Tectonophysics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Tectonophysics

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

Geometry and slip rates of active blind thrusts in a reactivated back-arc rift using shallow seismic imaging: Toyama basin, central Japan

Tatsuya Ishiyama [a,*], Naoko Kato [a], Hiroshi Sato [a], Shin Koshiya [b], Shigeru Toda [c], Kenta Kobayashi [d]

[a] Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[b] Graduate School of Science and Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[c] Department of Geosciences, Aichi Educational University, 1 Hirosawa, Igaya-cho, Kariya 448-8542, Japan
[d] Department of Geology, Faculty of Science, Niigata University, 8050 Ikarashi 2-no-cho, Nishi-ku, Niigata 950-2181, Japan

ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form 16 July 2017
Accepted 1 August 2017
Available online xxxx

Keywords:
Shallow seismic reflection imaging
Blind-thrust faults
Reactivated back-arc rift
Sea of Japan
Seismic hazards
Fault-related folds

ABSTRACT

Active blind thrust faults, which can be a major seismic hazard in urbanized areas, are commonly difficult to image with seismic reflection surveys. To address these challenges in coastal plains, we collected about 8 km-long onshore high-resolution two-dimensional (2D) seismic reflection data using a dense array of 800 geophones across compressionally reactivated normal faults within a failed rift system located along the southwestern extension of the Toyama trough in the Sea of Japan. The processing of the seismic reflection data illuminated their detailed subsurface structures to depths of about 3 km. The interpreted depth-converted section, correlated with nearby Neogene stratigraphy, indicated the presence of and along-strike variation of previously unrecognized complex thrust-related structures composed of active fault-bend folds coupled with pairs of flexural slip faults within the forelimb and newly identified frontal active blind thrusts beneath the alluvial plain. In addition, growth strata and fold scarps that deform lower to upper Pleistocene units record the recent history of their structural growth and fault activity. This case shows that shallow seismic reflection imaging with densely spaced seismic recorders is a useful tool in defining locations, recent fault activity, and complex geometry of otherwise inaccessible active blind thrust faults.

1. Introduction

Finding blind thrust faults in onshore urbanized areas on alluvial plains is challenging due to both anthropogenic factors caused by human activities and to geological factors. Human factors include noise in urbanized areas and logistic difficulties such as narrow roads and densely distributed buildings that prevent the deployment of seismic instruments and impede shooting, which degrades the quality of the seismic section. Geological factors include thick and young sedimentary units that hinder the upward propagation of the fault tips due to bedding slip, forming blind thrust structures (Roering et al., 1997; Niño et al., 1998). Even if geomorphic evidence of active folding was recognized based on geologic and geomorphic methods, the lack of connection between these surficial features and seismic images commonly prevent us from understanding their structural and seismological significance. In other words, geomorphic evidence suggesting thrust-related structures should be underpinned by structural information indicating the geometry of underlying thrust faults. Furthermore, especially in the case of Neogene sedimentary basins such as the Sea of Japan coast, rapid and dynamic subsidence in the Quaternary related to the reactivation of failed rift structures (Ishiyama et al., 2017) has acted to produce sediment sinks, which are in turn filled by increased fluvial sediment supplies that have covered many older faults.

The Toyama plain lies in the southern extension of the Toyama trough which comprises the lower topographic and structural domain above a Miocene failed rift. Previous deep seismic reflection data across the Toyama trough show that more than 5 km thick Neogene sediments underlie the Toyama plain along the Miocene failed rift axis (Ishiyama et al., 2017). Compressional horizontal stress perpendicular to the rift axis resulted in compressional reactivation of rift-related normal fault systems. While the deep seismic reflection data revealed the overall large-scale architectures of these reactivated structures, higher-resolution and finer-scale imaging of the fault-related folds is required to test their downward structural continuation to deeper structures.

Using a densely spaced seismic array that covered the whole seismic line, we obtained two-dimensional (2D) seismic reflection data across the Kurehayama Fault, a west-dipping active thrust fault, to define its subsurface geometry and identify unknown blind faults beneath the Toyama plain. Based on our new seismic profile, we traced stratigraphic horizons by tying seismic reflectors to Neogene stratigraphy from surface geology nearby to estimate the subsurface distribution of folds related to blind thrusts. We then further interpreted the structural growth of the fault-related folds and scarps during the Quaternary.

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

http://dx.doi.org/10.1016/j.tecto.2017.08.002
0040-1951/

This excellent dataset enabled us to examine the otherwise inaccessible subsurface geometries and the tectonic origins of active faults in the southernmost part of the failed rift system. Our discussion mainly focuses on (1) the shallow structural characteristics of the compressionally reactivated active thrusts beneath the Toyama plain based on our interpretation of the 2D seismic data in combination with the Neogene stratigraphy, (2) fault activity based on growth architecture and fold scarp geomorphology, (3) the identification of a previously unknown blind thrust fault beneath the alluvial plain, and (4) the hypothesized fault segment boundaries based on along-strike structural variation of thrust faults inferred from the shallow seismic data.

2. Geologic setting

In the Sea of Japan, sedimentary basins formed as a result of back-arc opening within a subduction system between the Eurasian and Pacific plates in the Neogene period (Tamaki et al., 1992; Baba et al., 2007; Otofuji and Matsuda, 1987; Otofuji et al., 1991; Van Horne et al., 2017) (Fig. 1). Among these back-arc basins, the Northern Honshu rift zone, which extends subparallel to the Yamato basin to the west, is interpreted as playing a significant role in the Miocene opening of the Sea of Japan, as well as the rifting along the Yamato and Japan basins (Sato et al., 2004) (Fig. 1(a)). The Toyama trough and the Toyama plain are located in the southern extension of the Northern Honshu rift zone and constitute a 100-km wide sedimentary basin (Toyama basin) underlain by more than 5 km of Neogene sediments (Geological Society of Japan (Eds.), 2006; Fujii et al., 1992) (Figs. 2 and 3). The chronology of the Neogene strata in the Toyama basin has been established based on radiometric dating of volcanic rocks, paleomagnetic records, and biostratigraphy (Hayakawa and Takemura, 1987; Ishiyama et al., 2017 and referenced herein) (Fig. 3 and S1). The stratigraphy of the Pliocene-Pleistocene strata, composed of alternating shallow marine and fluvial sequences, has also been established using regional volcanic tephra with radiometric ages traced from southwestern to central Japan (Amano et al., 2008; Goto et al., 2014; Ohkubo, 1999; Ohkubo and Arai, 2002; Shimizu and Fujii, 1995; Tamura and Yamazaki, 2004).

Based on extensive stratigraphic, paleontologic and structural analyses, the late Cenozoic tectonic history of this region is subdivided into three stages: (1) pre-rift, (2) syn-rift, and (3) post-rift stages, mostly similar to the back-arc basins in northeast Japan (Sato and Amano, 1991; Sato, 1994). Focal mechanisms and the trend and sense of slip on active faults suggest that an arc-perpendicular maximum horizontal stress field has been dominant during the Quaternary (e.g., Sato, 1994).

Ishiyama et al. (2017) presented the results and interpretations of onshore-offshore deep seismic reflection profiles across the Toyama trough and its southern extension to illustrate their deep to shallow crustal structures and compressionally reactivated active faults. The deep seismic data provided high-resolution crustal images of the failed rift and thick (~5 km) Neogene sediments underlain by the pre-Neogene basement rocks. The sedimentary basin units are strongly faulted and folded by thrust faults, which are reactivated normal faults originally formed during the Miocene rifting stages (Fig. 2(b)). Shallower high-resolution seismic reflection profiles also clearly illustrated the structural growth of these reactivated structures during the Quaternary, which is also recorded by deformed marine and fluvial

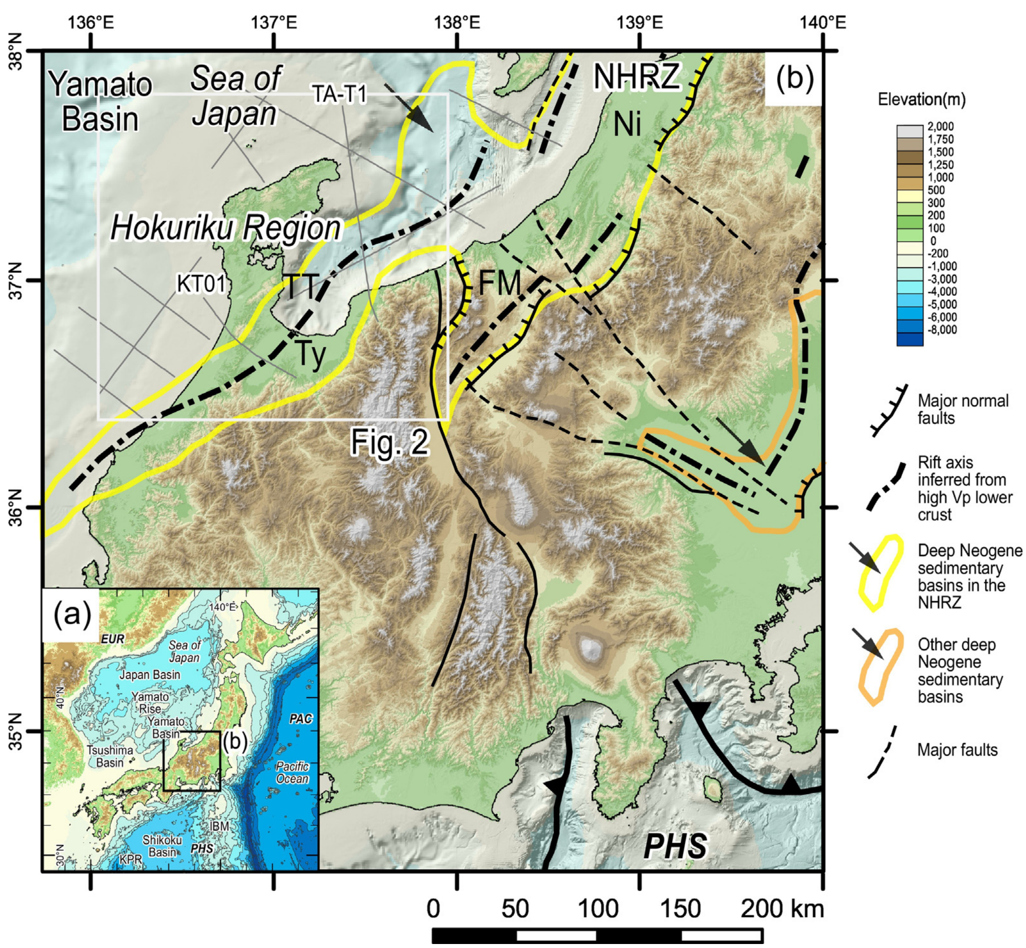

Fig. 1. (a) Regional topographic and bathymetric map around the Japanese islands. (b) Regional tectonic map of the Sea of Japan near the Hokuriku region. Modified from Ishiyama et al. (2017). The grey lines are other recent multichannel seismic lines. Abbreviations are EUR: Eurasian plate; PAC: Pacific plate; PHS: Philippine Sea plate; IBM; Izu-Bonin-Mariana arc; KPR: Kyushu-Palau ridge; NHRZ; Northern Honshu rift zone (Sato et al., 2004); Ni: Niigata basin; FM: Fossa Magna basin TT: Toyama trough; Ty: Toyama basin.