Structure and Morphology of an Active Conjugate Relay Zone, Messina Strait, Southern Italy

Dorsey, R.J.[1], Longhitano, S.G.[2], Chiarella, D.[3]

[1] Department of Earth Sciences, University of Oregon, Eugene, OR (USA)
[2] Department of Sciences, University of Basilicata, Potenza (Italy)
[3] Department of Earth Sciences, Royal Holloway University of London (UK)

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ABSTRACT

The 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 constriction of the Messina Strait is a graben undergoing active subsidence within the relay zone. Pronounced curvature of normal faults near their tips results from large strain gradients and clockwise rotations related to fault interactions. Based on regional fault geometries and published age constraints, we propose a model for northwest (oceanward) migration of normal faults in southern Calabria during the past ~2–2.5 Myr in response to rapid crustal extension at the southeast margin of the Tyrrhenian Sea.

KEY WORDS: Messina Strait, Pleistocene, normal faults, relay zone, sedimentation

INTRODUCTION

Accommodation zones are a common feature of rift systems where offset is transferred along strike between adjacent normal faults (Rosendahl, 1987; Morley et al., 1990; Gawthorpe and Hurst, 1993; Peacock and Sanderson, 1994; Childs et al., 1995; Morley, 1995; McClay et al., 2002). They comprise 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 commonly display high lateral strain gradients and vertical-axis rotations related to slow lateral propagation of overlapping faults (Acocella et al., 1999, 2000; Ferrill and Morris, 2001; Imber et al., 2004; Childs et al., 2019). Graben-type conjugate relay zones are those in which normal faults dip toward each other to produce a subsiding graben in the zone of fault overlap (Fig. 1) (Childs et al., 2019).

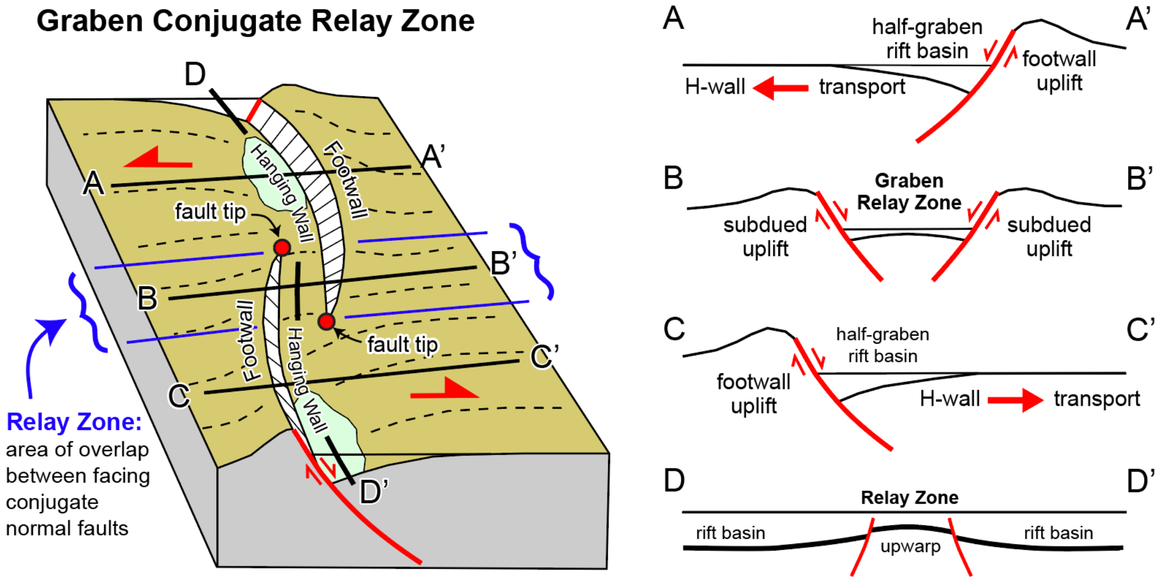


Figure 1. Major 3D geometries, idealized cross sections, and kinematics of interacting normal faults in a graben conjugate relay zone. Large strain gradients are commonly observed in the area of overlap (relay zone) where offset decreases along strike toward the fault tips.

The Messina Strait (Southern Italy) sits in a seismically active region where ongoing NW-SE extension is driven by southeastward retreat of the Ionian subduction zone and Calabrian forearc crust (Fig. 2) (Faccenna et al., 2003; Rosenbaum and Lister, 2004; Gutscher et al., 2016). 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 producing a diversity of bedforms and facies (e.g., Longhitano, 2018a; Martorelli et al., 2023). Numerous studies have documented active faults, earthquakes, tsunamis, sedimentation, and uplift in this region (Ghisetti, 1981, 1992; Monaco and Tortorici, 2000; Doglioni et al., 2012; Aloisi et al., 2013; Ridente et al., 2014; Longhitano, 2018b, 2018a; Longhitano and Chiarella, 2020; Barreca et al., 2021; Antonioli et al., 2021; Meschis et al., 2022a, 2022b), 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 paper 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 reflects large strain gradients and CW 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.

TECTONIC and GEOLOGIC SETTING

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 and retreat of the Ionian subduction zone (Wortel and Spakman, 2000; Rosenbaum et al., 2002; Rosenbaum and Lister, 2004). Forearc crust in Calabria and NE Sicily has translated ~ 800 km to the southeast over the past ~ 30 Myr in response to rollback of the highly arcuate Ionian subduction zone (Fig. 2) (Faccenna et al., 2003, 2004; Gutscher et al., 2016; Romagny et al., 2020; van Hinsbergen et al., 2020; Loreto et al., 2021). The Calabria-Peloritani terrane is a belt of Paleozoic 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 (Rossetti et al., 2001; Vitale and Ciarcia, 2013; Cirrincione et al., 2015). 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 (Fig. 2) (Faccenna et al., 2004, 2011; Gallais et al., 2013; Scarfì et al., 2018; Maesano et al., 2020; Jolivet et al., 2021; Pirrotta et al., 2021, 2022; Sgroi et al., 2021).

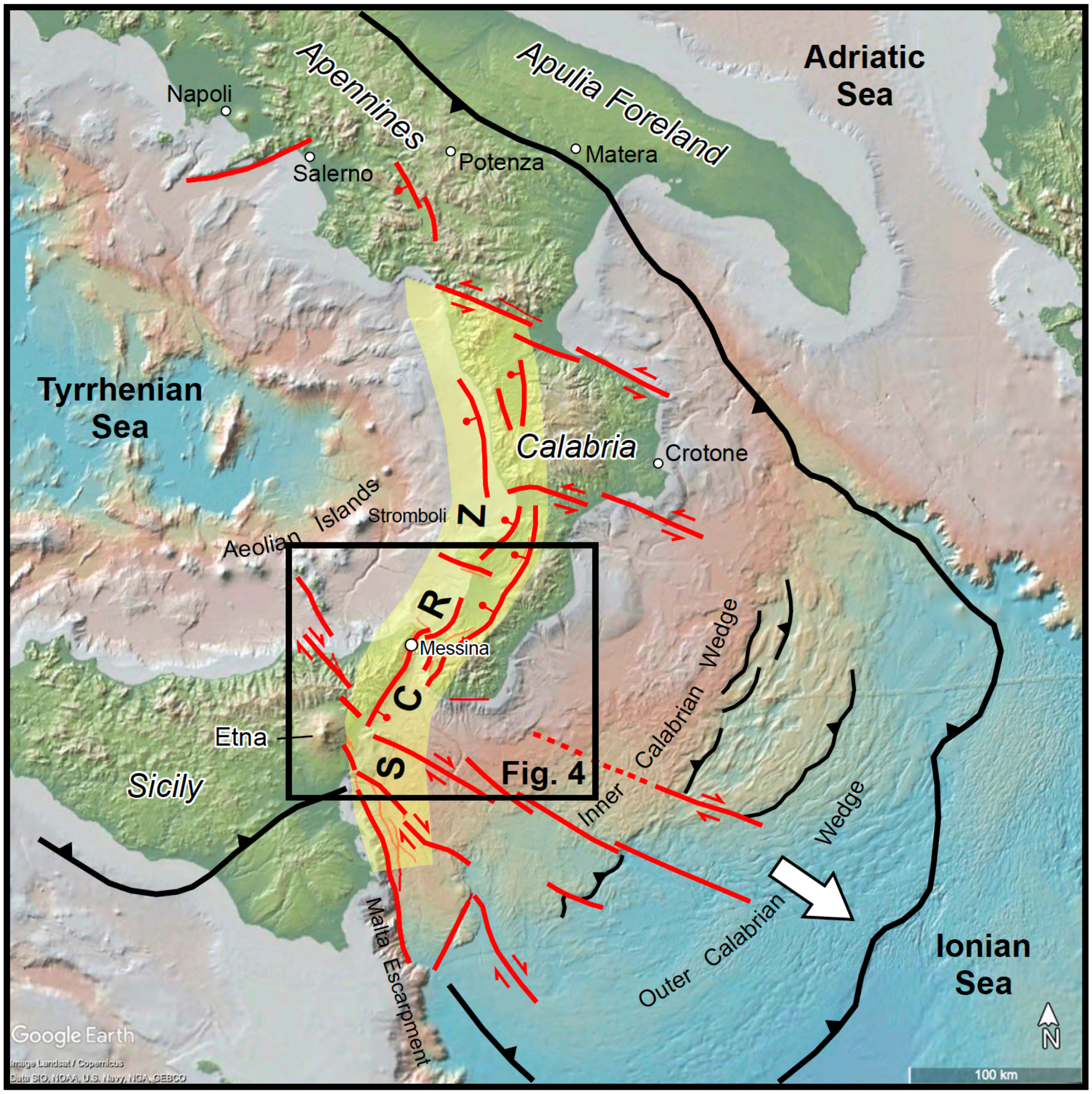


Figure 2. Regional tectonics of southern Italy showing major subduction zones and faults (compiled from Polonia et al., 2011; Gutscher et al., 2016; Scarfì et al., 2018; Maesano et al., 2020). SCRZ is the Siculo-Calabrian Rift Zone. Topography and bathymetry from GeoMapp App.

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 (Monaco et al., 1996; Cavazza et al., 1997; Tripodi et al., 2013). 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 and Ingersoll, 2005; Critelli et al., 2017; Rohais et al., 2021; Critelli and Martín-Martín, 2022). 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 (Tansi et al., 2007; del Ben et al., 2008; Longhitano et al., 2014; Brutto et al., 2016), consistent with microplate kinematics predicted for southeastward lateral extrusion of the subduction zone and highly arcuate offshore accretionary wedge (Fig. 2) (Serpelloni et al., 2010; Zecchin et al., 2015; Viti et al., 2021).

Pliocene-Pleistocene deposits of southern Calabria and NE Sicily are divided into four tectono-sedimentary sequences (P1 to P4; Fig. 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; Zecchin et al., 2015; Tripodi et al., 2018). Sequence P1 overlies Messinian evaporites and consists of lower Pliocene coccolith-foraminiferal marls and marly rhythmites of the Trubi and Cavalieri formations 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 (Cavazza et al., 1997; Bonardi et al., 2001; Di Stefano et al., 2007), which record continued offshore marine deposition with increasing input of fine-grained siliciclastic sediment from distal sources (Cavazza and Ingersoll, 2005). Sequence P3 is composed of early Pleistocene mixed bioclastic-siliciclastic cross-bedded sandstones of the Calcareniti di Vinco Formation (Vinco Calcarenites) and equivalent mudstones and conglomerates that accumulated in tidal straits during development of the modern fault system (di Stefano and Longhitano, 2009; Longhitano, 2011, 2018b; Longhitano et al., 2012, 2021; Zecchin et al., 2015; Rossi et al., 2017; Chiarella et al., 2021). The Pellaro paleo-high is a fault-bounded horst in the footwall of the southern Armo fault, east of the Messina Strait (Fig. 4), that underwent uplift during deposition of the Early Pleistocene (Gelasian) Vinco Calcarenite (Longhitano, 2018b; Chiarella et al., 2021). 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 from the uplifting horst during early stages of fault growth (Chiarella et al., 2021; Longhitano et al., 2021).

The 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; Lentini et al., 2000; di Stefano and Longhitano, 2009; 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 ~ 1.0 to 2.5 Myr (Figs. 3, 4) (Antonioli et al., 2006, 2021; Roda-Boluda and Whittaker, 2017).

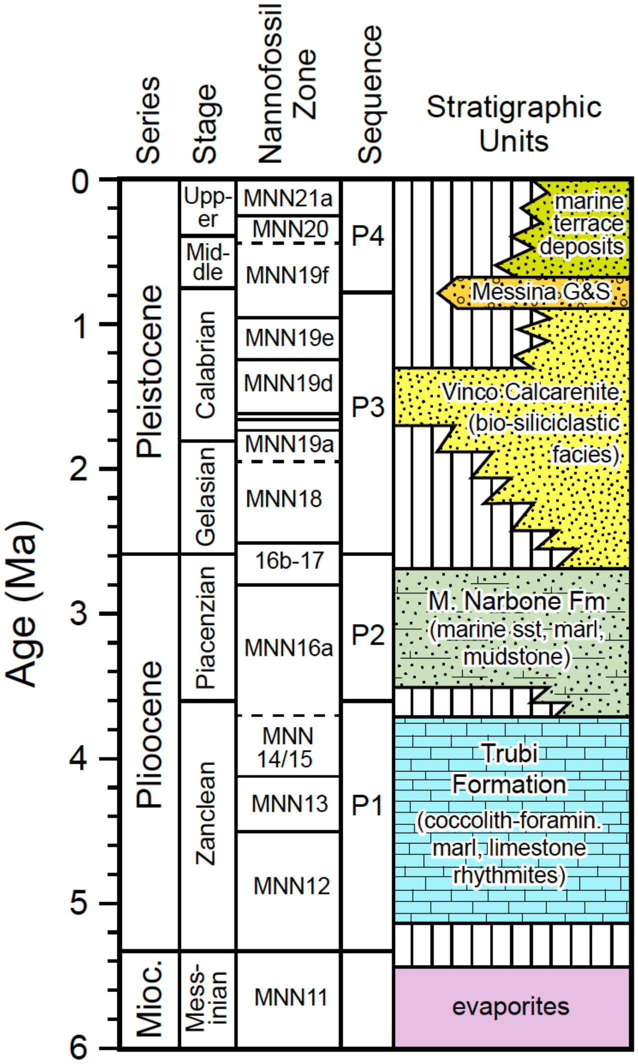


Figure 3. Generalized Pliocene - Pleistocene stratigraphy of the Messina Strait region (compiled from Di Stefano et al., 2007; Longhitano et al., 2012; Zecchin et al., 2015). P1 to P4 are tectono-stratigraphic sequences of Zecchin et al. (2015). MNN = Mediterranean Neogene Nannoplankton zone (Rio et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

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

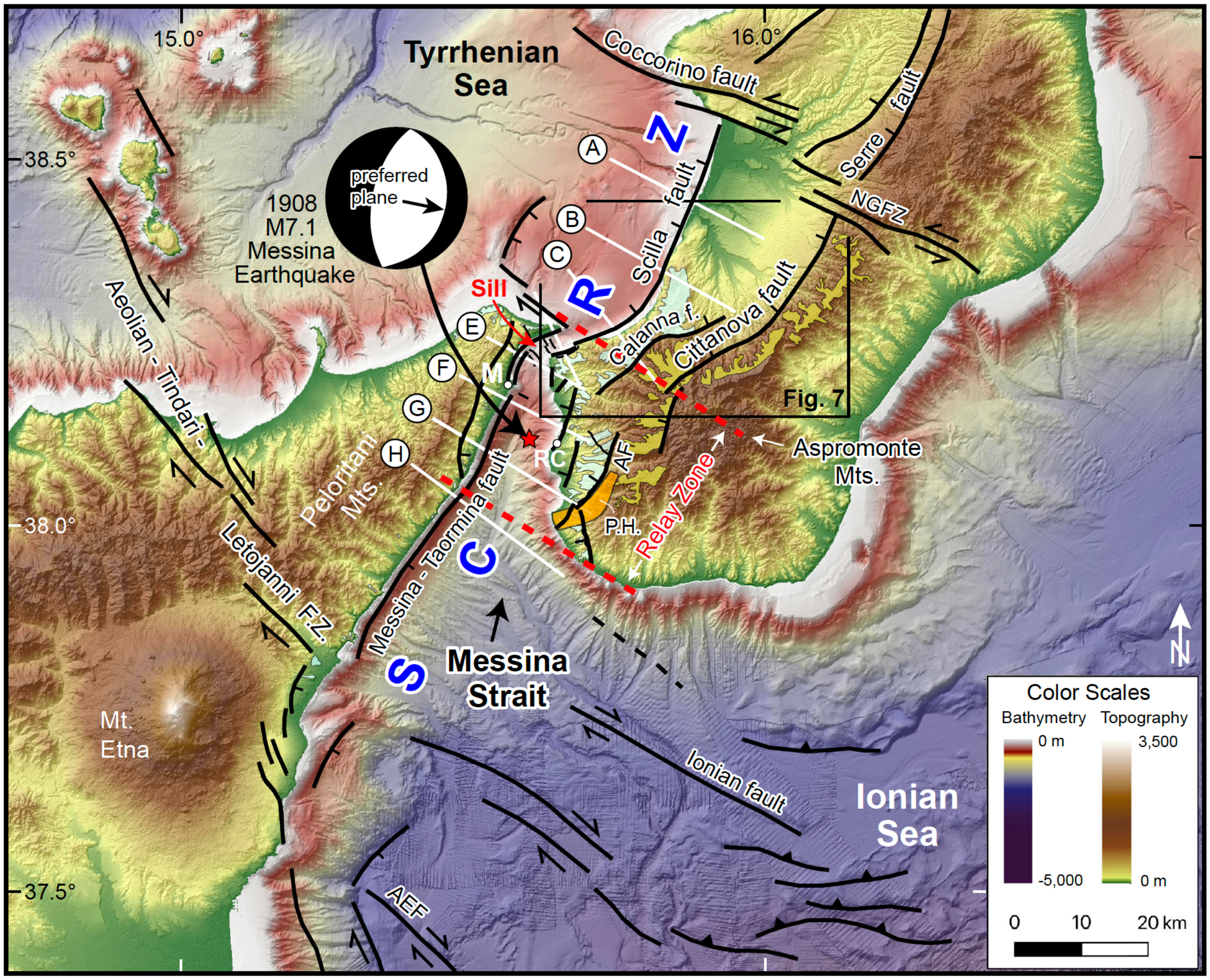


Figure 4. Topographic and bathymetric map showing major faults, location of profile transects in Fig. 5 (white lines with letters), and uplifted marine terraces (from Catalano and De Guidi, 2003; Roda-Boluda and Whittaker, 2017; Monaco et al., 2017; Antonioli et al., 2021) (faults compiled from Antonioli 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 ~ 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) (epicenter of Gasparini et al., 1982). Abbreviations: AEF, Alfeo–Etna fault; AF, Armo fault; M, Messina; NGFZ, Nicotera-Gioiosa fault zone; P.H. Pellaro paleo-high; RC, Reggio Calabria; 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.

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., Pino et al., 2000, 2009; Serpelloni et al., 2010; Meschis et al., 2019), 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 the narrow linear shelf, steep seafloor bathymetry (Fig. 4), and consistent patterns of regional uplift and erosion in northeast Sicily (Monaco and Tortorici, 2000; Catalano and De Guidi, 2003b; Catalano et al., 2003, 2008; De Guidi et al., 2003; 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 et al., 2009; Argnani, 2021, 2022; Argnani and Pino, 2023). However, existing offshore seismic lines in Messina Strait (Argnani et al., 2009) stop just short of the likely trace of the fault, at the top of the steep marine slope with abundant submarine slides and debris cones (Fig. 4), and thus do not offer a definitive test of this fault. Moreover, GPS data and modeling point to the Messina-Taormina fault as a major structure on 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 (Argnani and Pino, 2023).

GPS velocities reveal NW-SE extension across the Siculo-Calabrian Rift Zone at rates of 3 – 4 mm/yr (Serpelloni et al., 2010; Palano et al., 2012). 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 (Figs. 2, 4) (Palano et al., 2015; Gutscher et al., 2016, 2017; Scarfì et al., 2018; Maesano et al., 2020). 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., Goes et al., 2004; Faccenna et al., 2011). The Peloritani Mountains in northeast Sicily represent a semi-independent crustal block east of the Aeolian-Tindari-Letojanni fault zone, northwest of the Messina-Taormina normal fault, that accommodates northwest motion away from southern Calabria (Fig. 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 (Serpelloni et al., 2010; Meschis et al., 2019; Barreca et al., 2021).

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 (Fig. 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 in phase opposition of ca. 35 cm between the two marine basins produces a gradient of the water surface and consequent gravity-driven water mass transfers every six hours per day (Vercelli, 1925; Defant, 1940). This tidal difference stimulates collinear tidal currents moving axially along the Strait that accelerate up to velocities of > 3 m sec^{-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 center (Longhitano, 2018a; Martorelli et al., 2023). Because of the high shear stress exerted by tidal currents, the sill is mostly 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).

FAULT ZONE ANALYSIS

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 (Fig. 4). Both fault sets are present within the relay zone and dip toward each other to form a graben where subsidence maintains the basin floor below sea level. The width of the strait decreases to ~ 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 farther to the south and north (Fig. 4), similar to the along strike pattern of subtle uplift see in classic conjugate relay zones (Fig. 1D).

The morphological expression of normal faults in the Messina Strait is revealed in a series of onshore-offshore profiles that were constructed from topographic and bathymetric data (Fig. 5) and integrated with published fault maps (Fig. 4) (Antonioli et al., 2006; Ferranti et al., 2008; Doglioni et al., 2012; Ridente et al., 2014; Pavano et al., 2016; Tripodi et al., 2018). The profiles show large fault displacements with structural relief up to ~1,200 m on individual normal faults. The magnitude of implied fault offsets are likely minimum values in areas where sediment is accumulating in offshore basins. The Scilla fault forms a precipitous NW-facing escarpment with ~1,000 m of vertical relief northeast of the constriction (Figs. 4, 5B, 5C). Structural relief decreases along strike to ~400 m within the sill where strain is transferred from the NW-dipping Scilla fault to the SE-dipping Messina Strait fault (Fig. 5D). Topographic and structural relief both increase again along strike to the southwest along the Messina-Taormina fault, which has up to 2,200 m of combined offset on the master fault and adjacent smaller normal faults (Fig. 5H).

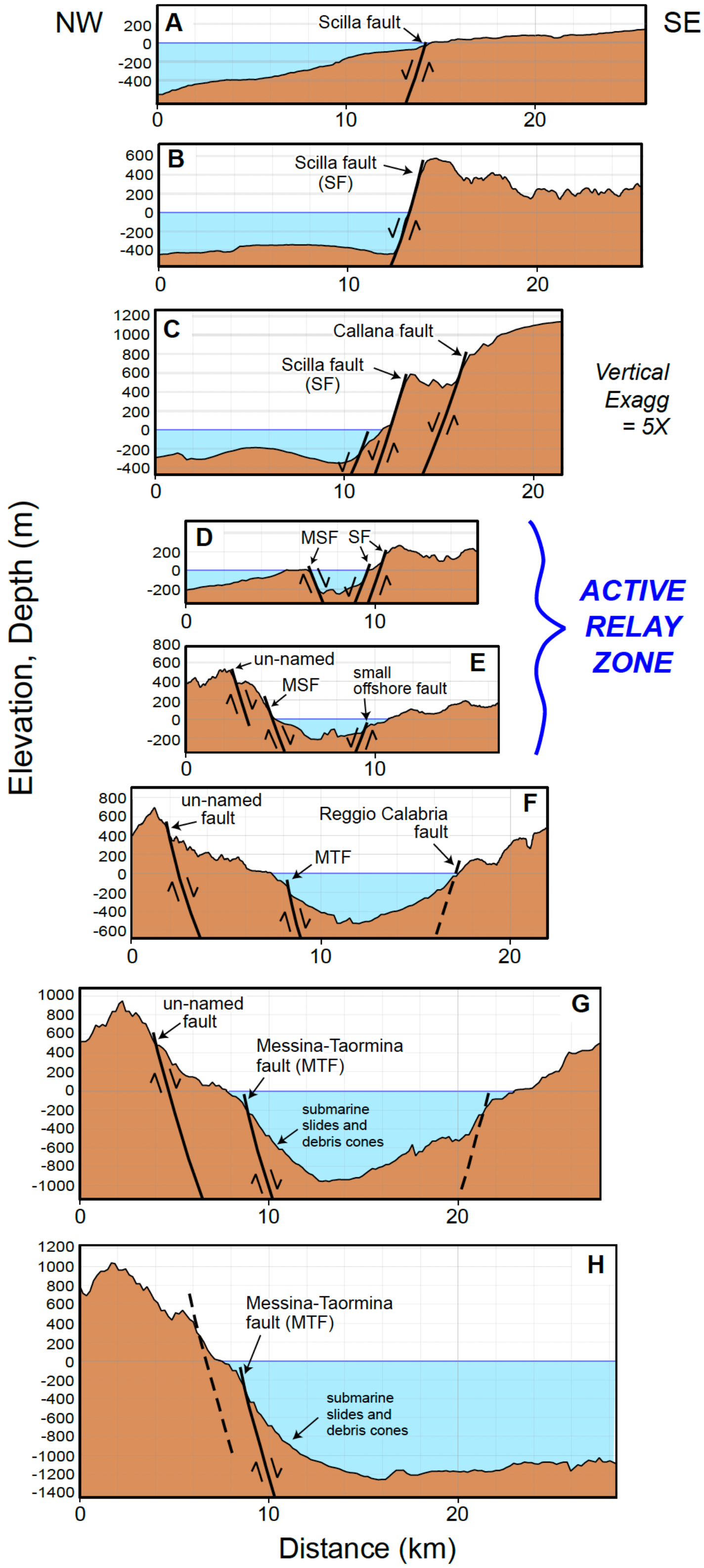


Figure 5. Topographic-bathymetric profiles and major faults. Location of profiles in Fig. 4. SF is Scilla fault; MSF is Messina Strait fault; MTF is Messina-Taormina fault.

Figure 6A 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 Fig. 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 (Fig. 6B) (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 NNE-striking faults and fault segments where the shape of the coastline is controlled by active fault slip. West-facing promontories are produced by footwall uplift near southern fault terminations, and scallop-shaped bays form in areas of hanging-wall subsidence (Fig. 6A). 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 (Longhitano, 2011, 2018b; Chiarella et al., 2021).

A distinctive feature of the conjugate relay zone is a pronounced plan-view curvature of normal faults adjacent to the central sill (Figs. 4, 6). Outside of the relay zone the regional strike of normal faults is 030°–035°. Faults curve progressively along strike into the relay zone at the margins of the sill, where strike values increase to 070°– 075°, deviating from the regional fault strike by 40°–45° (Fig 6). The area of greatest strike deviation coincides with minimum fault offset and subdued footwall topography near the tips of the overlapping faults (Figs. 5D, 5E). The Messina Strait relay zone is thus characterized by strong fault curvature where fault offset, footwall elevation, and water depth all decrease along strike toward the tips of facing normal faults in the area of extensional strain transfer and maximum reorientation of fault strike.

Normal Fault Initiation and Migration

Figure 7 shows the evolution of river catchments in response to initiation and migration of normal faults in southwest Calabria (Pirrotta et al., 2016) (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, Fig. 7A), 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; Fig. 7B), the Calanna fault was initiated, slip on the Cittanova fault likely slowed, the SCA marine shelf was uplifted, and the margin of the paleo-Messina Strait shifted ~5–8 km to the northwest. Biostratigraphic data show that the Calanna fault was activated ~1.7 Ma (Longhitano et al., 2012). During the middle Pleistocene (Fig. 7C), initiation of the Palmi fault led to uplift and inversion of the Gioia basin as normal faults shifted again to the northwest. In late Pleistocene time (Fig. 7D), activation of 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 8 shows 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 modeling (Westaway, 1993; Roda-Boluda and Whittaker, 2017; Monaco et al., 2017; Antonioli et al., 2021). 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 and Whitaker, 2017) are not

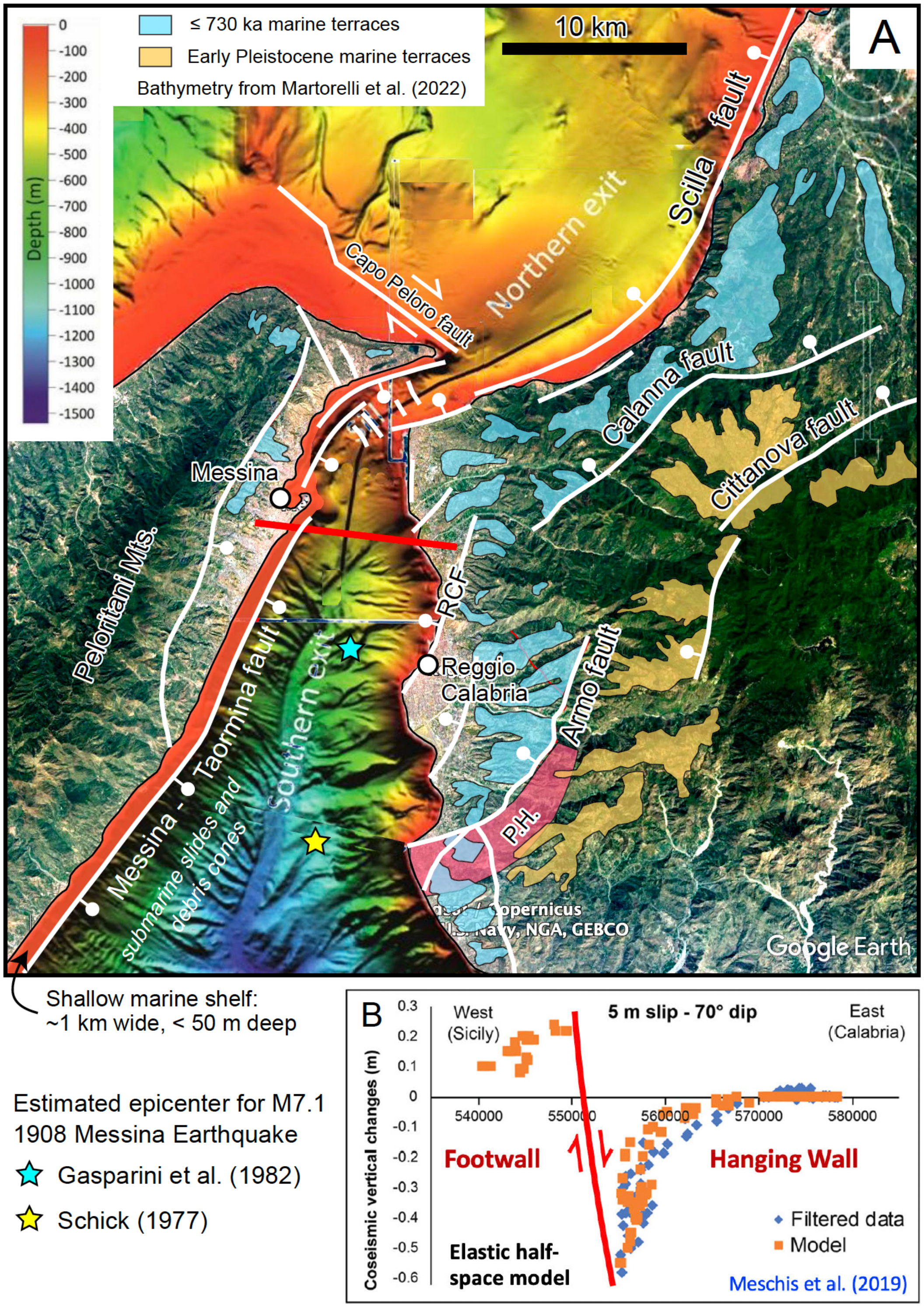


Figure 6. Faults and bathymetry of Messina Strait. (A) Map of active faults and related onshore-offshore surface morphology (modified from Martorelli et al., 2023). Red line is approximate position of transect in part B. P.H. is Pellaro paleo-high; RCF is the Reggio Calabria fault. (B) Profile view of surface displacements associated with the 1908 M7.1 Messina earthquake, showing close agreement between observed surface motions (filtered data) and modeled 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.

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 (Fig. 6A). The Armo fault, oldest in the en-echelon array, formed southeast margin of the paleo-Messina strait during deposition of the early Pleistocene Calcareniti di Vinco Formation (Longhitano, 2011, 2018b; Chiarella et al., 2021). 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 immediately adjacent to the central sill of the modern strait (Figs. 6A, 8).

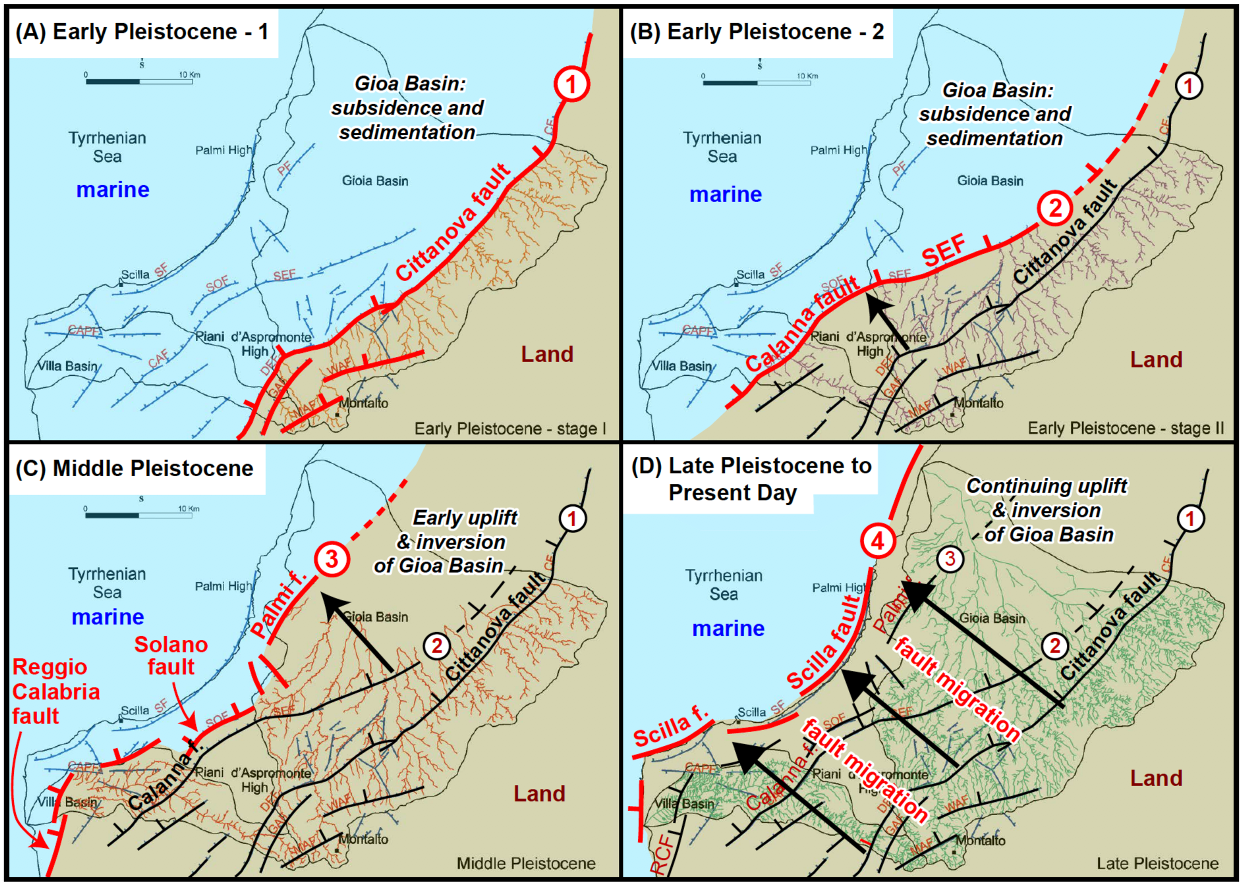


Figure 7. Reconstructed evolution of river channels in response to initiation and migration of normal faults in the Petrace and Catona river catchments, southwest Calabria (modified from Pirrotta et al., 2016). Bold red lines are faults that became active in each stage of structural and geomorphic development. Older faults in the southeast are still active today, likely with slower slip rates than the most active faults at the modern coastline (part D). (A) During early Pleistocene Stage 1 (Gelasian), a first phase of uplift was controlled by slip on the Cittanova, Delianuova and Gambarie faults which produced uplift and erosion inthe 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 the Palmi fault led to early uplift and inversion of the Gioia basin, and the Solano fault and minor faults of the Villa Basin 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. CAPF = Cappuccini fault; CAF = Calanna fault; SF = Scilla fault; SOF = Solano fault; SEF = Santa Eufemia fault; PF = Palmi fault; CF = Cittanova fault; DEF = Delianuova fault; GAF = Gambarie fault; WAF = Western Aspromonte fault.

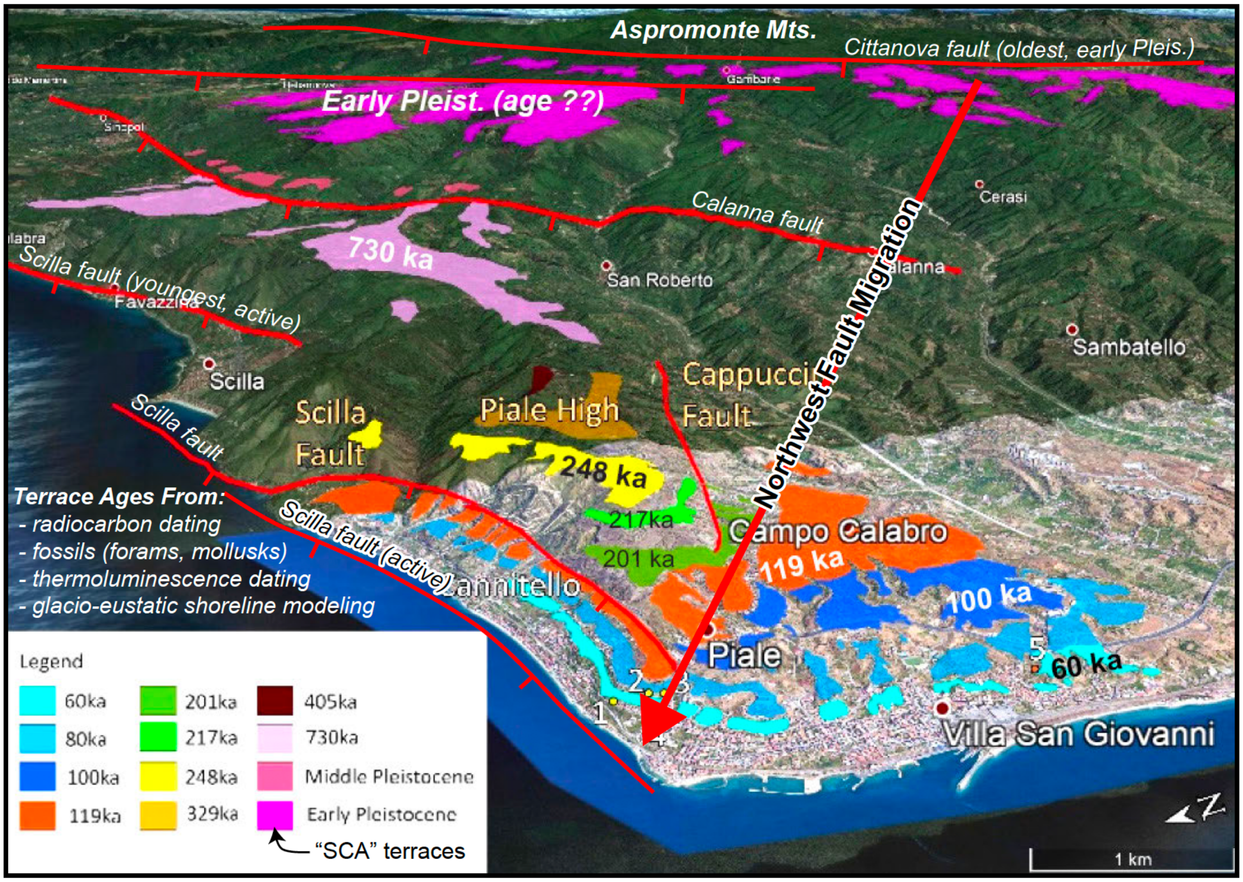


Figure 8. Flight of uplifted and faulted marine terraces in southern Calabria (modified from Antonioli et al., 2021). "SCA" terraces are Serre–Cittanova–Armo terraces, named for the faults that cut them (Roda-Boluda and Whittaker, 2017). The relative ages and elevations of faulted marine terraces suggest northwest migration of normal faults through time, but 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.

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 (Figs. 7 – 9). Fault activity is currently focused at the narrow central sill of the modern strait, where normal faults display the strongest curvature in plan view and local fault strikes deviate up to 40° – 45° from the regional fault strike (Fig. 6A).

DISCUSSION

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 (Fig. 9). 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 (Figs. 4, 8). 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.

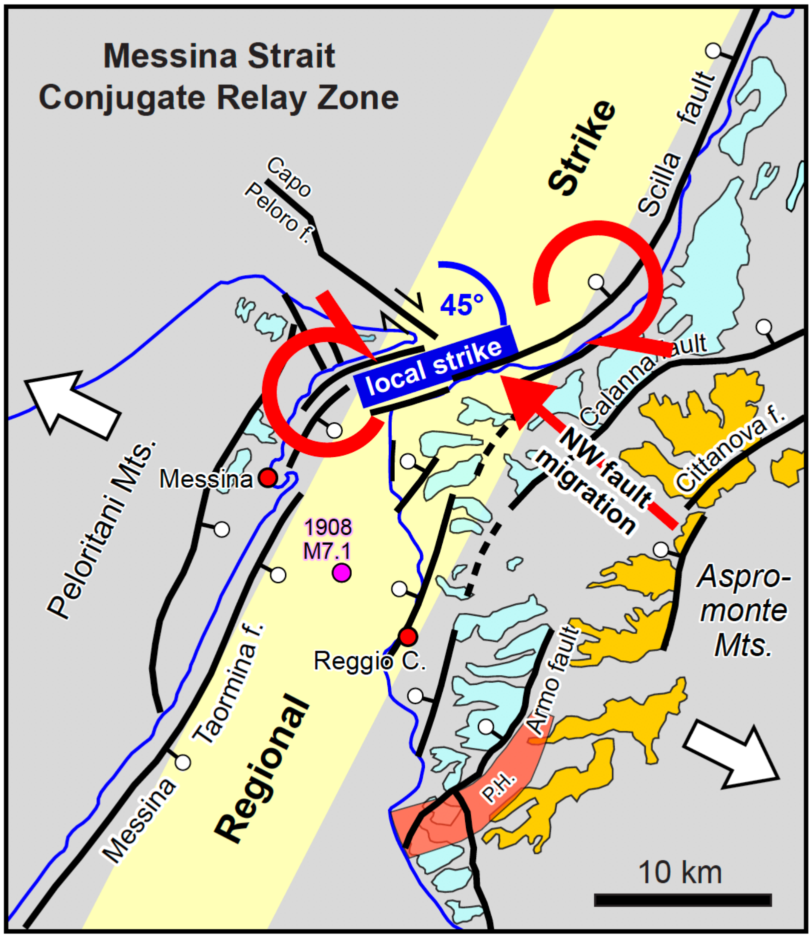
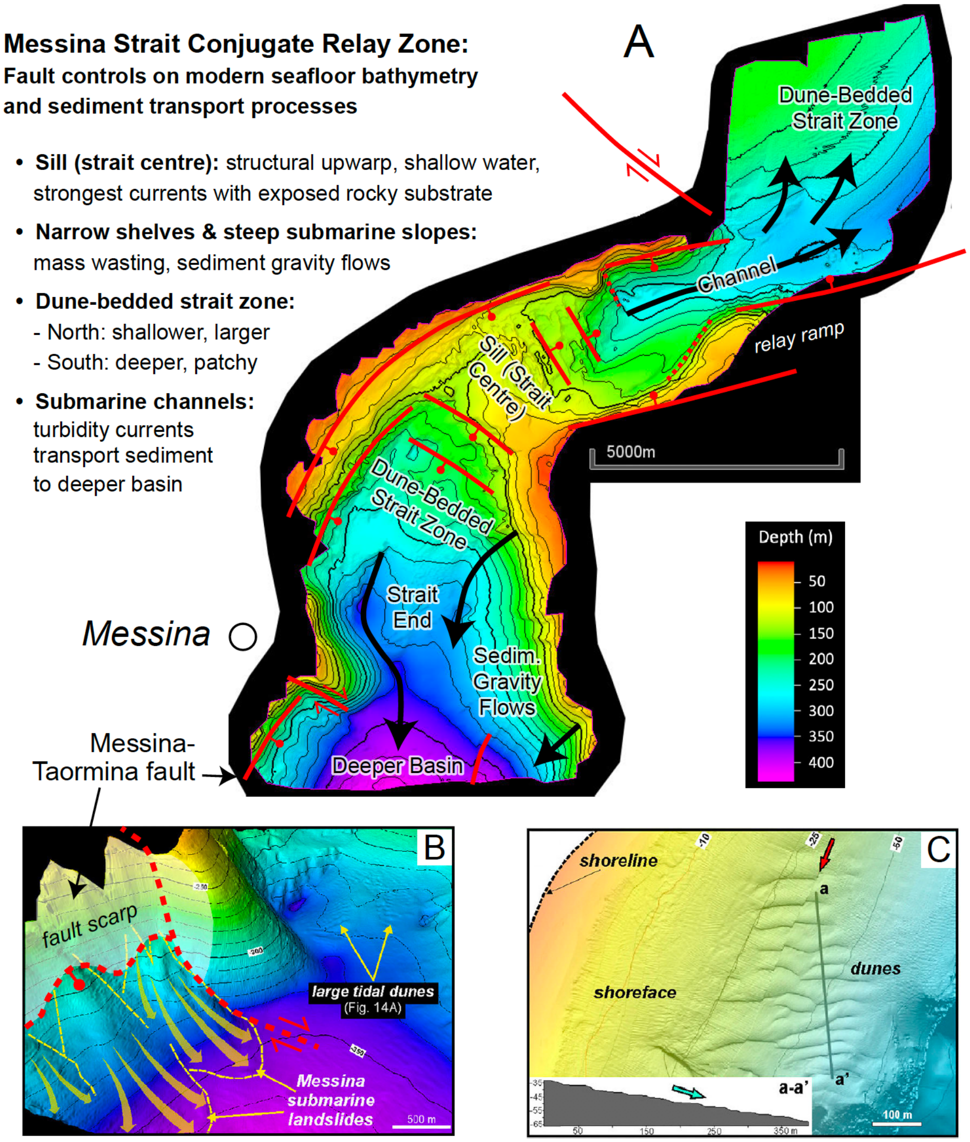


Figure 9. Proposed structural model for the Messina Strait conjugate relay zone. Strong fault curvature results from clockwise rotation in the area of active fault-tip interactions, where the strike of normal faults deviates from the regional fault strike by ~ 40-45°. The Pellaro paleo-high (P.H.) formed an early Pleistocene fault-bounded structural high that separated north- and south-directed currents (Longhitano, 2018b), suggesting that the narrow constriction of Messina Strait has migrated north ~20 km in the past ~ 2.0 to 2.5 Myr.

The plan-view curvature of facing normal faults in Messina Strait resembles that of extensional relay zones worldwide (Ebinger, 1989; Morley et al., 1990; Peacock and Sanderson, 1994; Acocella et al., 2000, 2005). The 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 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 (Figs. 6, 9) is oriented favorably to act as a transfer fault, a geometry seen in other relay zones undergoing rapid, large magnitude extension (Acocella et al., 2005). The geometry of fault curvature around the central sill, combined with dextral offset on the Capo Peloro fault (Figs. 6, 8), suggests that CW rotation of faults and crustal blocks in the relay zone are 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 active strain transfer (Figs. 4, 5). Thus, the fault geometries, fault-tip interactions, and evidence for kinematic development of normal faults in Messina Strait are all consistent with extensional conjugate relay zones worldwide (Childs et al., 2019).



Submarine slides, offshore Messina

Bedform transport by tidal currents

Figure 10. (A) Detailed bathymetry of Messina Straight showing fault controls on modern seafloor bathymetry and sediment transport processes (tidal strait depositional zones of Longhitano, 2013). (B) Oblique view of steep submarine slope near Messina, showing active submarine slides in hanging wall of the Messina-Taormina fault near its northern termination. (C) Migrating asymmetric bedforms produced by transport and deposition from daily tidal currents, nearshore eastern Sicily. B and C modified from Longhitano (2018a).

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 southeastward retreating Ionian subduction zone (Figs. 2, 4). The Strait is maintained as a shallow marine connection by subsidence within the active relay zone (Figs. 4, 6A). Normal faults in this region are cut and segmented by NW-striking strike-slip faults that have formed above growing tears in the subducting slab since middle to late Miocene time (Fig. 2) (Faccenna et al., 2004, 2011; Sgroi et al., 2021; Civile et al., 2022). We infer that clockwise rotation, curvature of normal faults, and associated dextral offset on the Capo Peloro fault may be the surface expressions of a tear fault in the subducting Ionian slab as it propagates upward into the overlying crust.

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 (e.g., Roda-Boluda and Whittaker, 2017; Quye-Sawyer et al., 2021) conclude that normal faulting and uplift of raised SCA marine terraces started ~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 (Dumas et al., 1981, 1987; Ghisetti, 1981; Westaway, 1993; Miyauchi, 1994; Monaco et al., 1996; Catalano et al., 2008). 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; Fig. 3) is now placed at 2.58 Ma and is recognized as the start of major northern hemisphere glaciation and global cooling (Head et al., 2008; Gibbard and Head, 2010; Cohen et al., 2013). 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, ~1.7-1.8 Ma (Gibbard and Head, 2010; Crippa and Raineri, 2015; Crippa et al., 2019; Bizzarri and Baldanza, 2020), earlier than the widely cited age of 1.0 ± 0.2 Ma. Biostratigraphic data from Vinco Calcarenite in the hanging wall of the Armo fault (Fig. 6) 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 ~ 1.0 and 2.6 Ma.

Two hypotheses could potentially explain the difference in 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 ~ 1 Ma (widely cited age for the onset of regional uplift). This explanation is unlikely because full suppression of footwall uplift is unusual for active normal faults, and there is abundant evidence for early Pleistocene siliciclastic input from the footwalls of the normal faults in question (Longhitano, 2011; Chiarella and Longhitano, 2012; Longhitano et al., 2012, 2021; Rossi et al., 2017; Chiarella et al., 2021), which requires footwall uplift and erosion. (2) The "northern guest" faunas may have arrived in southern Calabria earlier than 1.0 Ma, in which case the high SCA marine terraces may also be older than ~1 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 and Head, 2010). In this case the oldest SCA marine terraces may be early Gelasian (~ 2.4-2.6 Ma), normal faults would have initiated in the southeast around then, and faulting migrated northwest through time (Fig. 7) (Pirrotta et al., 2016). The second hypothesis is challenged by studies that find northern faunas arrived in the central Mediterranean region at the start of the Calabrian stage, ~1.7-1.8 Ma (Crippa and Raineri, 2015; Crippa et al., 2019; Bizzarri and Baldanza, 2020), not early Gelasian, so this explanation cannot fully resolve the age discrepancy.

Despite existing age uncertainties, our interpretation of northward migrating faults east of the Messina Strait (Figs. 7, 9) is consistent with a history of northward propagating faults, erosion, and sedimentation at the west margin of Messina Strait in northeast Sicily during Middle to Late Pleistocene time (di Stefano and Longhitano, 2009). Northward migration of faults on both sides of the strait may be driven by tectonic translation of the Peloritani Mountains away from southwest Calabria (Fig. 4). GPS data show that the Peloritani Mountains move as a semi-independent block located east of the Aeolian-Tindari-Letojanni fault zone (Fig. 4), and motion of this block results in extensional opening of the Siculo-Calabrian Rift Zone at rates of 3 – 4 mm/yr (Catalano and De Guidi, 2003a; Catalano et al., 2003; Serpelloni et al., 2010; Palano et al., 2012; Pavano et al., 2015, 2016). Thus, the structural evolution and migration of the Messina Strait conjugate relay zone is driven by microplate translation and opening of an upper-plate rift zone in response to ongoing rollback and retreat of the Ionian subduction zone (Fig. 2).

Fault Controls on Sedimentary Processes

The above analysis identifies the modern Messina Strait as a tectonically active marine passageway (Rossi et al., 2023; Dalrymple, 2023), where faults of the conjugate relay zone exert a direct control on modern seafloor bathymetry, depozone partitioning, and sedimentary processes (Fig. 10) (Longhitano, 2013, 2018a; Pierdomenico et al., 2019; Chiarella and Hernández-Molina, 2021; Martorelli et al., 2023). The strait-center zone forms a shallow structural upwarp relative to deeper areas to the north and south, coincident with the area of greatest fault curvature and reduced offset in the modern relay zone. This unique structural geometry causes tidal currents to accelerate to their maximum-peak velocity and sweep sediment away to erode and expose a rocky marine substrate at the narrow central sill (Fig. 10A). North and south of the sill, water depth increases into two wider, deeper depositional zones where gravel- and sand-size sediments accumulate at ca. 200 – 300 m depth due to deceleration of tidal currents exiting the sill. These zones host large-scale tidal dunes organized into continuous or patchy bedform fields (Martorelli et al., 2023). Tidal dunes move at a rate of several cm per hour under the strong effect of tidal currents (Santoro et al., 2004). Dunes pass distally into smaller sandy bedforms interfingering with muddy deposits in the northern and southern exits of the strait (Fig. 10A), where currents decelerate and reverse direction (Longhitano, 2018a).

Along the margins of the Strait, active fault displacements maintain narrow marine shelves that are flanked by steep slopes dominated by mass wasting and sediment gravity flows (Fig. 10A). Numerous submarine slides at the western margin of the strait have been documented on the steep subaqueous slope of the active Messina-Taormina fault (Fig. 10B) (Billi et al., 2008; Goswami et al., 2014, 2017; Longhitano, 2018a; Schambach et al., 2020). Bedforms derived from mouths of local rivers and fan deltas are deflected by tidal currents and migrate along the narrow shelves parallel to the tectonically controlled strait margins (Fig. 10C). Retreating submarine gullies follow the arcuate structural grain of curved normal faults, transporting sediment into the deeper basin via turbidity currents and debris flows that converge in the Messina Canyon at the southern strait exit (Fig. 10) (Longhitano, 2018a; Pierdomenico et al., 2019). This complex tidal sediment dynamic likely has affected the Messina Strait during the last ~ 2.5 Myr, producing tidal deposits exposed today around the flanks of the modern strait (Longhitano, 2018b).

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. The region is distinguished by a rich cultural legacy recorded in Homer's Odyssey (c. 8th 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 (source of the 1908 M7.1 Messina earthquake). Strong curvature of facing normal faults within the active relay zone results from clockwise rotation related to ongoing fault-tip interactions.

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. Strong curvature of normal faults, local crustal rotations, and dextral offset on the Capo Peloro fault may be the surface expressions of a growing tear in the Ionian slab as it propagates upward into the overlying lithosphere. These deformation processes and resulting fault geometries exert a direct control on modern topography, seafloor bathymetry and sedimentary processes of the Messina Strait tidal depositional system.

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FIGURE CAPTIONS

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 toward 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 GeoMapp App.

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).

Figure 4. Topographic and bathymetric map showing major faults, location of profile transects in Fig. 5 (white lines with letters), and uplifted marine terraces (from Catalano and De Guidi, 2003; Roda-Boluda and 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 ~ 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) (epicenter of Gasparini et al., 1982). Abbreviations: AEF, Alfeo–Etna fault; AF, Armo fault; M, Messina; NGFZ, Nicotera-Gioiosa fault zone; P.H. Pellaro paleo-high; RC, Reggio Calabria; 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.

Figure 5. Topographic-bathymetric profiles and major faults. Location of profiles in Fig. 4. SF is Scilla fault; MSF is Messina Strait fault; MTF is Messina-Taormina fault.

Figure 6. Faults and bathymetry of Messina Strait. (A) Map of active faults and related onshore-offshore surface morphology (modified from Martorelli et al., 2023). 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 modeled 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.

Figure 7. Reconstructed evolution of river channels in response to initiation and migration of normal faults in the Petrace and Catona river catchments, southwest Calabria (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 are still active today, likely with slower slip rates than the most active faults at the modern coastline (part D). (A) During early Pleistocene Stage 1 (Gelasian), a first phase of uplift was controlled by slip on the Cittanova, Delianuova and Gambarie faults which produced uplift and erosion inthe 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 the Palmi fault led to early uplift and inversion of the Gioia basin,

and the Solano fault and minor faults of the Villa Basin 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. CAPF = Cappuccini fault; CAF = Calanna fault; SF = Scilla fault; SOF = Solano fault; SEF = Santa Eufemia fault; PF = Palmi fault; CF = Cittanova fault; DEF = Delianuova fault; GAF = Gambarie fault; WAF = Western Aspromonte fault.

Figure 8. 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 and Whittaker, 2017). The relative ages and elevations of faulted marine terraces suggest northwest migration of normal faults through time, but 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.

Figure 9. 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 ~ 40-45°. The Pellaro paleo-high (P.H.) formed an early Pleistocene fault-bounded structural high that separated north- and south-directed currents (Longhitano, 2018b), suggesting that the narrow constriction of Messina Strait has migrated north ~20 km in the past ~ 2.0 to 2.5 Myr.

Figure 10. (A) Detailed bathymetry of Messina Straight showing fault controls on modern seafloor bathymetry and sediment transport processes (tidal strait depositional zones of Longhitano, 2013). (B) Oblique view of steep submarine slope near Messina, showing active submarine slides in hanging wall of the Messina-Taormina fault near its northern termination. (C) Migrating asymmetric bedforms produced by transport and deposition from daily tidal currents, nearshore eastern Sicily. B and C modified from Longhitano (2018a).