Upper Messinian conglomerates in Calabria, southern Italy: Response to orogenic wedge adjustment following Mediterranean sea-level changes

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ABSTRACT

Widespread uppermost Miocene conglomerate and sandstone along the Apenninic-Maghrebian orogenic belt in the central Mediterranean region cannot be explained as a result of the Messinian base-level falls. Along the Ionian coast of Calabria, southern Italy, these rocks were deposited in marine fan deltas and rest in angular unconformity or disconformity upon the internal part of the Calabrian accretionary wedge. We propose that the upper Messinian deposits were produced by internal shortening of the Calabrian accretionary wedge as it compensated for the decrease in upper surface slope caused by flexural rebound as the ~3.4-km-thick Ionian water mass evaporated. Latest Miocene-Pliocene marine inundation reloaded the basin, restored the wedge to a critical state, and caused the rear part of the wedge again to become tectonically stable. This isostatically driven mechanism could explain widespread latest Messinian thrust faults and coarse siliciclastic deposits along much of the Apenninic-Maghrebian orogen.

INTRODUCTION

During Messinian (latest Miocene) time, convergence between the African and Eurasian plates, coupled with glacioeustatic sea-level falls, isolated the Mediterranean basin from the world ocean (Müller and Hsü, 1987); the basin episodically desiccated, and widespread shallow-water evaporites precipitated on the floor of what had been a deep (locally >4.0 km) marine basin (Hsü et al., 1973). Somewhat overshadowed by the spectacular sea-level events is the fact that the late Messinian was also a period of widespread tectonic activity all along the front of the Apenninic-Maghrebian orogenic belt in Italy and northern Africa, as indicated by shallow thrust faults that cut lower Messinian rocks and are unconformably covered by uppermost Messinian–lower Pliocene rocks (Marabini and Vai, 1985; Kastens et al., 1988). Intra-Messinian unconformities and laterally equivalent disconformities are known from the subsurface of the Po Plain in northern Italy (Dondi, 1985) to the Caltanissetta Basin in Sicily (Decima and Wezel, 1973; Butler et al., 1995). In the Tyrrhenian Sea, intra-Messinian marginal unconformities and basinal disconformities have been seismically imaged (Fabbri and Curzi, 1979) and drilled during Ocean Drilling Project Leg 107 (Kastens et al., 1988).

Upper Messinian (postevaporite) units throughout much of the central Mediterranean basin consist of widely variable, locally coarse-grained, nonmarine and shallow-marine siliciclastic rocks (e.g., Carloni et al., 1971; Decima and Wezel, 1973; De Feyter and Molenaar, 1984; Cita and McKenzie, 1986; Butler et al., 1995). Resedimented evaporites are also common. The upper Messinian rocks are invariably overlain by basal Pliocene coccolith-foraminiferal mudrocks (Trubi Formation and equivalents), which signal the end of the Messinian desiccation and the return to normal, open-marine sedimentation (Decima and Wezel, 1973; Cita and McKenzie, 1986). Clearly, the upper Messinian rocks represent an important transition between the evaporites and fully marine sedimentation, but the cause of the influx of coarse sediment remains obscure. The fact that the coarse siliciclastic rocks rest in angular unconformity on top of basin-margin evaporites suggests that they are not solely the result of overincision along the basin margin owing to the Messinian base-level falls. Neither are they plainly related to the active tectonic regime that prevails in the central Mediterranean, for no major reorganization or acceleration of lithospheric plates occurred during late Messinian time (Dewey et al., 1989; Mazzoli and Helman, 1994). In this paper, we hypothesize that deposition of the coarse-grained upper Messinian rocks in southeastern Calabria (southern Italy) was related to the isostatic effects of Mediterranean desiccation and the consequent tectonic response in the Calabrian orogenic wedge. A similar mechanism must have operated throughout the deeper parts of the Mediterranean and may explain the widespread intra-Messinian tectonic event in the Apenninic-Maghrebian orogenic belt.

GEOLOGIC SETTING

The Calabrian microplate is a small block of continental crust that, together with the Corsica-Sardinia microplate, has rifted away from the southern margin of the Eurasian plate over the past 25 m.y., probably in response to southeastward retreat of a segment of the subduction zone between the African and Eurasian plates (Fig. 1; Alvarez et al., 1978; Malinverno and Ryan, 1986; Dercourt et al., 1993). In late Serravallian time, Calabria detached from Corsica-Sardinia, and the Tyrrhenian Sea began to form, first as a shallow sea underlain by extended continental crust (Serravallian–early Messinian), then as a deep oceanic basin (late Messinian–Pliocene). Since at least early Miocene time, the southeastern part of Calabria has occupied a fore-arc position between the northwest-dipping Ionian subduction zone and the volcanic arc, located during late Oligocene–early Miocene time along the eastern side of Sardinia and during late Pliocene–Quaternary time in the Aeolian Islands. From the early Miocene to the present, a broad accretionary wedge has developed on the Ionian side of Calabria (Fig. 1; Van Dijk, 1994), and a thick succession of Aquitanian-Tortonian fore-arc strata was deposited (Cavazza and DeCelles, 1993; Patterson et al., 1995). In southeastern Calabria, extensive Messinian rocks overlie these older rocks at present-day elevations of <250 m, on top of the *internal* part of the Calabrian orogenic wedge (Fig. 1). Lower Messinian evaporites and pelites are conformable with the older units, whereas the coarse-grained, upper Messinian siliciclastic deposits are essentially undeformed and are separated from the underlying sequence by an angular unconformity or a laterally equivalent disconformity.

STRATIGRAPHY AND SEDIMENTOLOGY

Lower Messinian evaporites (limestone and gypsum) are present along the Ionian coast but are absent in the study area, where the upper Messinian rocks rest unconformably on top of various older units (Fig. 2). Throughout southeastern Calabria, upper Messinian strata are overlain by nearly flat lying beds of the

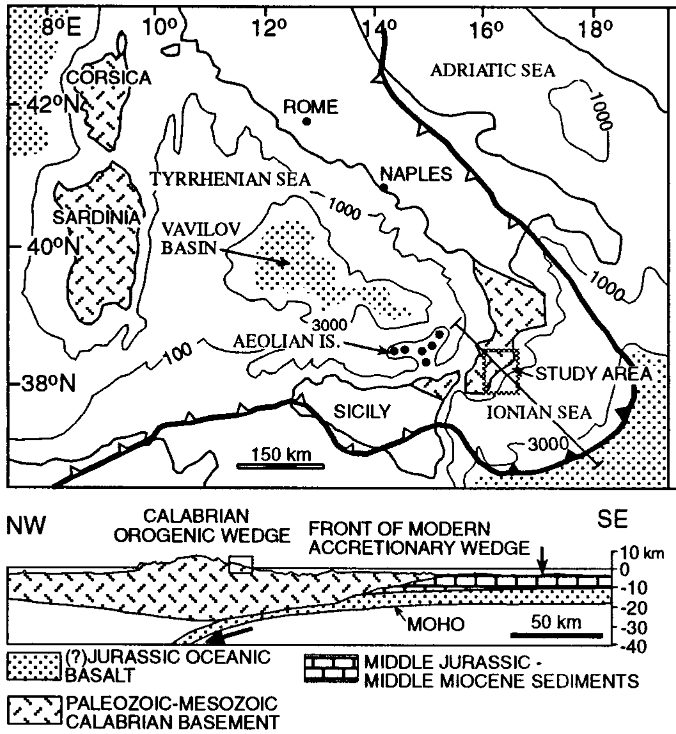

Figure 1. Geodynamic sketch of central Mediterranean region and generalized crustal cross section through Calabrian orogenic wedge and Ionian subduction zone (after Van Dijk, 1994). Toe of accretionary wedge is restored to its probable Messinian position; large arrow indicates modern toe of wedge, and box shows location of study area.

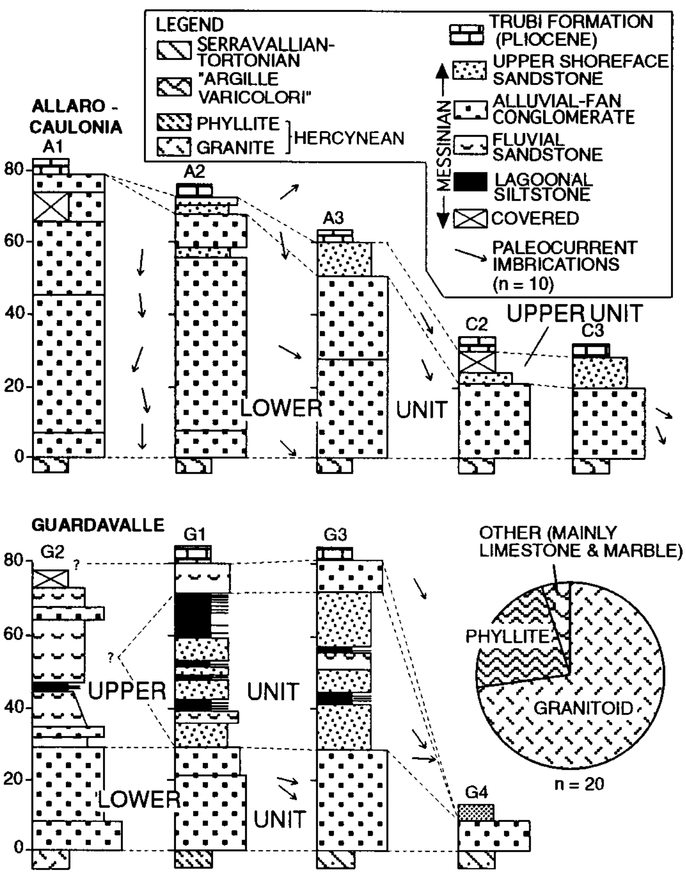

Figure 2. Stratigraphic columns of upper Messinian rock units in study area. Pie diagram depicts average composition of Messinian conglomerates (average of 20 clast counts of 100 clasts each, distributed throughout sections).

lower Pliocene Trubi Formation. Although the upper Messinian rocks discussed herein are unfossiliferous and have not been directly dated, underlying and overlying units have been dated by integrating planktic foraminiferal biostratigraphy and Sr isotopic stratigraphy (Patterson et al., 1995). The pre-evaporitic units yielded late Tortonian foraminiferal faunas and Sr ages ranging from 8.55 to 7.34 Ma; the lowest part of the Trubi yielded basal Zanclean foraminiferal faunas and Sr ages ranging between 4.87 and 4.43 Ma.

Upper Messinian rocks in southeastern Calabria are up to ~80 m thick and can be subdivided into a lower conglomeratic unit and an upper arenaceous unit (Fig. 2). The lower unit is 8–65 m thick and becomes thinner and finer eastward. It consists of amalgamated, lenticular beds of poorly sorted, clast-supported, cobble- to boulder-conglomerate, dominated by horizontally stratified, imbricated, and massive lithofacies. Imbricated clasts indicate south-southeastward paleoflow (Fig. 2). We interpret the lower unit as the deposits of stream-dominated alluvial fans (e.g., Ridgway and DeCelles, 1993). The upper unit is 0–28 m thick and consists mostly of sandstone, with subordinate mudrock and conglomerate. The upper unit has been interpreted as progradational, storm-dominated, shallow-marine to fluvial parasequences that accumulated in systems similar to the present southeastern Calabrian coastal zone (DeCelles and Cavazza, 1992). The intimate association of alluvial-fan, braided-stream, and shallow-shoreface deposits indicates deposition by marine fan deltas that prograded from a rugged mountainous source terrane directly into the late Messinian Ionian Sea. The overall sequence is transgressive, with entirely nonmarine facies giving way upsection to shallow-marine facies, followed by the open-marine Pliocene Trubi Formation.

The upper Messinian conglomerates in southeastern Calabria are composed of granite and phyllite clasts, with minor amounts (generally <5%) of Mesozoic and lower Tertiary limestone clasts (Fig. 2). Coupled with the paleocurrent data, this clast composition indicates that the upper Messinian deposits were derived exclusively from the Calabrian basement massif to the west-northwest, which is composed mostly of granitic rocks that intruded low- to middle-grade metamorphic rocks and a thin cover of Mesozoic and lower Tertiary carbonate rocks (Cavazza, 1989).

TECTONIC MODEL

Erosional incision during the Messinian sea-level fall, alone, does not explain the coarse-grained upper Messinian rocks in southeastern Calabria, because they are near sea level now and they contain transgressive marine deposits. In addition, we find no evidence that the upper Messinian filled paleovalleys. Even if the upper Messinian section was uplifted several hundred metres during the Quaternary, it would not have originated far below present sea level. Lowstand deposits should be preserved much farther downslope, beneath the Ionian Sea (currently ~3.4 km deep offshore Calabria).

Evidence that the upper Messinian rocks of southeastern Calabria are instead primarily the result of a regional tectonic event includes the basal angular unconformity and their textural and compositional immaturity. In the study area, the unconformity is on top of Hercynian granitic and phyllitic rocks, upper Chattian-Burdigalian turbidites, Langhian olistostromal deposits, and Serravallian-Tortonian turbidites (Patterson et al., 1995). Older Tertiary rocks generally dip 30°–50° eastward and must have been rotated after Tortonian time but prior to deposition of the Messinian fan deltas. Outside of the study area, where the lower Messinian evaporites are present, a sharp angular unconformity or a disconformity is present between the evaporites and the overlying coarse-grained siliciclastic rocks. Simple stratigraphic considerations indicate that the intra-Messinian tectonic event occurred in the middle-late Messinian (Sartori, 1990), probably over a time span of $<10^5$ yr (G. B. Vai, 1994, personal commun.). This brief duration and the fact that the central Mediterranean is a mosaic of repeatedly reactivated crustal fragments caught between the European and African plates argue against horizontal plate-motion changes (which characteristically induce diachronous tectonic effects) as the cause of the intra-Messinian tectonic event.

Following Norman and Chase (1986), we propose that late Messinian uplift and erosion in eastern Calabria resulted from flexural rebound of the Calabrian-Ionian lithosphere following the desiccation of the Mediterranean. The flexural rebound caused by removal of the water mass can be modeled by subtracting the flexural subsidence due to the weight of the water from a hypothetical paleobathymetric profile offshore eastern Calabria during late Messinian time (Fig. 3). The paleobathymetry is limited in three respects: (1)

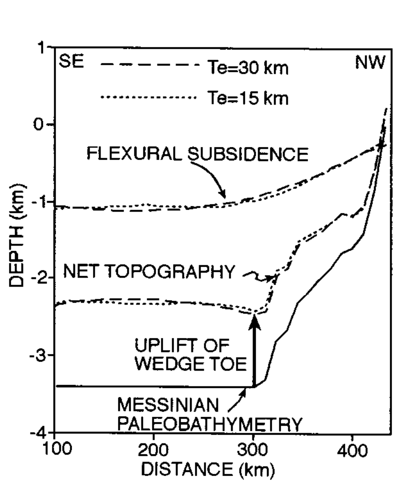

Figure 3. Probable Messinian paleobathymetry (lower, solid curve), flexural subsidence due to load of water represented by paleobathymetric curve, and net topography resulting from flexural rebound due to removal of water load (density of 1035 kg/m^3). Two sets of flexural subsidence and net topography curves are shown for lithospheric effective elastic thicknesses (Te) of 15 and 30 km (Watts and Ryan, 1976; Royden and Karner, 1984; Royden et al., 1987), corresponding to flexural rigidities of 2.1 × 10^{22} N · m and 1.7 × 10^{23} N · m, respectively. Young's modulus was assumed to be 70 GPa, and Poisson's ratio, 0.25.

had the Mediterranean not evaporated, the toe of the Messinian Calabrian accretionary wedge probably would have been at about the same depth as it is today (3.4 km; Fig. 1); (2) the top of the profile was slightly above sea level, as indicated by the Messinian fan-delta deposits; and (3) Messinian evaporites underlie the frontal 50 km of the wedge today (Van Dijk, 1994), which suggests that the submarine length of the Messinian wedge was ~122 km. These paleobathymetric constraints imply that the Messinian wedge had an average surface slope of ~1.6°. If the wedge was critically tapered, then its basal decollement must have sloped 8°–9° for reasonable internal and basal coefficients of friction and pore-fluid pressure ratios (Davis et al., 1983), which is consistent with the present configuration of the wedge (Van Dijk, 1994). Two-dimensional flexural profiles due to the water load were calculated using the flexural equation of Hetenyi (1946), as discussed by Turcotte and Schubert (1982); the load profile was approximated by seven rectangular block with a density of 1035 kg/m^3. The difference between the paleobathymetric profile and the calculated flexural profile due to the water load is the topographic profile resulting from removal of the water load.

It is important to note that, although the Tyrrhenian Sea was also desiccated during the Messinian (Kastens et al., 1988), it was then only about half its present size, was ~100–200 m deep, and was floored mainly by rifting continental crust (Patacca et al., 1990). Desiccation of the Tyrrhenian water load would have caused only a few tens of metres of flexural rebound. Flexural rebound across the Calabrian accretionary wedge, therefore, must have been highly asymmetrical. The flexural modeling suggests that the basin floor at the toe of the accretionary wedge and coastline would have been uplifted ~1.0 km and ~0.2 km, respectively (Fig. 3). Rebound decreased in an onshore direction because the load thickness decreased onshore. These results are similar to those obtained by Norman and Chase (1986) for rebound of the margins of the Mediterranean basin in transects across northern Algeria and southern France.

For an orogenic wedge with a triangular cross section 122 km in length (Fig. 1), the effect of the flexural rebound would have been a reduction in surface slope by ~0.4°. Assuming that the orogenic wedge had a critical taper prior to the Messinian desiccation and that the overall tectonic strain field did not change, such a decrease in topographic slope would have caused the wedge to become subcritically tapered (Davis et al., 1983; Dahlen, 1984). The other major effects of subaerially exposing the accretionary wedge would have been elimination of the buoyant force tending to support the wedge and a decrease in pore-fluid pressure within the wedge. These changes have offsetting effects on the value of critical taper—the former tending to reduce it and the latter tending to increase it (Davis et al., 1983)—and would not have offset the 0.4° reduction of surface slope due to flexural rebound. Subcritically tapered wedges must shorten internally (by out-of-sequence or synchronous thrusting, duplexing, and/or penetrative strain) in order to rebuild taper to a critical value (e.g., Stockmal, 1983); in this case, the rear of the wedge would have to have thickened by ~1 km to restore critical taper. We suggest that the intra-Messinian unconformity and overlying conglomeratic strata in southern Calabria are the record of the combined effects of shortening and thickening in the internal part of the wedge and flexural uplift along the Ionian coast.

The Ionian basin is the deepest body of water (locally >4 km) along the Apenninic-Maghrebian orogen, because oceanic crust is still being subducted (Fig. 1). The same situation existed just before the Messinian salinity crisis (e.g., Dercourt et al., 1993). Isostatic unloading and orogenic-wedge instability following the Messinian desiccation(s) therefore would have had a maximum effect in the circum-Ionian region. This inference may explain the presence of the most widespread and coarsest upper Messinian deposits in this area (Patacca et al., 1990).

We interpret the abrupt transition from the coarse-grained uppermost Messinian deposits to the overlying Trubi mudrocks as the result of flexural restoration of critical taper during refilling of the Mediterranean basin. Once critical taper was restored, the rear of the Calabrian wedge regained stability, and the locus of deformation was again concentrated at the toe of the submarine accretionary wedge.

CONCLUSIONS

Upper Messinian (postevaporite) marine fan-delta deposits in Calabria are primarily the result of a tectonic event in the internal part of the Calabrian orogenic wedge. This event can be explained as an adjustment of the taper of the orogenic wedge in response to flexural rebound of the toe of the wedge following the Messinian desiccation event(s). The toe of the wedge was uplifted ~1.0 km by flexural rebound, causing a decrease of ~0.4° in surface slope of the wedge. This decrease in slope was sufficient to cause the wedge to become subcritically tapered, whereupon deformation shifted to the internal part of the wedge to restore taper to a critical value. This mechanism could explain widespread late Messinian thrusting and syntectonic sedimentation in the central Mediterranean region.

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