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The implications of revised Quaternary palaeoshoreline chronologies for the rates of active extension and uplift in the upper plate of subduction zones

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ABSTRACT

We demonstrate a synchronous correlation technique to determine the chronology of Quaternary palaeoshorelines to test proposed relationships between tectonics, climate and sea-level change. The elevations of marine palaeoshorelines in Calabria around the active Vibo normal fault have been measured from TIN DEM 10 m data and fieldwork and correlated with global sea-level curves. A synchronous correlation method and new U/Th dates are used to ascertain how the slip-rate on the fault relates to uplift rates across the region. Regional uplift, possibly associated with subduction along the Calabrian trench or due to the cumulative effect of closely-spaced active normal faults, is rapid enough to uplift even the hangingwall of the Vibo normal fault; the actual value for the rate of background uplift can only be ascertained once the rate of slip on the Vibo fault is subtracted. Synchronous correlation of multiple palaeoshorelines sampled along 29 elevation profiles with global sea-levels shows that the resultant uplift rate (background uplift minus local hangingwall subsidence) is constant through time from 0 to 340 ka, and not fluctuating by a factor of 4 as previously suggested. The uplift rate increases from 0.4 mm/yr at the centre of the hangingwall of the fault to 1.75 mm/yr in the hangingwall in the vicinity of the fault tip. Palaeoshorelines can be traced from the hangingwall to the footwall around the fault tip and hence correlated across the fault. The throw-rate on the fault averaged over 340 ka decreases from a maximum at the centre of the fault (1 mm/yr) to zero at the tip. This gradient in throw-rate explains the spatial variation in resultant uplift rates along the fault. We interpret the 1.75 mm/yr resultant uplift rate at and beyond the fault tip as the signature of a regional uplift, presumably related to subduction, although we cannot exclude the possibility that other local faults influence this uplift; the lower uplift rates in the hangingwall of the fault are due to interaction between "regional" uplift and subsidence associated with the local active normal faulting. We discuss (a) how our synchronous correlation technique should trigger a re-appraisal of palaeoshoreline chronologies worldwide, and (b) the implications for the tectonics and seismic hazard of Calabria, suggesting that perturbations in the uplift-rate field are a key criterion to map the locations of active faults, their deformation rates, and hence seismic hazard above subduction zones.

1. Introduction

Uplift rates derived from raised Quaternary palaeoshorelines are commonly the only way to derive deformation rates from plate boundary zones over timescales that are long enough to average out deformation over multiple seismic cycles (10^4–10^5 years). Such long timescales are needed to avoid transient strain-rates associated with individual earthquakes, or temporal clusters of earthquakes, so that the results can be used for long-term seismic hazard analysis. Unfortunately, it is common for age control to exist for only a few palaeoshorelines within a flight of marine terraces that contain a record of many sea-level changes. Thus, it is common for studies to extrapolate ages from dated terrace deposits to the next higher or lower palaeoshorelines by assuming they date from the next older or younger sea-level highstand (e.g. Armijo et al., 1996 for a review). This sequential correlation technique is prone to fail at low uplift rates when palaeoshorelines from sea-level highstands that were lower than

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present-day sea-level are overprinted and/or destroyed by younger, higher sea-levels. This paper presents a new synchronous method for correlation that overcomes this problem, which we suggest should trigger a review of such records from other geographic areas. The new method exploits the fact that sea-level highstands in the Quaternary are not evenly-spaced in time, so flights of palaeoshorelines resulting from constant uplift rates will not be evenly-spaced in elevation. With knowledge of the uneven sea-level highstand timing one can recover the ages of the resulting palaeoshorelines through a method that resembles a fingerprinting technique. Here we present this method with respect to a set of well-exposed, but partially-dated Quaternary marine palaeoshorelines in Calabria. These palaeoshorelines are the only way to unravel the link between subduction and active normal faulting that both pose severe threats to human life through earthquake hazards in this part of Italy. Our new method allows us to differentiate between hypotheses involving fluctuating uplift-rate or constant uplift-rates in a way that has not been achieved to date. This case study and new method should prompt re-evaluation of uplift rates from other examples worldwide.

Calabria is undergoing uplift above a subduction zone evidenced by the existence of raised Quaternary and Holocene palaeoshorelines (Malinverno and Ryan, 1986; Dumas et al., 1987; Patacca et al., 1990; Westaway, 1992; Miyauchi et al., 1994; Balescu et al., 1997; Bianca et al., 1999; Bonardi et al., 2001; Doglioni et al., 2001; Tortorici et al., 2003; Faccenna et al., 2004; Cucci and Tertulliani, 2006; Bianca et al., 2011) (Fig. 1). Calabria also suffers from severe seismic hazard due to the presence of active normal faults in the upper crust associated with devastating earthquakes that have caused severe loss of life (e.g. the 5 events in one month in 1783 A.D. which killed in excess of 30,000 people; the 1905 Me 6.7 event near Vibo Marina which killed >500 people, and the 1908 Messina Straits earthquake ~M 7, which killed in excess of 80,000 people; Tortorici et al., 1994; Monaco et al., 1997; Bianca et al., 1999; Monaco and Tortorici, 2000; Jacques et al., 2001; Galli and Bosi, 2002; Ferranti et al., 2007). The slip-rates on these faults of a few mm/yr are known to some extent (e.g. Monaco and Tortorici, 2000; Jacques et al., 2001; Galli and Bosi, 2002; Catalano et al., 2008 and references therein), but precision is hampered by the lack of well-exposed fault scarps on fault-controlled hillsides that are thickly-vegetated and composed of crystalline rocks that appear not to support scarp preservation, with only rare opportunities for palaeoseismic trenching. Although Galli and Bosi (2002, 2003) derived palaeoseismic evidence of Holocene slip-rates in the region, it is unclear if such slip-rates are stable through the Quaternary or fluctuating. In this paper we use the presence of extensive marine terraces and palaeoshorelines related to Quaternary sea-level changes to derive fault slip-rates (Figs. 2 and 3). Some have argued that uplift-rates derived from studies of marine terraces in the vicinity of these active normal faults have fluctuated dramatically through time. For example, Tortorici et al. (2003) suggest rates fluctuate between 0.9 and 4.0 mm/yr for locations within 240 ka,

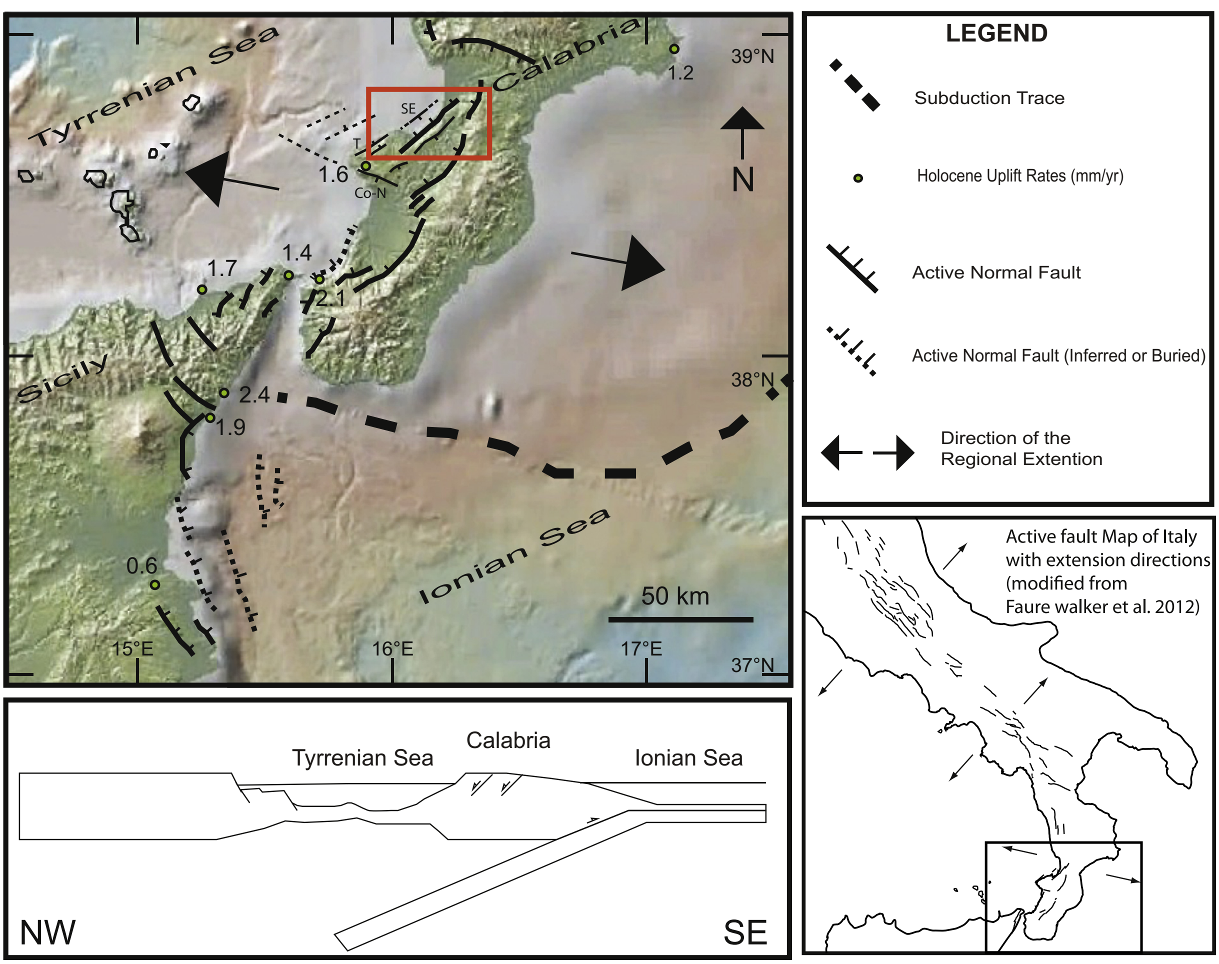

Fig. 1. Location map showing the tectonic setting of Calabria and the Vibo active normal fault. Holocene uplift-rate values from coastal notches are shown (Antonioli et al., 2006). SE – S. Eufemia Fault; T – Tropea Fault; Co–N – Coccorino and Nicotera Faults.