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Late Quaternary uplift rate inferred from marine terraces, Muroto Peninsula, southwest Japan: Forearc deformation in an oblique subduction zone

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ABSTRACT

Tectonic uplift rates across the Muroto Peninsula, in the southwest Japan forearc (the overriding plate in the southwest Japan oblique subduction zone), were estimated by mapping the elevations of the inner edges of marine terrace surfaces. The uplift rates inferred from marine terraces M1 and M2, which were correlated by tephrochronology with marine isotope stages (MIS) 5e and 5c, respectively, include some vertical offset by local faults but generally decrease northwestward from 1.2–1.6 m ky^{-1} on Cape Muroto to 0.3–0.7 m ky^{-1} in the Kochi Plain. The vertical deformation of the Muroto Peninsula since MIS 5e and 5c was interpreted as a combination of regional uplift and folding related to the arc-normal offshore Muroto–Misaki fault. A regional uplift rate of 0.46 m ky^{-1} was estimated from terraces on the Muroto Peninsula, and the residual deformation of these terraces was attributed to fault-related folding. A mass-balance calculation yielded a shortening rate of 0.71–0.77 m ky^{-1} for the Muroto Peninsula, with the Muroto–Misaki fault accounting for 0.60–0.71 m ky^{-1}, but these rates may be overestimated by as much as 10% given variations of several meters in the elevation difference between the buried shoreline angles and terrace inner edges in the study area. A thrust fault model with flat (5–10° dip) and ramp (60° dip) components is proposed to explain the shortening rate and uplift rate of the Muroto–Misaki fault since MIS 5e. Bedrock deformation also indicates that the northern extension of this fault corresponds to the older Muroto Flexure.

1. Introduction

Forearc deformation in oblique subduction zones is not simple because its strain distribution reflects both arc-parallel and arc-normal components of the plate motion. In theory, the forearc forms a sliver (microplate) bounded by a strike–slip fault that accommodates the arc-parallel component of the plate motion (Fitch, 1972). However, if the slip rate on the strike–slip fault is less than its share of the plate motion rate, the forearc sliver may undergo internal deformation to compensate for the slip deficit. In such a case, the forearc sliver does not behave as a rigid microplate and may undergo arc-parallel deformation (McCaffrey, 1992), resulting in arc-parallel strike–slip faults or arc-normal dip–slip faults accompanied by folds. For example, the 2004 Sumatra–Andaman earthquake (M_w 9.3) was generated by pure dip–slip thrust faulting (Lay et al., 2005; Okal, 2007), and the arc-parallel component of the overall oblique plate motion remained to be compensated by slip on a strike–slip fault within the Sumatra–Andaman arc or by arc-parallel forearc deformation. Therefore, in forearc deformation studies and for seismic hazard evaluation in oblique subduction zones, it is important to understand the interplay between interplate megathrust faults and upper-plate faults.

Since the disastrous Tonankai earthquake of 1944 and Nankai earthquake of 1946 (M_w 8.1 and 8.4, respectively), coseismic and short-term deformations in the southwest Japan oblique subduction zone have been the subject of intensive research in connection with expected future large earthquakes (e.g., Central Disaster Prevention Council, 2013; Headquarter of Earthquake Research Project, 2013) (Fig. 1a, b). In the subduction zone, the forearc coastline is characterized by several capes with arc-normal axes, including Capes Ashizuri, Muroto, and Shiono (Fig. 1). In particular, Cape Muroto extends far into the Pacific and is situated on an anticline related to offshore faults (Fig. 2a; Okamura, 1990).

Permanent coastal uplift often results from local thrust faulting and folding within the upper plate (McCalpin and Carver, 2009). For example, local thrust faulting within the upper plate associated with the 1964 Alaska megathrust earthquake caused large amounts of uplift, but the recurrence interval of such local events is probably longer than the interval between megathrust events (Plafker, 1972, 1987). Therefore, long-term deformation of the forearc related to upper-plate structures is also fundamental to understanding the accumulation and distribution of strain in subduction zones.

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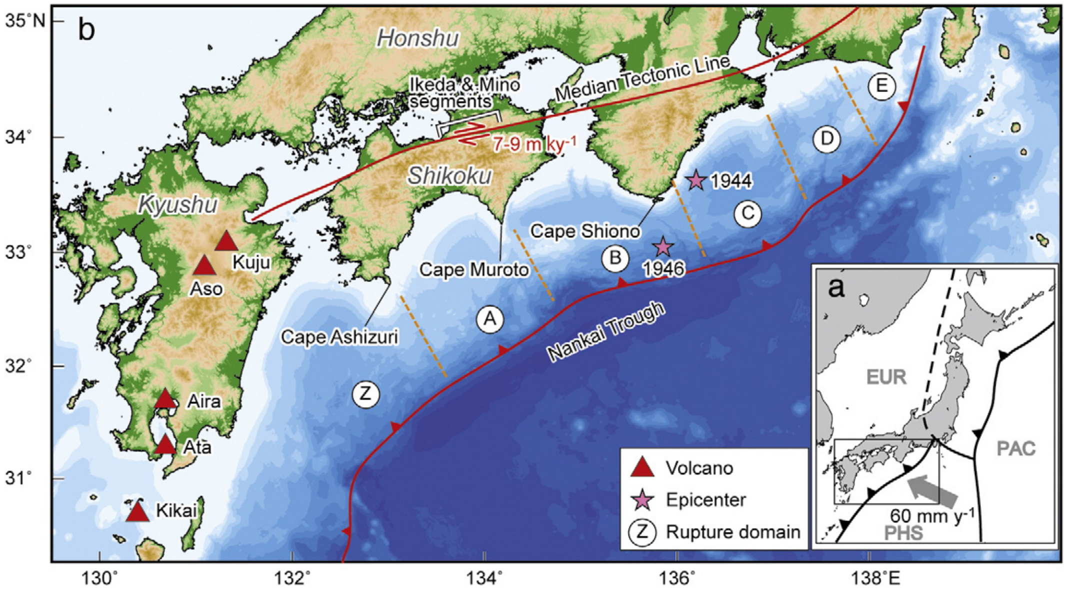

Fig. 1. Location maps showing the southwest Japan forearc. (a) Inset showing the tectonic setting of the southwest Japan arc and the outline of map (b). The Pacific plate (PAC) and Philippine Sea plate (PHS) are subducting under the Eurasia plate (EUR). Lines show plate boundaries (dashed is inferred). Arrows on the lines show plate convergence. (b) Southwest Japan subduction zone. Areas Z, A, B, C, D, and E are rupture segments of interplate earthquakes (Ando, 1975; Yonekura, 1975). Epicenters of the 1944 Tonankai and 1946 Nankai earthquakes are from Headquarter of Earthquake Research Project (2013). Strike–slip rate on the Median Tectonic Line is from Research Group for Active Faults of Japan (1991).

To evaluate offshore fault activity, it is essential to compare short-term deformations with long-term (geologic) deformation data (e.g., Plafker, 1972; Matsu'ura et al., 2009). Long-term deformation data across the southwest Japan forearc have been inferred from late Quaternary marine terraces (Yoshikawa et al., 1964) (Fig. 1a). The deformation of a terrace in a fault-related fold provides critical information for determining the amount of displacement due to the fault. Excess-area analyses, which balance cross-sectional areas of crustal deformation (shortening amount × depth) and use fluvial terrace deformation as a proxy for growth strata, have been useful for determining the slip magnitude on blind thrust faults (e.g., Lave and Avouac, 2000; Bernard et al., 2007; Matsu'ura and Kimura, 2010). The technique can be applied to assess slip on offshore faults by using dated marine terraces, although the age of a marine terrace is generally poorly constrained. Cryptotephras (concentrations of tephra-derived grains in sediments that are not visible as layers; Lowe, 2011), which are powerful age indicators and which have recently been detected in weathered sediments on the Muroto Peninsula (Matsu'ura et al., 2011), offer a promising means for dating late Quaternary marine terraces. In turn, the use of well-dated marine terraces to assess offshore fault activity has global applicability as a tool for helping to assess seismic and tsunami hazards in oblique subduction zones such as the Alaska–Aleutian, Nankai–Ryukyu, Philippine, Andaman–Java–Sumatra, and Hikurangi subduction zones.

This paper reports the late Quaternary deformation rate of the southwest Japan forearc across the Muroto Peninsula, in the southwest Japan subduction zone (Fig. 2a). First, tephrostratigraphy was used to estimate marine terrace ages, and then uplift rates were estimated from the elevation differentials between the inner edges of terrace surfaces and the corresponding eustatic paleo-sea levels. Next, more accurate uplift rates were estimated from the relative heights of the shoreline angle (the intersection between the gently sloping wave-cut platform and the steep sea cliff) and eustatic sea levels during marine isotope stages (MISs) 5e and 5c. Sediment cores obtained from the inner edges of two marine terraces were used to evaluate the thickness of their cover sediments and determine accurate elevations of the buried shoreline angles. Finally, the shortening rate for the Muroto Peninsula was calculated and then divided into two components, the rate for the offshore Muroto–Misaki thrust fault east of Cape Muroto, newly named in this paper, and a rate for other local faults. The geometry and location of the Muroto–Misaki fault were also estimated and its slip rate was calculated.

2. Setting

2.1. Geodynamics and geology

The southwest Japan arc is characterized by the convergence of the Philippine Sea and Eurasia plates at a rate of about 60 mm y^{-1} at the Nankai Trough (Fig. 1a; Seno et al., 1996). The subduction zone is divided into segments corresponding to historical ruptures since AD 684 (Ando, 1975; Yonekura, 1975), labeled Z, A, B, C, D, and E in Fig. 1a. The 1944 Tonankai and 1946 Nankai earthquakes were produced by ruptures on segments C + D and Z (eastern part) + A + B, respectively. Although the Philippine Sea plate is subducting obliquely under the Eurasia plate, the P-axis direction of large earthquakes is not oblique but is partitioned into an arc-normal (NNW–SSE trending) component within the subducting Philippine Sea plate (>20 km depth) and an arc-parallel (ESE–WNW trending) component within the upper crust of the overriding plate (<20 km depth) (Kimura, 2001).

The surface geology of the study area consists of the Shimanto Supergroup (Oligocene to Miocene), the Tonohama Group (Pliocene), terrace deposits (Pleistocene), and Holocene alluvium (Taira et al., 1980; Iwai et al., 2006; Matsu'ura et al., 2011). The Shimanto Supergroup is distributed throughout the Muroto Peninsula (Fig. 2b) and consists of consolidated mudstone. The Tonohama Group commonly underlies terrace deposits, and is composed mainly of sand and gravel with marine mollusk fossils and microfossils, plus terrestrial sediments that include lignite (Iwai et al., 2006). The terrace deposits that are distributed along the current coastline are composed of gravel, sand, and silt, but they do not contain any fossils. Most of them are interpreted as marine sediments because of their coastal distribution and the presence of well-sorted rounded gravel clasts. Some terrace deposits located at river mouths include poorly sorted gravel, probably deposited by fluvial processes (Yoshikawa et al., 1964). Paleosols in the terrace deposits include