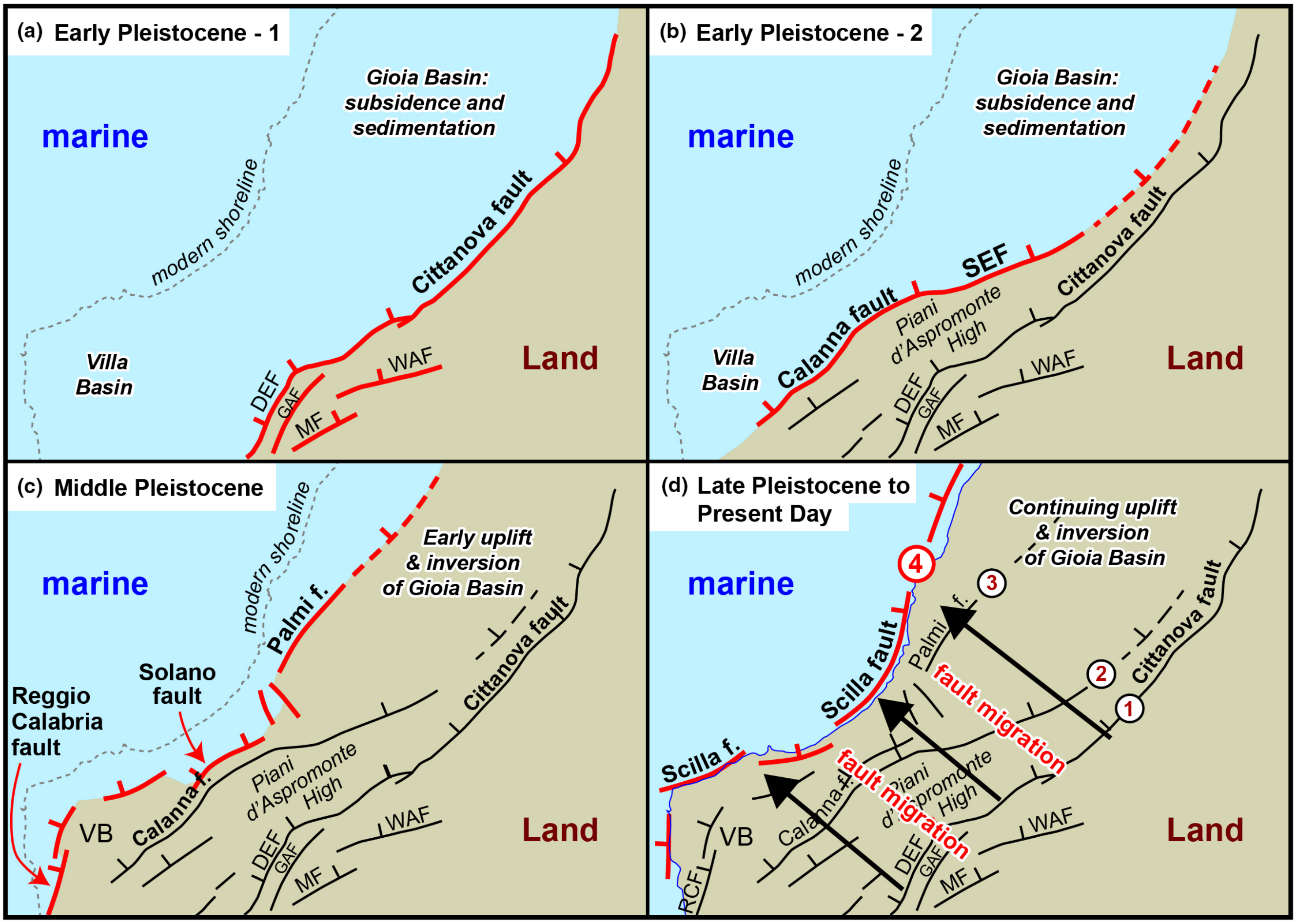


FIGURE 9 Maps showing initiation and migration of normal faults in southwest Calabria based on river channel evolution and fault analysis, modified from Pirrotta et al. (2016). Bold red lines are faults that became active in each stage of structural and geomorphic development. Older faults in the southeast (black fault lines) are still active today, likely with slower slip rates than the most active faults at the modern coastline. (a) During early Pleistocene Stage 1 (Gelasian), an early phase of fault slip on the Cittanova, Delianuova and Gambarie faults produced uplift and erosion in the southeast. (b) In a second stage of the Early Pleistocene (Calabrian), the Calanna and Santa Eufemia Faults were activated to initiate uplift of the Piani d'Aspromonte High, while the Gioia and Villa basins continued subsiding. (c) During Middle Pleistocene time, initiation of the Palmi fault led to early uplift and inversion of the Gioia and Villa basins; the Solano and Reggio Calabria faults also were activated at this time. (d) In Late Pleistocene time, activation of the Scilla fault zone caused depocentres to migrate into their present location during continued uplift of the Piani d'Aspromonte High.
Abbreviations: CAF, Calanna fault; CAPF, Cappuccini fault; CF, Cittanova fault; DEF, Delianuova fault; GAF, Gambarie fault; MF, Montalto fault; PF, Palmi fault; SEF, Santa Eufemia fault; SF, Scilla fault; SOF, Solano fault; VB, Villa Basin; and WAF, Western Aspromonte fault.

(faults from Atzori et al., 1983; Ghisetti, 1992; Jacques et al., 2001). The reconstruction is based on quantitative morphometric analysis that highlights the relative ages of river channel features, which are controlled by—and preserve a record of—progressive initiation and migration of normal faults through time (Pirrotta et al., 2016). Older faults in the southeast are still active today, likely with slower slip rates than the most active faults at the modern coastline. During early Pleistocene time (Gelasian, Figure 9a), a first phase of uplift was controlled by slip on the Cittanova, Delianuova and Gambarie faults, producing footwall uplift and erosion in the southeast. The western Aspromonte and Montalto faults were also active during this time, and areas northwest of the Cittanova fault formed a subsiding marine realm that included the Gioia and Villa basins. In a second stage (Calabrian; Figure 9b), the Calanna fault was initiated, slip on the Cittanova fault likely slowed, the former marine shelf was uplifted and the margin of the paleo-Messina Strait shifted ca. 5–8 km to the northwest. Biostratigraphic data show that the Calanna fault was activated ca. 1.7 Ma (Longhitano et al., 2012). During the middle Pleistocene (Figure 9c), initiation of the Palmi fault led to early uplift and inversion of the Gioia and Villa basins as normal faults shifted again to the northwest. In late Pleistocene time (Figure 9d), activation of

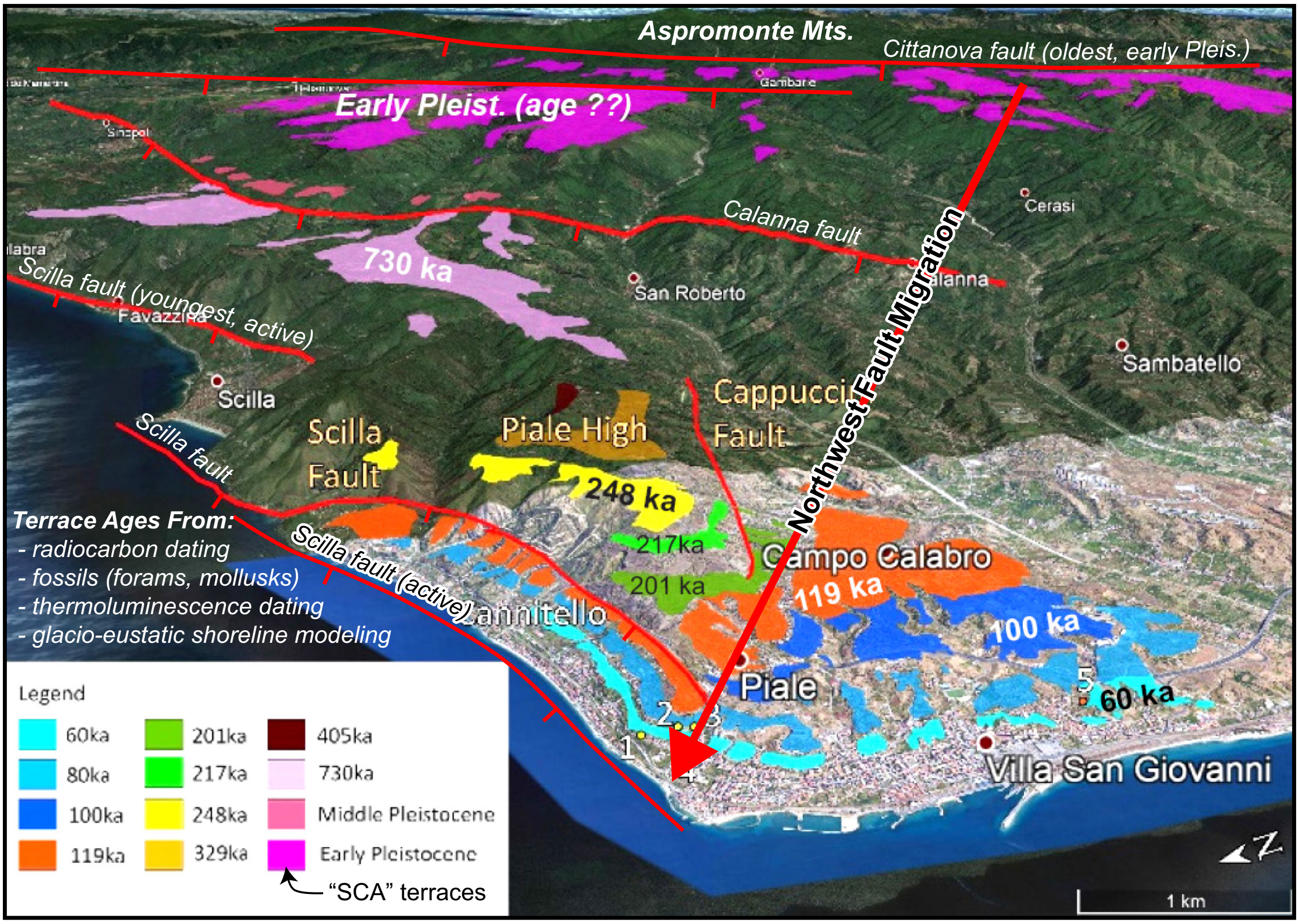


FIGURE 10 Flight of uplifted and faulted marine terraces in southern Calabria (modified from Antonioli et al., 2021). 'SCA' terraces are Serre–Cittanova–Armo terraces, named for the faults that cut them (Roda-Boluda & Whittaker, 2017). The relative ages and elevations of faulted marine terraces suggest northwest migration of normal faults through time. The timing of the start of this sequence is uncertain because the high SCA marine terrace (early Pleistocene) is not well dated. See text for discussion.

the modern Scilla fault zone caused depocentres to shift northwest into their present location. Thus, the configuration of the modern Messina Strait rift zone was established in Late Pleistocene time (Pirrotta et al., 2016).

Figure 10 is an oblique view looking southeast at a flight of uplifted and faulted Pleistocene marine terraces in southern Calabria (Antonioli et al., 2021), providing further evidence for a history of northwest fault migration in this region. Terrace ages are estimated from radiocarbon dating, biostratigraphy, thermoluminescence dating and glacio-eustatic shoreline modelling (Antonioli et al., 2021; Miyauchi et al., 1994; Monaco et al., 2017; Roda-Boluda & Whittaker, 2017; Westaway, 1993). The timing of earliest fault motion is uncertain because the oldest Pleistocene marine terraces at elevations up to 1.2 km (named 'SCA' terraces after the Serre-Cittanova-Armo faults that cut them; Roda-Boluda & Whittaker, 2017) are not well dated. Regardless of absolute age constraints, the morphology and elevation of offset marine terraces show that the relative age of the faults decreases from southeast to northwest (see also Discussion below). A history of fault migration can similarly be inferred for en-echelon normal faults east of Messina Strait (Figure 7a). The Armo fault, oldest in the en-echelon array, formed the southeast margin of the paleo-Messina strait during deposition of the early Pleistocene Calcareniti di Vinco Formation (Chiarella et al., 2021; Longhitano, 2011, 2018b). The Reggio Calabria fault to the north is inferred to be younger than the Armo fault based on the younger age (≤730 ka) of marine terraces in its footwall. The northernmost faults of the en-echelon fault array are active strands of the Scilla fault zone directly adjacent to the central sill of the modern strait (Figures 7a and 8).

In summary, fluvial geomorphology and biostratigraphic data suggest a history in which NE-striking normal faults in southwest Calabria migrated northwest into the Tyrrhenian Sea during the same period (past ca. 2.5 Myr) that initiation of faults in the en-echelon array on the east margin of Messina Strait migrated north (Figures 9–11). Fault activity is currently focused at the narrow central sill of the modern strait, where normal faults display the strongest curvature in

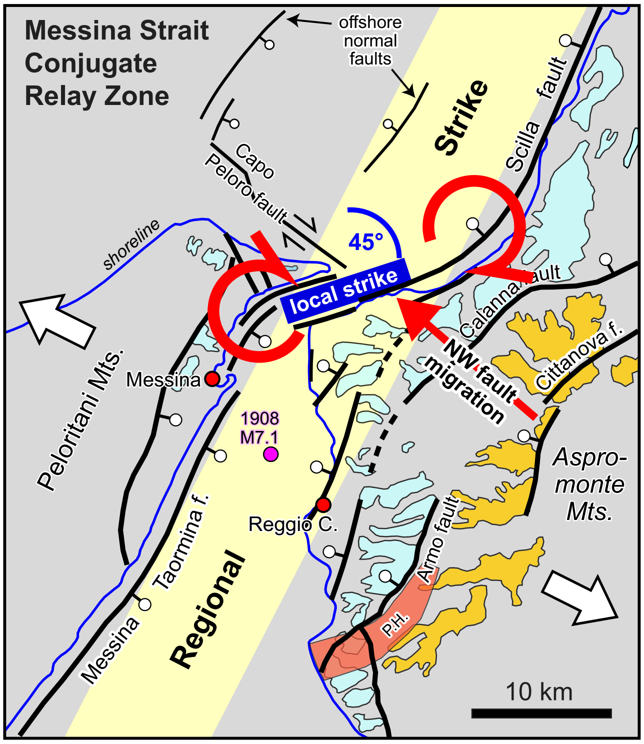


FIGURE 11 Proposed structural model for the Messina Strait conjugate relay zone. Strong fault curvature results from clockwise rotation in the area of active fault-tip interactions, where the strike of normal faults deviates from the regional fault strike by ca. 40°–45°. The dextral Capo Peloro fault accommodates transfer of some extensional strain from a SE-dipping offshore normal fault to northern strands of the Messina-Taormina fault system. The Pellaro paleo-high (P.H.) formed an early Pleistocene fault-bounded structural high that separated north- and south-directed tidal currents (Longhitano, 2018b), suggesting that the narrow constriction of Messina Strait has migrated north ca. 20 km in the past ca. 2.0–2.5 Myr.

plan view and local fault strikes deviate up to 40°–45° from the regional fault strike (Figure 7a).

4 | DISCUSSION

4.1 | Significance of the conjugate relay zone

Based on the preceding synthesis of regional fault data, we propose a kinematic model for development of the Messina Strait conjugate relay zone (Figure 11). As seen in other examples (Childs et al., 2019), faults in this region display a distinctive pattern of overlap and strain transfer between opposed-dipping normal faults (Figures 4 and 7). While the general pattern of facing faults has been recognized in previous studies (e.g. Catalano et al., 2003, 2008), the tectonic significance of fault geometries, strain transfer and fault migration history has not been fully explored.

The plan-view curvature of facing normal faults in Messina Strait is observed in some but not all other extensional relay zones (Acocella et al., 2000, 2005; Ebinger, 1989; Morley et al., 1990; Peacock & Sanderson, 1994). Deviation of local fault strike within the relay zone from regional fault strike outside the relay zone (up to 40°–45°) overlaps the range of angular difference documented from active relay zones in Iceland, where fault curvature results from rotation of local extension direction due to interaction with adjacent faults (Acocella et al., 2000). Degree of fault curvature is related to extension rate and magnitude (with faster extension producing more rotation), magnitude of far-field stress, orientation of inherited basement structures if present, and fault surface roughness (Acocella et al., 2000). The NW-striking Capo Peloro strike-slip fault (Figure 7a) is oriented favourably to act as a transfer fault (e.g. Acocella et al., 2005), but the dextral sense of offset inferred by Doglioni et al. (2012), and confirmed here, is opposite to the left-lateral offset predicted for a simple relay zone. This apparent discrepancy likely reflects the complicating influence of an offshore normal fault that accommodates some extension north of Capo Peloro (Figures 7a and 12). The geometry of fault curvature suggests that clockwise rotation in the relay zone is related to active fault interactions. The area of strongest plan-view curvature coincides with minimum values of fault offset, footwall elevation and water depth near the tips of facing normal faults in the area of fault overlap (Figures 5 and 6). Thus, the observed fault geometries and evidence for active strain transfer between adjacent normal faults in Messina Strait are consistent with extensional conjugate relay zones worldwide (Childs et al., 2019).

The Messina Strait conjugate relay zone occupies a unique position within the Siculo-Calabrian Rift Zone, which accommodates regional extension in the upper plate of the Ionian subduction zone (Figure 2). The modern Strait is maintained as a shallow marine connection by active subsidence within the relay zone that results from extension and divergence between southern Calabria and NE Sicily. This interpretation is supported by GPS data that indicate extensional opening of the Siculo-Calabrian Rift Zone at rates of 3–4 mm/year (Catalano & De Guidi, 2003; Catalano et al., 2003; Palano et al., 2012; Pavano et al., 2015, 2016; Serpelloni et al., 2010). Some studies propose that southeastward retreat of the Ionian subduction zone and related extension stopped by ca. 2 Ma (e.g. Goes et al., 2004), but active extension across the Messina Strait suggests that rollback of the subduction zone continues today. Alternatively, extension in this region may be due to other mechanisms such as gravitational collapse or crustal block rotations (Palano et al., 2012). Rapid Pleistocene to modern uplift is attributed to slab fragmentation and related changes in mantle dynamics

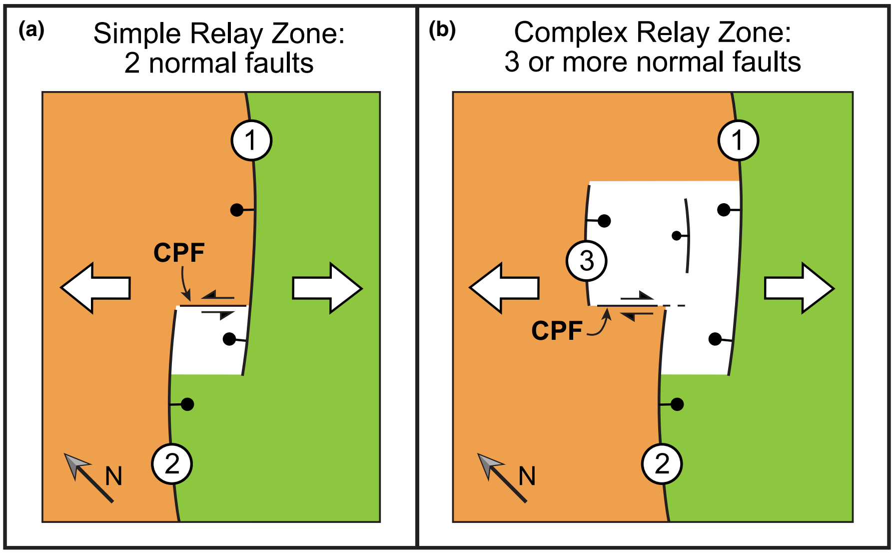


FIGURE 12 Hypothetical sketch maps showing kinematics of normal and strike-slip faults in a graben conjugate relay zone, to help evaluate behaviour of the Capo Peloro fault (CPF). (a) Simple relay zone with two normal faults and transfer of strain across a relatively small zone of fault overlap (white area). This geometry predicts left-lateral offset on the Capo Peloro fault. (b) Complex relay zone with three or more interacting faults and a larger area of strain transfer (white area). Fault 3 represents a SE-dipping offshore normal fault observed in seafloor bathymetry (Figure 7a). This geometry predicts observed right-lateral offset on the Capo Peloro fault, which acts as a kinematic link between normal faults 2 and 3.

and isostasy (Gallen et al., 2023), which counteract the effects of extension-related crustal thinning and subsidence.

4.2 | Age of fault initiation and growth of topography

The age of initiation of normal faults in southern Calabria is poorly understood due to conflicting information about the age of marine deposits in the uplifted footwalls of the faults. Some studies (Quye-Sawyer et al., 2021; Roda-Boluda & Whittaker, 2017) conclude that normal faulting and uplift of raised SCA (Serre-Cittanova-Armo) marine terraces started ca. 1.0 ± 0.2 Ma, based on the presence of 'northern guest' faunas that are believed to have migrated into this region ca. 1 Ma (Catalano et al., 2008; Dumas et al., 1981, 1987; Ghisetti, 1981; Miyauchi et al., 1994; Monaco et al., 1996; Westaway, 1993). Because footwall uplift must post-date deposition of the marine deposits, it is logical to conclude that the normal faults initiated after arrival of northern faunas. However, the timing of arrival of northern faunas in the central Mediterranean region is not well known. The start of the Pleistocene (base of Gelasian; Figure 3) is now placed at 2.58 Ma and is recognized as the start of major northern hemisphere glaciation and global cooling (Cohen et al., 2013; Gibbard & Head, 2010; Head et al., 2008). The first arrival of northern faunas (e.g. *Arctica islandica*, *Hyalinea balthica*) due to climate deterioration is at least as old as the start of the Calabrian stage, ca. 1.7–1.8 Ma (Bizzarri & Baldanza, 2020; Crippa et al., 2019; Crippa & Raineri, 2015; Gibbard & Head, 2010), earlier than the widely cited age of 1.0 ± 0.2 Ma. Biostratigraphic data from Vinco Calcarenites in the hanging wall of the Armo fault record syn-tectonic deposition *during fault offset* in early Gelasian time, ca. 2.4–2.6 Ma (Barrier, 1984, 1986; Barrier et al., 1987; Guarnieri et al., 2004; Longhitano et al., 2012), and the Calanna fault was active by ca. 1.7–1.8 Ma (Longhitano et al., 2021). Thus, the age of onset of major normal faults and footwall uplift in southern Calabria is loosely bracket between ca. 1.0 and 2.6 Ma.

Two hypotheses can potentially explain conflicting published estimates for the timing of earliest extension and uplift in southern Calabria. (1) Normal faults may have initiated in early Pleistocene time (ca. 2.4–2.6 Ma) as indicated by biostratigraphic data, but with little or no uplift in their footwalls until ca. 1 Ma (widely cited age for the onset of regional uplift). This explanation is consistent with evidence that during early stages of extension, the Armo fault was a blind fault that formed a basin-facing monocline above the propagating tip of the growing fault (Chiarella et al., 2021), which may have involved slow footwall uplift. However, full suppression of footwall uplift is unusual for active normal faults, and there is abundant evidence for early Pleistocene siliciclastic input from footwalls of the faults in question (Chiarella et al., 2021; Longhitano, 2011; Longhitano et al., 2012, 2021; Rossi et al., 2017), which requires active footwall uplift and erosion. (2) Alternatively, the high SCA marine terraces may be older than ca. 1 Ma if 'northern guest' faunas arrived in southern Calabria prior to 1.0 Ma. This hypothesis is supported by recognition that northern boreal faunas (e.g. *Arctica islandica*, *Hyalinea balthica*) migrated south into the central Mediterranean region during early Pleistocene time (Gibbard & Head, 2010). If the oldest SCA marine terraces are early Gelasian (ca. 2.4–2.6 Ma), normal faults may have initiated in the southeast around that time and then migrated to the northwest (Figure 9). The second hypothesis is challenged by studies that find northern faunas arrived in the central Mediterranean region at the start of the Calabrian stage, ca. 1.7–1.8 Ma (Bizzarri & Baldanza, 2020; Crippa et al., 2019; Crippa & Raineri, 2015), not early Gelasian, so this explanation cannot fully resolve the age discrepancy.

Despite existing age uncertainties, the interpretation of northward migrating faults east of the Messina Strait is consistent with evidence for northward migrating faults, erosion and sedimentation in northeast Sicily during Middle to Late Pleistocene time (di Stefano & Longhitano, 2009). In addition, uplifted Pleistocene marine deposits in the footwall of the Messina-Taormina fault (Figure 7a; Lentini et al., 2000; di Stefano & Longhitano, 2009) indicate that normal faults in NE Sicily have stepped to the southeast in the past 1–2 Myr. Combined with northwest migration of normal faults in southern Calabria (Figure 9; Pirrotta et al., 2016), this pattern indicates that the relay zone and Messina Strait have become narrower through time. Tectonic narrowing of the marine passage despite ongoing extension is likely due to inward migration of facing normal faults and rapid regional uplift (Gallen et al., 2023; Meschis, Roberts, et al., 2022; Meschis, Teza, et al., 2022; Pavano et al., 2016; Quye-Sawyer et al., 2021; Roda-Boluda & Whittaker, 2017), suggesting that mantle-driven uplift has overwhelmed and now exceeds extension-related subsidence in many areas where Pleistocene marine deposits are exposed above sea level.

5 | CONCLUSIONS

This study identifies an active conjugate relay zone in the Messina Strait of southern Italy, where NW-SE extension results from rapid rollback and retreat of the Ionian subduction zone. This region is distinguished by a rich cultural legacy recorded in Homer's Odyssey (c. eighth century BC), and a modern record of major earthquakes and persistent seismic hazards. The relay zone is defined by an along-strike transfer of extensional strain from active NW-dipping normal faults in southwest Calabria to the SE-dipping Messina-Taormina normal fault offshore eastern Sicily (likely source of the 1908 M7.1 Messina earthquake). Strong curvature of facing normal faults in the active relay zone results from clockwise rotation related to ongoing fault-tip interactions. Integrated topographic and bathymetric profiles show that fault throw, footwall elevation and water depth, all decrease along strike towards the tips of facing normal faults in the area of extensional strain transfer and maximum reorientation of fault strike. The observed fault geometries and related processes exert a strong control on modern topography, seafloor bathymetry and active sedimentary processes of the Messina Strait region.

Published evidence from fluvial geomorphology and biostratigraphy shows that normal faults and footwall uplift in southern Calabria migrated northwest from early Gelasian time (ca. 2.4–2.6 Ma) to the present day, with the most active faults currently located at the modern coastline, though there is some uncertainty regarding the age of initiation of regional faulting and uplift. During the same period, basin-bounding normal faults in NE Sicily migrated southeast to the modern Messina-Taormina fault. The net inward migration of facing normal faults has resulted in progressive narrowing of the Strait through time. Tectonic narrowing of the marine passage despite regional extension suggests that mantle-driven uplift now exceeds extension-related subsidence in many areas. This pattern, if it continues in the geologic future, may eventually result in permanent closure of the Messina Strait.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of Interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/bre.12818.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Rebecca J. Dorsey https://orcid.org/0000-0001-8390-052X
Sergio G. Longhitano https://orcid.org/0000-0003-4978-4582
Domenico Chiarella https://orcid.org/0000-0003-2482-0081

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