Rift and supradetachment basins during extension: insight from the Tyrrhenian rift

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The style of extensional basins provides key insights into the magnitude of extension and their kinematic evolution. The newly documented Stilo rift (off Calabria, Italy) features a Serravallian–Tortonian rift basin bounded by a high-angle normal fault and a Messinian adjacent supradetachment basin bounded by a low-angle normal fault. We propose a kinematic model suggesting the abandonment of the high-angle normal fault and the beginning of low-angle normal fault activity, followed by a rapid increase in extension. The triggering mechanism of the low-angle normal faults can be attributed to rapid rollback of the subducting plate and/or to isostatic crustal uplift.

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Lithospheric extension is characterized by two contrasting styles of deformation corresponding to the low-angle normal faults of the Basin and Range Province (e.g. Wernicke 1981) and the high-angle normal faults of rifted continental margins. The development of the controlling basement elements affects the distribution and pattern of internal deformation in the evolving sedimentary fill, resulting in a characteristic basin architecture. The latter has profound implications for models of the stratigraphy and sedimentology of basins, and provides an insight into the occurrence of certain facies and stratigraphic changes (Gibbs 1987). It is commonly assumed that a variation in the balance between sediment supply and subsidence rate, changes in lithological signatures and stacking patterns can reflect variations in fault-related subsidence rate (Leeder & Gawthorpe 1987; Ravanas & Steel 1998; Milia 1999). The variety of structural geometries and their effect on the sedimentation and deformation of the sedimentary fill can be used to understand the main structural elements and the pattern of linked fault arrays at depth. Friedman & Burbank (1995) proposed that high-angle rift basins and supradetachment basins present different characteristics such as original crustal thickness, dip of normal fault, basin depth, slip rate and magnitude of extension. The mode of crustal extension is relevant when rift basins are inherited into orogenic belts because it influences the localization and amplification of contractional structures during mountain building (Tavarnelli 1996; Butler et al. 2006).

To solve the mechanical problem of low-angle normal faults a rotation of initial steeper normal faults has been invoked (e.g. Buck 1988; Wernicke & Axen 1988). However, field evidence has revealed some late low-angle normal faults that are geometrically consistent with mapped bedding and truncations of high-angle normal faults only when they were initiated at a low angle (e.g. Scott & Lister 1992). To generate low-angle normal faults non-Andersonian conditions are necessary. These may be caused by a basal shear stress, such as regional ductile flow in the lower crust or between the crust and the mantle (Yin 1989), or by igneous intrusion (Parsons & Thompson 1993).

The Tyrrhenian Sea is an extensional area (Fig. 1) formed since the middle Miocene as a consequence of the eastward rollback of a west-dipping subduction zone (e.g. Malinverno & Ryan 1986). Rosenbaum & Lister (2004) postulated a rapid rollback in Messinian times. The Tyrrhenian Sea opening was a polyphase rifiting with a migration of activity and a change of style over time (e.g. Sartori 2003; Milia et al. 2013). Recently, the early rifting of the Tyrrhenian region (in late Miocene time) was interpreted as an upper plate extension (back-arc and forearc extension) affecting both margins of Calabria (Milia & Torrente 2014). At that time high-angle normal faults affected the western Tyrrhenian margin bounding synrift basins (Sartori et al. 2004), whereas low-angle normal faults were documented on the eastern margin of the Tyrrhenian Sea in Tuscany (Pandeli et al. 2010) and Calabria (Mattei et al. 2002).

Our study was conducted on the Ionian margin of Calabria (Figs 1 and 2) by means of well logs and seismic reflection profile data. We document new sedimentary basins of Serravallian–Messinian age offshore Stilo that evolved from rift to supradetachment basins and we propose a kinematic model for this change of extensional style.

Stilo rift basins. The Stilo rift is 40 km long and 40 km wide and trends north–south (Fig. 2). The interpretation of the seismic profiles calibrated by well logs discloses a thick elastic succession deposited within two detached depocentres (Figs 2 and 3). The section across the Stilo rift (Fig. 3b) displays in the west a 3 km deep and relatively narrow rift basin bounded by a ~60° east-dipping normal fault, and eastward a shallower and wider supradetachment basin overlying a ~20° east-dipping normal fault. The western depocentre, of Serravallian–Tortonian age, is characterized by vertical aggradation of the succession whereas the eastern one, of
Messinian age, features lateral aggradation of the succession. At the end of tectonic activity the whole area was buried by a Lower Pliocene succession.

The sedimentary succession recognized in the Luisa well (Fig. 3) allowed for the recognition of three unconformity-bounded units (Ser3, Tor1, Tor2; Milia & Torrente 2014). Palaeozoic granitoid rocks are overlain by the Ser3 sequence, which consists of stratified polygenetic conglomerates (the 12 Ma San Nicola Formation; Ogniben 1955), passing upward into transgressive, coarse-grained arkosic sandstones with clays. The sandstones are covered by a regressive succession of clays, passing upwards to clays and sands. The Tor1 sequence displays a conglomerate covered abruptly by clays, sands and conglomerates with a regressive trend. The Tor2 sequence shows clays and sands covered by clays.

The adjacent supradetachment basin, calibrated by the Fosca well, rests above Langhian olistostrome deposits (varicoloured clays). It is characterized by tilted strata of a c. 700 m thick Serravallian conglomerate (San Nicola Formation, age 12 Ma) passing upward to c. 90 m of Late Tortonian clays conformably overlain by Messinian deposits. The lower Messinian unit (Ma), formed by clays, corresponds to a wedge featuring continuous reflectors with high amplitude; it displays a lateral aggradation and downlaps the...
substrate toward the west; it is separated by an Intra-Messinian unconformity (IMU) from the upper Messinian unit (Mb); the latter is more or less isopachous and features a chaotic seismic facies; the Mb unit, corresponding to shallow-water coarse deposits (Cavazza & De Celles 1998), abruptly covers the basement in the central and western part of the supradetachment basin and its upper boundary corresponds to an erosional surface. The Lower Pliocene succession conformably covers the upper Messinian unit, onlaps the basin flanks and buries the Stilo rift area. Onshore at Stilo a remarkable uplift of Quaternary age exposes the stratigraphic succession (Cavazza & De Celles 1998). In particular, a Hercynian crystalline basement is overlain by a stratigraphic succession that dips 30–50° eastward and is made up of Chattian–Burdigalian deposits, Langhian olistostrome deposits, and Serravallian–Tortonian and lower Messinian clastic deposits. An angular unconformity or a disconformity between the lower Messinian evaporites and the overlying Messinian coarse-grained siliciclastic rocks clearly indicates Intra-Messinian tectonic activity.

The tilting of the Serravallian–Tortonian succession and the lateral aggradation of the Messinian wedge allow for the recognition of the low-angle normal fault at the base of the sedimentary succession. The termination of reflectors provides a fairly precise marker for the location of the boundary fault, which corresponds to a strong reflector. The 3D geometry of the low-angle normal fault reveals the following features: (1) a staircase trajectory in cross-section formed by different segments that dip eastwards at 5–20° (with the exception of the northern boundary of listric shape); (2) high displacement (heave up to 14 km), changing considerably along strike.

Serravallian conglomerates are the response to the first step of block faulting and could be due to the erosion of uplifted crestal blocks. The successive increase of the clay/sand ratio suggests a rapid deepening of the basin and fault-controlled subsidence (Milia & Torrente 2014). A second, tectonic event is recorded by thick conglomerates at the base of the Tor1 sequence followed by clays that indicate a rapid deepening of the basin; this tectonic subsidence continues during the deposition of the Tor2 sequence. The upper part of the succession terminates with thick clays (Ponda Formation; Ogniben 1955) that abruptly cover all the Calabria basins, thus suggesting the contemporaneous subsidence of a wide region. A submarine synsedimentary wedge was deposited at the beginning of the Messinian fault activity followed by no deposition or erosion with increasing fault displacement immediately before the deposition of the continental deposits (Mb), which rest directly on the fault. The basin infill architecture documents a continuous extension in the Stilo rift with an almost constant throw rate of 0.9 mm a⁻¹ for the rift basin and 0.65 mm a⁻¹ for the supradetachment basin. However, the horizontal displacement rate of these faults increased abruptly with time from 0.7 mm a⁻¹ during the Serravallian–Tortonian to 7 mm a⁻¹ during the Messinian. The tilting of the hanging wall (affected by an important erosional surface), the shallow-water facies and the architecture of the Messinian unit imply a fault block rotation and tectonic uplift during the basin formation.

**Similarities between the Stilo, Amantea and Elba rifts.** The detachments of the Stilo and Amantea rifts show a notable similarity because both basins display low-angle normal faults in direct contact with variably tilted rift basin fills. Field stratigraphic data for the Amantea basin (Mattei et al. 2002) reveal an older sequence corresponding to the Serravallian sandstone cropping out mainly in the eastern part of the basin. A Tortonian succession rests on the Serravallian deposits and, in the central part of the basin, on the metamorphic substrate. These strata dip 20–37° westwards. The Messinian succession overlies the substrate and crops out in the western part of the basin. The similar stratigraphic architecture, the common metamorphic substrate and the east–west-directed extension of the Amantea and Stilo basins suggest an analogous evolution of these supradetachment basins.

Low-angle normal faults, of Messinian age, have been described in Elba (Dini et al. 2002; Pandeli et al. 2010; Fig. 1). There, the intrusion of two plutons and uplift gave rise to two major low-angle normal faults: the central Elba detachment and the Zuccale detachment (active between 6.0 and 5.0 Ma).

The Stilo, Amantea and Elba low-angle normal faults developed in the Messinian Eastern Tyrrhenian rift at shallow structural levels and are in direct fault contact with variably tilted rift basin fill. A final observation is that magma intrusions occurred in Elba during the early stages of low-angle normal fault formation; however, these are not reported in Calabria.

**Kinematic development of the late Miocene Tyrrhenian rift.** We propose a kinematic model for late Miocene Tyrrhenian rift development that is based on the premise that rift segments with varying magnitudes of extension provide snapshots of a regional continuous extensional process. The rift initiated as a half-graben basin system (e.g. Leeuer & Gawthorpe 1987), bounded by a master high-angle normal fault (Fig. 4a). The basin was affected by continuous subsidence and was filled by clastic sediments that recorded the Serravallian–Tortonian tectonic events. With increasing extension the initiation of a low-angle normal fault resulted in a new sedimentary basin, which was filled by an early Messinian synrift marine clastic succession (Fig. 4b). The abandonment of the high-angle normal fault led to the oldest rift basin being cannibalized into the footwall, where it remained fossilized in...
its original position and architecture (Fig. 4b). The rift development then showed a dramatic change in style marked by a strong increase in the extension rate and the formation of the supradetachment basin (Fig. 4c). Tectonic unloading resulted in isostatic rebound. In particular, the low-angle normal fault became gentler and a back-rotation of the hanging wall occurred. The deposition of the continental deposits directly on the substrate and the widely distributed erosional surface are the signature of a rapid uplift. The progressive migration of normal faults and upwarping of the low-angle normal fault result in a detachment that was active in the uppermost crust.

Conclusions

The study of Stilo rift evolution reveals how extensional faults and associated basins develop, and provides fresh insight into this topic in general. Extensional basins generally have a low potential for preservation in the geological record because they are continuously uplifted and eroded. The Stilo rift is a rare example where the sedimentary basin is completely preserved, permitting the analysis of the kinematic evolution from rift to supradetachment basin formation. The rift basin experienced a continuous subsidence as documented by the sedimentary infill, whereas the supradetachment system was affected by isostatic and flexural uplift. The proposed kinematic evolution, consistent with the rolling hinge model (e.g. Wernicke & Axen 1988; Kapp et al. 2008), shows that the low dip of the low-angle normal fault results from upwarping of the incipient moderate normal fault in response to progressive deformation. The Stilo rift represents the development of two end-member basins during a continued extension with an abrupt change in style linked to a marked increase in extension rate. During the Messinian two distinctive geological events affected the Tyrrhenian region: the Messinian salinity crisis and the rapid rollback of the subduction plate. Govers et al. (2009) speculated that the removal of the water load in the Mediterranean during Messinian time resulted in isostatic–flexural rebound of the crust. On the other hand, the rates and amount of extension must also play a determining role in basin configuration and crustal response (Kusznir & Park 1987; Braun & Beaumont 1989). These parameters are governed in part by plate-tectonic forces, such as slab pull or subduction rollback (Royer 1993). The abandonment of the high-angle normal fault and the beginning of the low-angle normal fault activity in the study area occurred in the early Messinian, followed by an intra-Messinian rapid increase in extension. The unique evolution of the eastern Tyrrhenian rift and the triggering mechanism of the Messinian low-angle normal faults can be attributed to the increase of extension linked to rapid rollback of the subducting plate and/or to isostatic crustal uplift.

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