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High-resolution 3D seismic reflection imaging across active faults and its impact on seismic hazard estimation in the Tokyo metropolitan area

Tatsuya Ishiyama [a,*], Hiroshi Sato [a], Susumu Abe [b], Shinji Kawasaki [b], Naoko Kato [a]

[a] *Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan*
[b] *JGI Inc., 1-5-21 Otsuka, Tokyo 112-0012, Japan*

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ABSTRACT

We collected and interpreted high-resolution 3D seismic reflection data across a hypothesized fault scarp, along the largest active fault that could generate hazardous earthquakes in the Tokyo metropolitan area. The processed and interpreted 3D seismic cube, linked with nearby borehole stratigraphy, suggests that a monocline that deforms lower Pleistocene units is unconformably overlain by middle Pleistocene conglomerates. Judging from structural patterns and vertical separation on the lower–middle Pleistocene units and the ground surface, the hypothesized scarp was interpreted as a terrace riser rather than as a manifestation of late Pleistocene structural growth resulting from repeated fault activity. Devastating earthquake scenarios had been predicted along the fault in question based on its proximity to the metropolitan area, however our new results lead to a significant decrease in estimated fault length and consequently in the estimated magnitude of future earthquakes associated with reactivation. This suggests a greatly reduced seismic hazard in the Tokyo metropolitan area from earthquakes generated by active intraplate crustal faults.

1. Introduction

Acquisition of direct geologic evidence of recent activity on active faults and folds in urban areas is difficult due to extensive urbanization and high population density. Nevertheless, seismic hazards in such urbanized areas are necessarily of great consequence. The seismic hazard in and around Tokyo is one of the highest among the world's megacities because Tokyo is located in an actively deforming region below which the Pacific and Philippine Sea plates are subducting (Sato et al., 2005; Wu et al., 2007). Seismic potential here is primarily associated with plate subduction processes, including (1) interplate earthquakes such as the 1923 Kanto earthquake (M 7.9), which occurred on the subduction megathrust between the Philippine Sea and the Eurasia plates (Sato et al., 2005), (2) intra-slab earthquakes in the structurally complex plate configuration beneath the Kanto basin (Wu et al., 2007), and (3) earthquakes generated by active intraplate crustal faults. When compared to scenarios (1) and (2), scenario (3) from active intraplate faults remains poorly understood in such an extremely urbanized area (Ishiyama et al., 2013).

Most high-resolution seismic reflection profiling across active faults has been two dimensional (2D) (e.g., Ishiyama et al., 2004, 2007, 2013; Pratt et al., 1998, 2002; Improta and Bruno, 2007; Kaiser et al., 2009; Bruno et al., 2010). Despite its apparent advantages in imaging along-strike variations in structural characters, three-dimensional (3D) seismic reflection profiling has been applied more often in deep natural resource exploration than in shallow exploration of active fault structure, due to high costs. Recently, Kaiser et al. (2011) pioneered the application of 3D shallow seismic reflection profiling to active faults to resolve 3D structural questions. Three-dimensional seismic reflection profiling across active faults in urbanized areas like Metropolitan Tokyo, where more than 35 million people are now living, is challenging, yet essential in reconstructing real geologic structure and evaluating fault activity. In the case of active thrust faults, geologic cross sections are commonly used to estimate vertical separation of horizons by repeated fault activity. However, unless the study site is located in sedimentary environments with high sedimentation rates and/or low erosion rates, such as floodplain and backmarsh areas, one cannot be sure that the surface defined across correlated geologic horizons, such as the base of conglomeratic units, marks an originally subhorizontal surface; it may include a significant amount of vertical separation due to erosional processes. Therefore, we must be certain whether a reconstructed horizon represents a depositional contact or, an erosional contact, in whole or in part, when we discuss fault separation on these horizons. By employing 3D horizons reconstructed from 3D seismic reflection data, tied to borehole stratigraphy, we may more accurately define the topography of horizons that can be traced continuously in space and better distinguish between depositional and erosional contacts.

Active thrust faults and folds in the Kanto basin are usually identified based on (1) the tectonic geomorphology of deformed late Pleistocene marine and fluvial terraces and (2) the interpretation of seismic

* Corresponding author.
E-mail address: ishiyama@eri.u-tokyo.ac.jp (T. Ishiyama).

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reflection profiles. Extreme urbanization of the metropolitan area makes it difficult to obtain even fundamental geologic field data for evaluating these structures yet even moderate-size (~M7) earthquake would lead to immense casualties and infrastructure damage as a result of the extreme concentration of population, industries, and economic resources in this area, with consequences for both the domestic and global economies.

In this study, we present new high-resolution 3D seismic reflection data across a topographic feature, presumed to be a fault scarp, that was thought to reflect repeated earthquake activity along the Tachikawa Fault, one of the most prominent active faults in Tokyo. This excellent dataset enables us to reconstruct the otherwise inaccessible 3D geometry of a horizon at the base of the middle Pleistocene fluvial deposits by use of borehole stratigraphy tied with reflectors that may be continuously traced throughout the 3D seismic cube. We then discuss the origin of the hypothesized fault scarp based on our interpretation of the 3D seismic data in combination with other data, including trench excavation. We consider the hypothesized fault scarp to be a terrace riser rather than an active fault structure. We find the 3D seismic reflection technique to be a useful tool in resolving recent fault activity across active inland faults in a highly urbanized area as it allows us to create a 3D picture of buried sedimentary horizons which can then be tied to other available geologic data.

2. Tachikawa Fault

2.1. Tectonic setting of the Kanto basin

Beneath the Kanto region, the Philippine Sea plate (PHS) subducts northwestward at about 30 to 40 mm/year (Seno et al., 1993). The Izu–Bonin arc, carried along by the PHS plate, creates two contrasting styles of forearc deformation around the Kanto: (1) in the east, a late Cenozoic accretionary prism is accumulating and being deformed in the trench where the PHS plate is subducting, while (2) in the west, a buoyant Izu–Bonin arc has been colliding with Honshu for at least 15 million years (Sato et al., 2005). A megathrust that generated the 1923 Kanto earthquake separates the downgoing PHS plate from the overlying forearc and the Honshu crust, composed of Mesozoic to early Cenozoic accretionary sediments and granitic intrusions (Sato et al., 2005).

Metropolitan Tokyo is underlain by more than 4000 m of sediments that accumulated in a 100 km wide forearc basin along the subduction margin between the PHS plate and the Honshu arc (Geological Society of Japan, Eds., 2008). In eastern Kanto, the Plio-Pleistocene Kazusa Group shows significant spatial changes in facies that reflect a shifting paleogeography within a forearc basin that is filled with deep-sea turbidites. In western Kanto, alternating shallow marine and fluvial sequences were formed in a shallower environment. Despite significant facies changes, correlation of strata between different locations has been well established through dating of numerous interbedded volcanic tephras. Similarly, Neogene strata are also correlated via volcanic tephra whose ages are constrained through radiometric dating and calcareous nanno-fossil biostratigraphy (Geological Society of Japan, Eds., 2008).

2.2. Active faults in the Kanto basin

Active faults and folds are mainly identified at the ground surface near the southwestern Kanto Basin by minor deformation of Late Pleistocene marine and fluvial terraces (e.g., Kaizuka, 1987; Sugiyama et al., 1997) (Fig. 1). However, the geometries of buried thrusts within this region are poorly understood and only partly resolved by shallow to deep seismic reflection profiles (Ishiyama et al., 2013; Sato et al., 2010). Active faults in the Kanto basin typically extend for 20 to 30 km with a northwest trend, and the late Quaternary rates of slip along these structures are less than 1 mm/yr. (Ishiyama et al., 2013). Spatial density and historical seismicity of active crustal faults in the

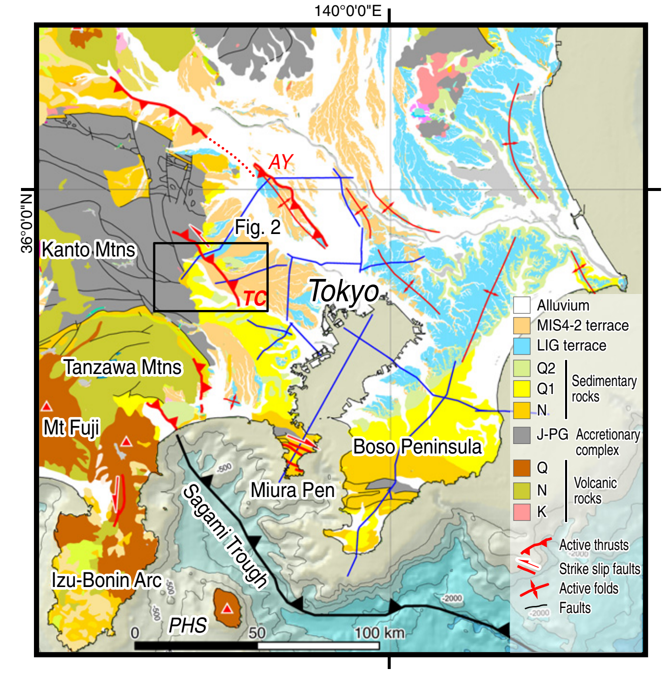

Fig. 1. Geologic map of the Kanto region including the Tokyo metropolitan area. Blue lines and white circles denote the locations of deep seismic reflection profiles and drilled boreholes used in this study. Abbreviations are TC: Tachikawa Fault; AY: Ayasegawa Fault; PHS: Philippine Sea plate; Q1–Q3: early, middle to late Quaternary; N1–N3: Neogene (early, middle Miocene and late Miocene and Pliocene); K1–K2: early to late Cretaceous; J1–J2: early to middle Jurassic.
The basemap is redrawn from Geological Survey of Japan (2009) and Kishimoto (2000). Locations of active faults are modified from Nakata and Imaizumi (2002), Sugiyama et al. (1997) and Watanabe (2007).

Kanto basin are lower than in western Kanto and central Japan. The difference in fault activity between the Kanto basin and other areas is probably a result of northwestward subduction of the PHS plate, which creates a strong horizontal stress heterogeneity within the overriding Honshu arc.

2.3. Tachikawa Fault

The Tachikawa Fault (Yamazaki, 1978; Fig. 2), which is located approximately 20 km west of the Tokyo Metropolitan area, is one of the largest active structures in eastern Kanto and extends for ca. 20 km in a northwest direction. Its proximity to the metropolitan area assures its importance in evaluating this region's potential seismic hazard. Moreover, judging from its clearer geomorphic expressions, it appears to have a faster rate of slip than other active structures in the Kanto basin, and it may experience more frequent and damaging earthquakes, although direct geological estimates of its recent activity have only been poorly resolved. The northern segment of the Tachikawa Fault is a steeply-dipping to vertical, sinistral strike-slip fault that deforms lower Pleistocene to Holocene sediments through repeated fault activity as seen in high-resolution seismic reflection profiling, tectonic geomorphological features, and trench stratigraphy (Ishiyama et al., in preparation). In contrast, the structural character and nature of faulting along its southern segment still remain poorly understood. Here a topographic scarp, which separates terrace surfaces correlated and dated on the basis of tephrochronology, has been interpreted as a thrust-related scarp rather than a terrace riser (Yamazaki, 1978). Nevertheless, direct geological evidence for active faulting, such as a fault outcrop, has not yet been identified. Therefore, intraplate earthquake scenarios in this region are poorly constrained because they require knowledge of fault length and magnitude–frequency of events, neither