Geomorphology 209 (2014) 1–17

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Late Quaternary uplift rate inferred from marine terraces, Shimokita Peninsula, northeastern Japan: A preliminary investigation of the buried shoreline angle

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ARTICLE INFO

Article history:
Received 14 April 2013
Received in revised form 5 November 2013
Accepted 13 November 2013
Available online 27 November 2013

Keywords:
Late Quaternary
Marine terrace
Buried shoreline angle
Shiriyazaki (Cape Shiriya)
Uplift rate
Northeastern Japan

ABSTRACT

After estimating tectonic uplift rates along the northern part of the northeast Japan forearc (the overriding plate in the northeast Japan subduction zone) by mapping the elevation of the inner edges of marine terrace surfaces, we refined this estimate through elevation measurements of the buried shoreline angle beneath well-dated marine terrace surfaces, from which we could derive more accurate paleo-sea levels. The uplift rate initially inferred from the inner edge of marine terrace T4, correlated with marine isotope stage MIS 5e by tephrochronology, increases eastward from 0.11–0.22 m ky^{-1} around the backarc volcanic front to 0.17–0.32 m ky^{-1} in the forearc on the peninsula of Shiriyazaki. We refined the uplift rates for T4, on the basis of the shoreline angle elevation, from the reconstructed profile of the paleo-sea cliff and wave-cut platform on a rocky coast and the reconstructed profile of the swash zone sediments and terrace deposits on a sandy coast. The refined uplift rates were 0.14–0.25 m ky^{-1} on the rocky coast and 0.14–0.23 m ky^{-1} on the sandy coast, slightly slower than the rates we inferred from the height of T4 and about one-half to three-fourths of previously reported rates. By extrapolation from the example of the sandy coast, the refined uplift rate around the volcanic front was 0.09–0.18 m ky^{-1}. The vertical deformation across the forearc of the Shimokita Peninsula since MIS 5e is possibly associated with regional isostatic uplift of 0.09–0.18 m ky^{-1} and anticlinal deformation by an offshore fault, interpreted from acoustic profiles, of 0.05–0.07 m ky^{-1}.

1. Introduction

Marine terraces are important indicators of paleo-sea level. In particular, marine terraces that formed during the penultimate eustatic sea-level highstand corresponding to marine isotopic stage (MIS) 5e (e.g., Bassinot et al., 1994; Siddall et al., 2006), before that of the present interglacial (MIS 1), are widely distributed (e.g., Pedoja et al., 2011). These provide a key horizon for assessing tectonic deformation along coasts at active margins, for example, in the Mediterranean (Ferranti et al., 2006), on the Western Pacific rim (Koike and Machida, 2001; Ota and Yamaguchi, 2004; Pedoja et al., 2006a, 2008) and on the Eastern Pacific rim (Pedoja et al., 2006b, c; Saillard et al., 2009).

Marine terraces that develop along erosional (rocky) coasts have several kinds of geomorphic components corresponding to different tidal levels; among these, shoreline angle corresponding to mean higher high water (MHHW) or mean high water springs (MHWS) has been widely used as a paleo-sea level indicator (Hull, 1987; Pinter et al., 2001; Keller and Pinter, 2002; ten Brink et al., 2006; Wang et al., 2013). Sea notches (surf and tidal notches corresponding to MHWS and mean sea level (MSL), respectively) are also a useful indicator (Ferranti et al., 2006; Wang et al., 2013), but because the notches are easily covered by rockslides, along many coasts they cannot be used to establish paleo-sea level. Marine terraces that develop along depositional (sandy) coasts, likewise, have several kinds of coastal deposits corresponding to different tidal levels (Reineck and Singh, 1980); among these, the transitions between beach and lagoon deposits and between backshore and foreshore deposits have been used (Ferranti et al., 2006). Elevation data derived from the surfaces of terrace deposits have a margin of error due to their thickness variation in outcrops (Shimoyama et al., 1999). The paleo-shoreline angle, inferred from the shore-normal topographic profile of these deposits and the slope (paleo-sea cliff) behind them, is an accurate indicator that is useful for measuring late Quaternary tectonic movements. On the other hand,

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0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.11.013

the terrace surface elevation is a relatively poor indicator of paleo-sea level because sediments (which may include marine sediments, colluvium, dune sand, loess, tephra, and soil) that cover the shoreline angle have variable thicknesses (Keller and Pinter, 2002; Coutard et al., 2006). Therefore, the thickness of sedimentary cover on the shoreline angle beneath the terrace surface must be evaluated by coring or by geophysical exploration techniques. We can then improve the accuracy of paleo-sea level indicators to calculate local rates of uplift due to offshore fault activity.

Since the disastrous Tohoku-Oki earthquake in 2011 (Mw 9.0), the coseismic and short-term deformations in the northeast (NE) Japan subduction zone have been the subject of intensive research (e.g., Fujii et al., 2011; Ozawa et al., 2011; Pollitz et al., 2011) (Fig. 1a). Moreover, long-term deformation of the NE Japan forearc is probably related to upper-plate structures, which are also fundamental to understanding the accumulation and distribution of strain across plate boundaries in this subduction zone. To evaluate offshore fault activity, it is essential to compare these short-term deformations with long-term (geologic) deformation data (e.g., Plafker, 1972; Matsu'ura et al., 2009). Long-term deformation data across the NE Japan forearc have been inferred from late Quaternary marine terraces (Kesennuma coast: Matsu'ura et al., 2009) and fluvial terraces (Isawa upland: Matsu'ura et al., 2008) (Fig. 1a). The data showed a slight increase toward the arc interior and was interpreted to be driven by regional isostatic uplift due to crustal thickening (Matsu'ura, 2003; Matsu'ura et al., 2009), not to moment release on the mega-thrust observed as the coseismic and postseismic vertical deformations of the Tohoku-Oki earthquake in 2011 (Ozawa et al., 2011). However the data are sparse in forearc highs such as the Kitakami Mountains, where fluvial terraces are not well developed. Because deformation data inferred from marine terraces are limited to the coast, they are not sufficient to reconstruct the deformation patterns relevant to local-scale folding or tilting due to offshore faulting.

However, along the northern coast of the Shimokita Peninsula, which is adjacent to the Tsugaru Strait, the marine terraces provide a dense set of deformation data aligned perpendicular to the forearc (Fig. 1b). Further, the Shimokita Peninsula includes both the forearc (non-volcanic arc) and backarc (volcanic arc) regions of the NE Japan arc, whereas the shore of Hokkaido across the strait does not include the forearc region. Therefore, the distribution of uplift on the coast of the Shimokita Peninsula provides useful information on long-term forearc deformation. In particular, the elevations of marine terraces on Shiriyazaki (Cape Shiriya) are critical information for determining the degree of deformation due to the offshore fault. The fault along the shelf edge is considered by Ikeda (2012) to be active since MIS 5e, but it is considered to be inactive since MIS 5e by the Nuclear and Industrial Safety Agency (2010). Without long-term deformation data, the activity of the fault is poorly constrained. Therefore, it is essential to investigate the elevation difference between the terrace surface and the buried shoreline angle at Shiriyazaki to re-evaluate the activity of the offshore fault.

We studied the late Quaternary deformation rate of the NE Japan forearc on the Shimokita Peninsula in the NE Japan subduction zone. We first investigated the ages of the marine terraces along the Tsugaru Strait by using tephrostratigraphy, and we estimated the uplift rate from the relative heights between the inner edges of terrace surfaces and eustatic sea levels. Next, we obtained sediment cores from the inner edge of a marine terrace dating from MIS 5e along the coast of Shiriyazaki (a rocky coast) and farther west at Inazaki (a sandy coast) (Fig. 1b) to determine accurate elevations of the buried shoreline angle. Then, we evaluated the elevation differences between the marine terrace surface and the buried shoreline angle. Next we estimated the uplift rate from the relative heights of the shoreline angle and eustatic sea level during MIS 5e. Finally, in light of our newly obtained uplift rate, we reconsidered the uplift rate distribution obtained for this part of NE

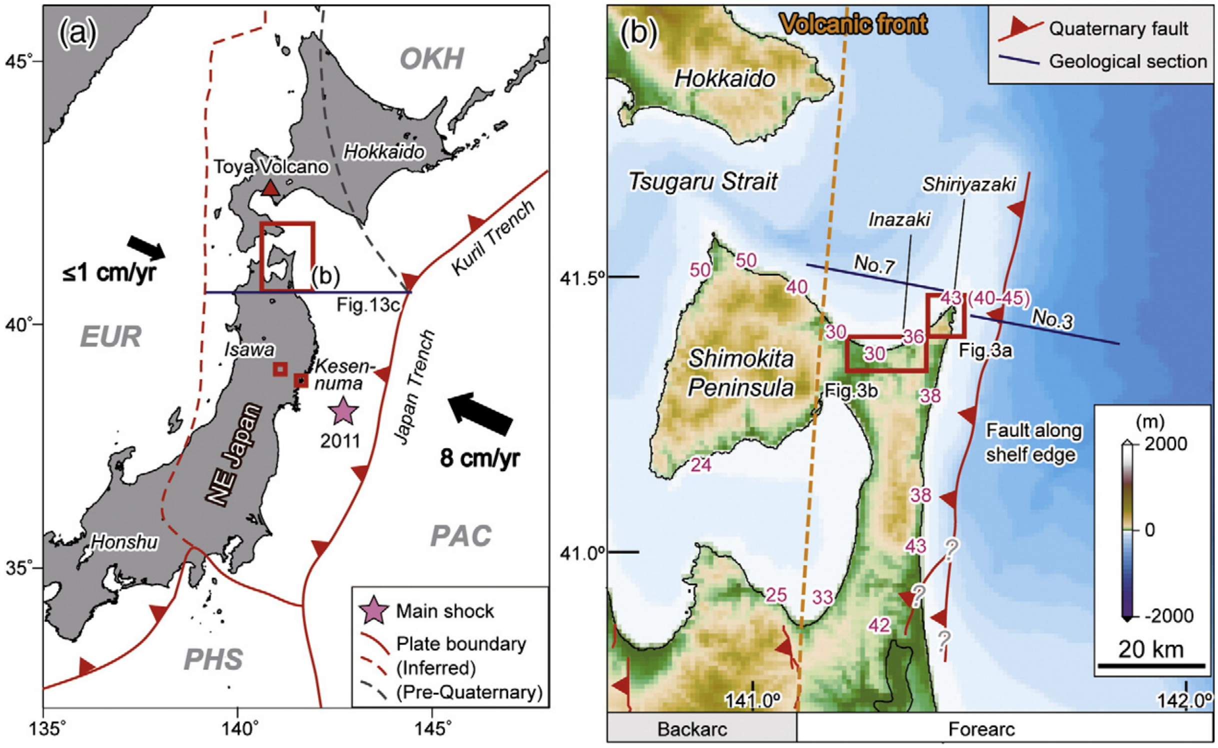

Fig. 1. Location maps showing the NE Japan forearc and the study area in the Shimokita Peninsula. (a) Tectonic setting of the NE Japan arc. The Pacific plate (PAC) and the Philippine Sea plate (PHS) are subducting under the Eurasia plate (EUR). The boundary between the Okhotsk (OKH) plate and EUR has been tectonically inactive during the Quaternary. The arrows show the convergence between the Pacific and Eurasia plates. The star shows the epicenter of the 2011 Tohoku-Oki earthquake (Mw 9.0). (b) Map of the Shimokita Peninsula and Shiriyazaki (Cape Shiriya). Forearc and backarc regions (labeled at bottom) are separated by the volcanic front (gold dashed line). The numbers along the coast indicate elevations (m) of the MIS 5e marine terrace surface as reported by Watanabe et al. (2008).
Numbers in parentheses on Shiriyazaki are from Koike and Machida (2001). The locations of geologic sections No. 3 and 7 are from Tohoku Electric Power (2008).