

Tectonic evolution and deep to shallow geometry of Nagamachi-Rifu Active Fault System, NE Japan

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The Nagamachi-Rifu fault is an active reverse fault which trends NE-SW across the central part of Sendai City for over 21 km distance. The fault does not emerge at the surface and, accompanied with the Dainenji-yama fault, shows wedge thrusting in the Tertiary sediments. The amount of net slip of the master part of the Nagamachi-Rifu fault is estimated to be one mm/year. Seismic reflection profiles across the fault plus a gravity anomaly reveal the thicker Neogene sediments on the hanging wall rather than on the footwall. The Neogene sedimentary basin was formed by normal faulting in early Miocene under an extensional stress regime associated with the formation of the northern Honshu rift system. Due to shortening deformation since the Pliocene, this Miocene normal fault reactivated as a reverse fault. Judging from the CMP deep seismic reflection profile and location of the 1998 M5.0 Sendai earthquake, the deep geometry of the Nagamachi-Rifu fault is listric.

1. Introduction

The Nagamachi-Rifu fault is an active reverse fault which runs in the NE-SW direction across the central part of Sendai City over a distance of 21 km. This fault is assessed by the local prefectural government with a potential to produce a destructive earthquake of magnitude 7 (Miyagi Prefectural Government, 1997). A multi-disciplinary investigation to detect the on-going slip along the deeper extension of the Nagamachi-Rifu fault was started in 1998 (Hasegawa *et al.*, 2001). To reveal the aseismic slip along the deeper extension of an active fault, the deep fault-geometry as well as monitoring of crustal movements are important keys. Also, the geometry of the source fault plays an important role for estimating the strong ground motion associated with a scenario earthquake. This paper provides the geologic information to estimate the deep fault-geometry of the Nagamachi-Rifu active fault system and explores the tectonic evolution of this fault system.

2. Geologic Setting

The geologic structure of Sendai and its adjacent area is largely affected by three Neogene tectonic events (Sato, 1994), such as extensional deformation in the early Miocene, formation of calderas in late Miocene and final shortening deformation since late Pliocene (Fig. 1). The formation of early Miocene half grabens started ca. 17 Ma. The Miocene half grabens were mapped by mainly surface geology and gravity anomaly data (Kitamura *et al.*, 1986; Kitamura,

1986; Nakamura, 1992; Amano, 1980; Hiroshima *et al.*, 1991). The early half grabens were controlled by normal faults trending NNW to NW and were followed by younger grabens trending NE-SW. After the middle Miocene subsidence associated with the formation of the northern Honshu rift system, the Ou Backbone Range was gently uplifted. From 7 Ma to 2 Ma a large number of calderas were formed in the western part of Sendai and Ou Backbone Range (Yoshida, 2001). They are mainly collapsed calderas, 10 km in diameter, that erupted felsic volcanics on land. Since the late Pliocene, due to regional compressional stress trending WNW-ESE, Miocene normal faults were reactivated as reverse faults. The style of volcanism also changed to andesitic strato-volcanoes in the Quaternary.

3. Active Tectonic Features of the Nagamachi-Rifu Fault

Based on the late Quaternary geomorphologic features, the Nagamachi-Rifu fault is traced NE-SW for 21 km distance across the central part of the Sendai City (Fig. 2). The Nagamachi-Rifu fault forms a fault system, including the Dainenji-yama fault and Nigatake blind fault. The Nigatake blind fault is identified based on a topographic flexure, which separates the gentle slope of the uplifted alluvial surface in the hanging wall to the flat alluvial surface in the footwall (Imaizumi *et al.*, 2002). This flexure is also detected by the seismic reflection profile shown in Fig. 3 as growth strata of latest Pliocene to Quaternary sediments. Based on the deformation of river terraces on the hanging wall, the vertical slip rate of the Nagamachi-Rifu fault was estimated to be more than 0.5 mm/year (Nakata *et al.*, 1976; Otsuki *et al.*, 1977).

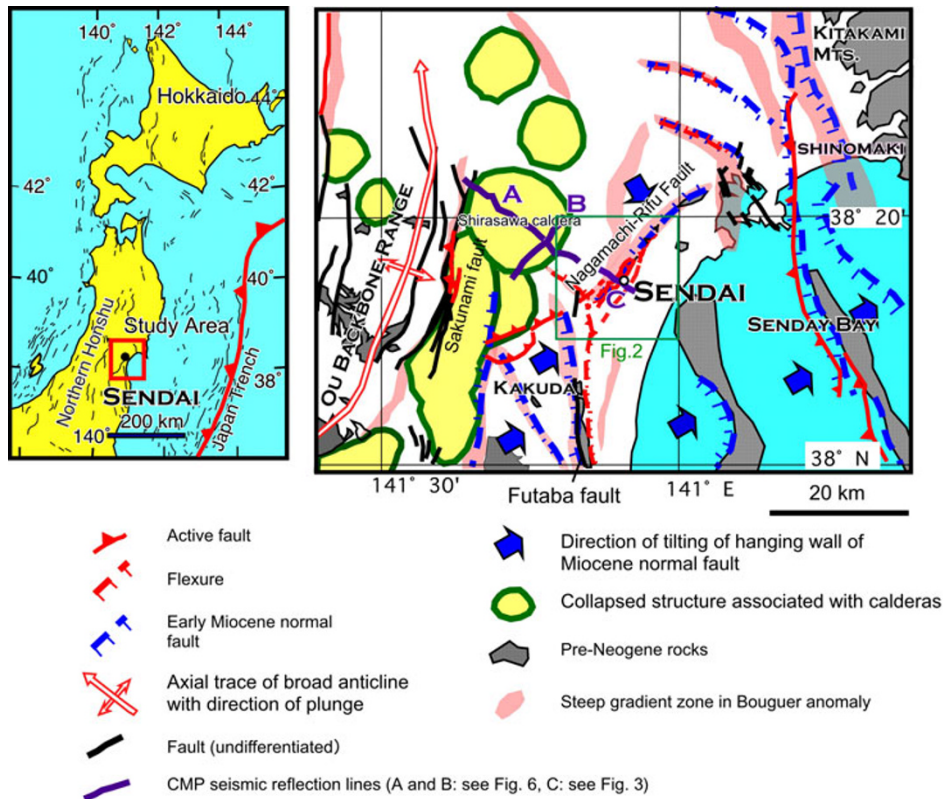


Fig. 1. Geologic structure around Sendai, NE Japan.

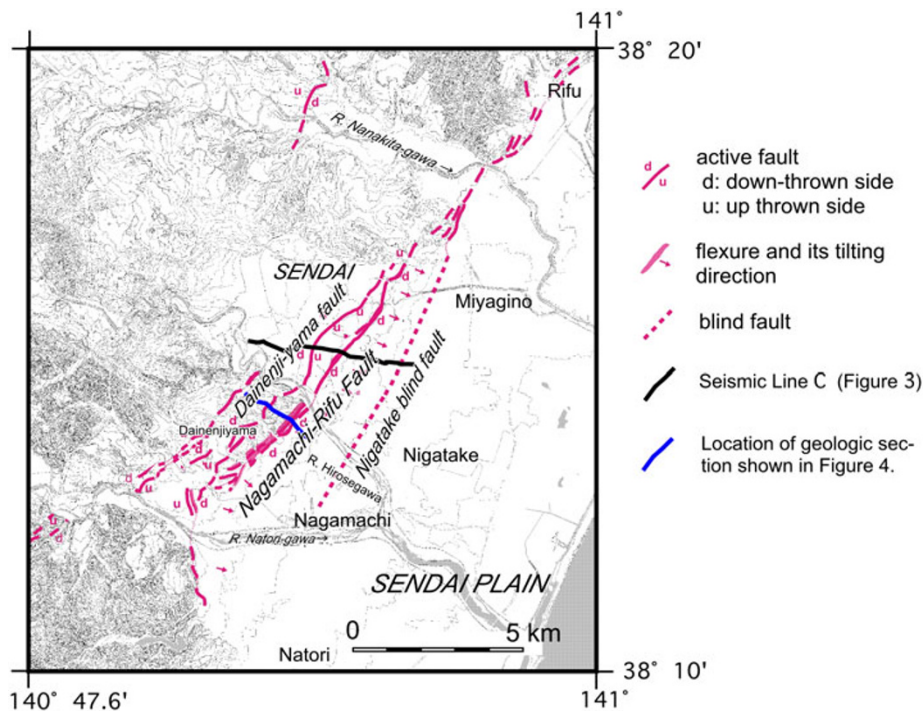


Fig. 2. Active fault map around Sendai City after Imaizumi *et al.* (2002). Contours of topographic map is 10 m. The area of this figure is shown in Fig. 1.

Recent research on the Nagamachi-Rifu fault revealed subsurface geologic structure of the footwall by drilling (Fig. 4; Miyagi Prefectural Government, 2000). According to the results, the averaged vertical slip rate of the main Nagamachi-

Rifu fault is about 0.7 mm/year and the value of the Dainenji-yama fault is 0.1 mm/year (Fig. 5). As this fault forms a fault system, the vertical slip rate of the master fault reaches nearly one mm/year. The total amount of horizontal short-

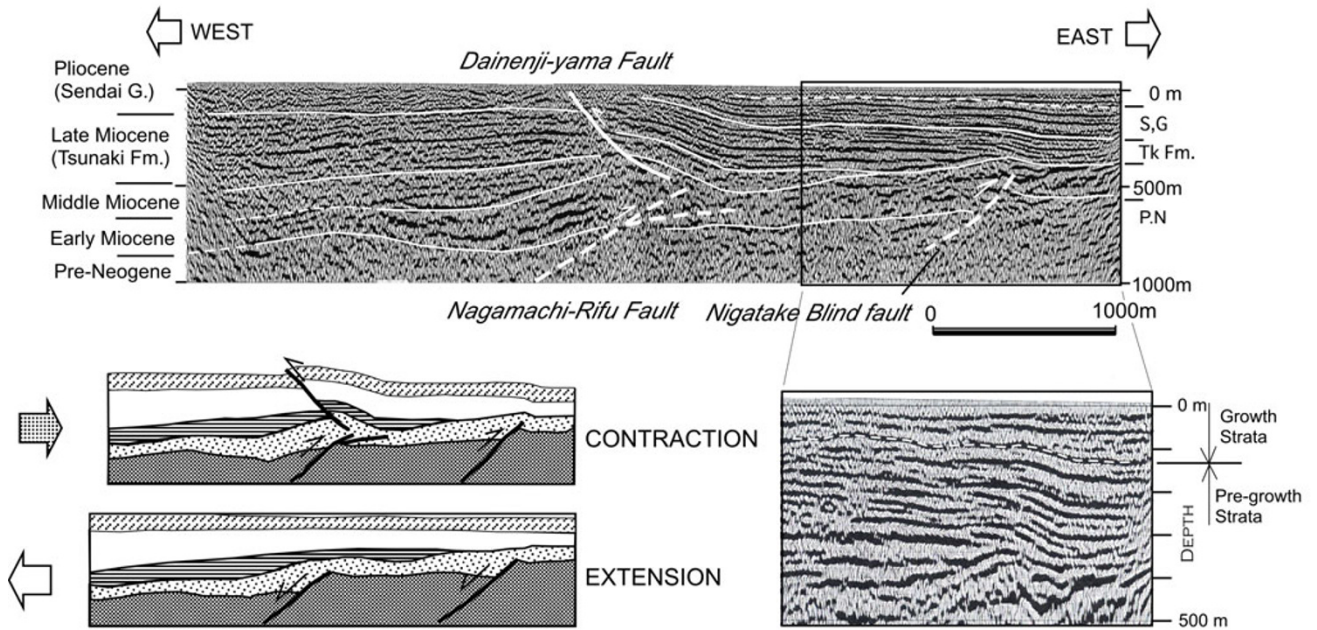


Fig. 3. Seismic reflection profiles across the toe of the Nagamachi-Rifu active fault system (Miyagi Prefectural Government, 1997) and its geologic interpretation. The location of the seismic section is shown in Figs. 1 and 2.

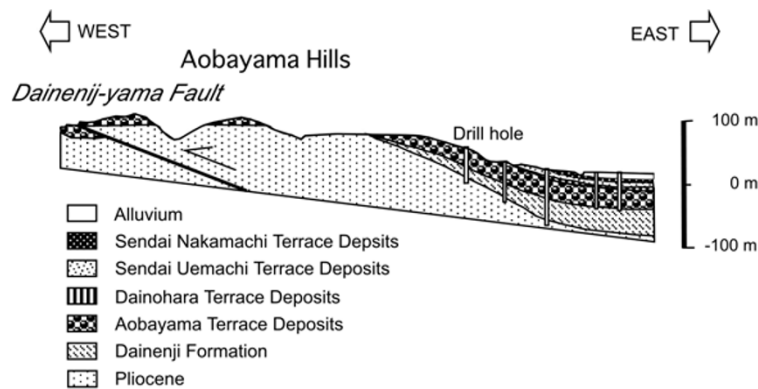


Fig. 4. Shallow geologic structure across the Nagamachi-Rifu fault after Miyagi Prefectural Government (1997). The location of the geologic section is shown in Fig. 2.

ening is about 250 m. Based on the liquefaction features observed in drill cores near Nagamachi-Rifu fault, two possible paleo-seismic events produced by this fault were estimated at 4,500–5,000 y.B.P and 2,500–2,800 y.B.P (Miyagi Prefectural Government, 2000).

4. Fault Reactivation

Figure 3 shows the migrated and depth converted seismic reflection profile across the Nagamachi-Rifu fault (Miyagi Prefectural Government, 1997). The Nagamachi-Rifu fault forms a flexure near the surface and does not appear on the surface. Alternatively, the east-dipping Dainenji-yama fault occurs as a back-thrust (Fig. 4). The uplift of the Aobayama Hills is attained by wedge-thrusting of the subsurface west-dipping Nagamachi-Rifu fault and the Dainenji-yama fault (emergent back-thrust). Above the Nigatake blind fault, systematic change of the sediment’s thickness occurred showing

growth strata in the latest Pliocene to Quaternary sediments.

The other outstanding feature in the seismic profile is the change in thickness of the Tertiary sediments between the Nagamachi-Rifu and Nigatake faults. On the hanging wall the thickness of sediments is thicker than on the footwall. This feature clearly demonstrates that the fault was reactivated from normal faulting in Miocene to reverse faulting since late Pliocene. In the northeastern part of the Nagamachi-Rifu fault, lower Miocene thrusts onto pre-Neogene rocks (Kitamura *et al.*, 1986). The value of the Bouguer anomaly decreases toward the hanging wall, suggesting a thicker sediment cover in the hanging wall than in the footwall (Hiroshima *et al.*, 1991). Fault reactivation from Miocene normal faulting to later reverse faulting was already reported for the eastern part of the Sea of Japan (Okamura *et al.*, 1995) and also in the Sendai Bay area (Nakamura, 1992).

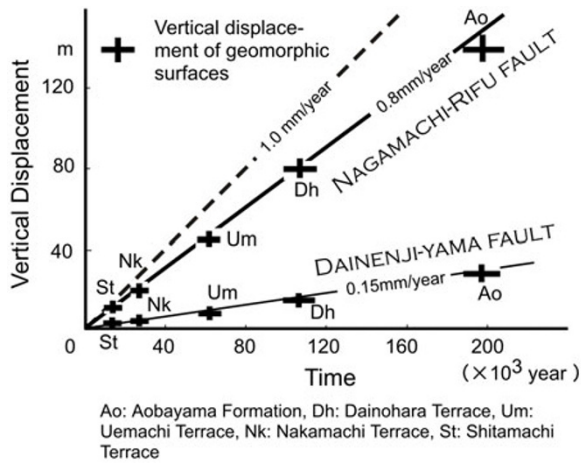


Fig. 5. The averaged vertical slip rate of the Nagamachi-Rifu active fault system, deduced by the vertical displacement of river terraces (after Miyagi Prefecture, 1997). The error in observed vertical displacement and age of topographic surfaces are marked by the length of bar.

5. The Deep Geometry of the Nagamachi-Rifu Fault

Deep CMP (common midpoint) seismic reflection profiling was carried out in western Sendai to reveal the deep geometry of the Nagamachi-Rifu fault (Ikawa *et al.*, 2001). On the CMP-reflection profile of seismic Line A (Fig. 6), there are some west-dipping reflectors near the hypocenter area of 1998 Mj 5.0 Sendai earthquake. The fault plane determined by the focal mechanisms and hypocentral distribution shows dip to the northwest at an angle of 30 degrees (Umino *et al.*, 1999; Okada *et al.*, 2001). The gently west-dipping reflectors at the depth of 12–13 km on the western half of seismic line A is interpreted as the probable deeper extension of the Nagamachi-Rifu fault (Fig. 6). The geometry of the Nagamachi-Rifu fault shows almost constant dip angle (45 degrees) in the upper crust and decreases its angle to 30 degrees near the bottom of seismogenic layer.

In the upper crust of the eastern-half of line A, many west-dipping reflectors are dominant. On the contrary, in the western part of line A the upper crust is marked by sub-horizontal

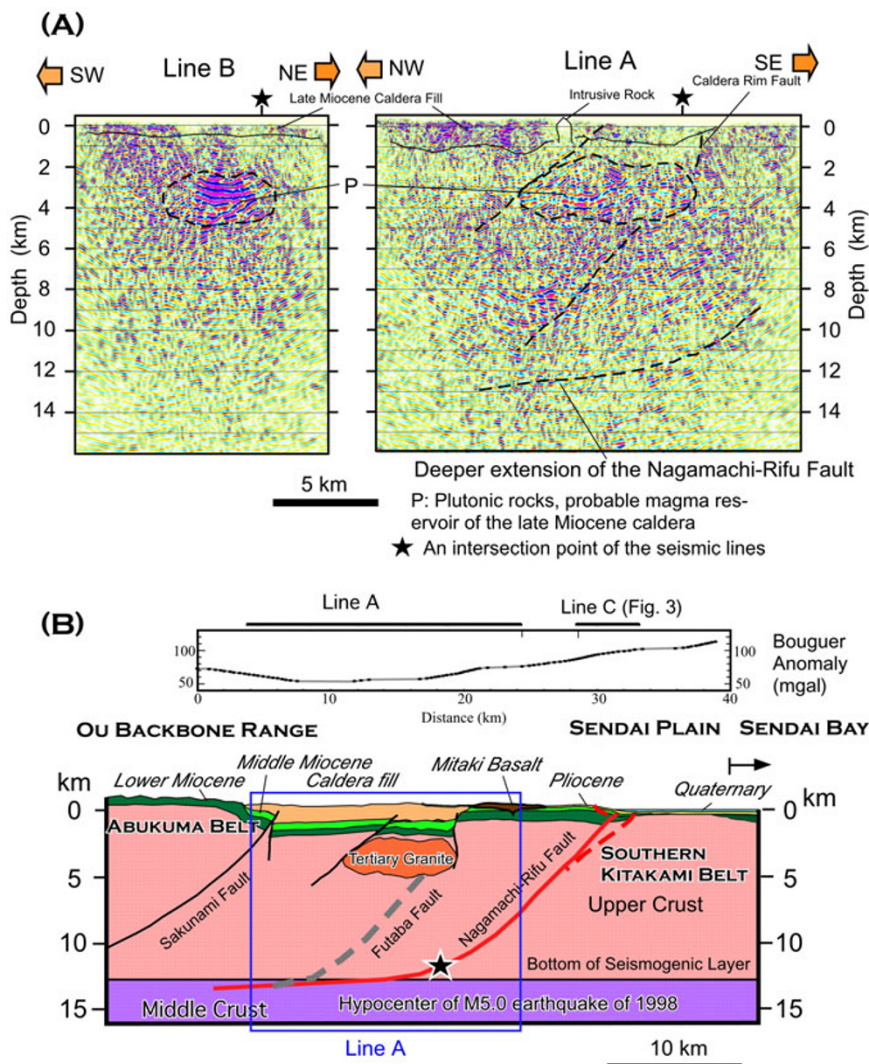


Fig. 6. Deep geometry of the Nagamachi-Rifu active fault systems. (A) Geologic interpretation of deep CMP reflection profiles after Ito *et al.* (2002). The location of the seismic lines are shown in Fig. 1. (B) Schematic diagram showing the deep geometry of the Nagamachi-Rifu active fault system. The Bouguer anomaly along the seismic line is obtained from the contour map after Hiroshima *et al.* (1991).

reflectors. This change in dip angle of reflectors occurs at the direct extension of the Futaba fault, which is a Cretaceous to Paleogene strike-slip fault that has large displacement. In the Kakuda basin, south of Sendai (Fig. 1), the early Miocene graben was formed along the Futaba fault. Judging from the west-dipping normal faulting in the early Miocene, the northwestern extension of the Futaba fault is interpreted as a west-dipping fault (Fig. 6). The boundary between the above-mentioned west-dipping and sub-horizontal reflection domains in the upper crust is traced by a west-dipping line in Fig. 6, suggesting the extension of the Futaba fault.

The area marked by lower frequency reflections (ca. 12 Hz) is identified in the central part of both seismic lines at the depth of 2–5 km in a region of 8 km diameter. As its special distribution is restricted within the Shirasawa caldera, we interpreted it as plutonic rocks which were formed in the late Miocene as a source reservoir of this felsic caldera. The low frequency reflections are associated with the top of the reservoir and its upper most internal structures. The shallow part (<1 km) above the possible plutonic rocks shows coherent reflectors and is interpreted as caldera fill (Fig. 6).

6. Conclusions

The Nagamachi-Rifu fault is a west-dipping reverse fault and splays in the uppermost crust forming a fault system with the Dainenji-yama fault and Nigatake blind fault. The master portion of the Nagamachi-Rifu active fault system shows the net slip rate of one mm/year. Judging from the shallow seismic reflection profile, surface geology and gravity anomaly, the fault system was originally formed as a normal fault in early Miocene and subsequently reactivated as a reverse fault. Based on the deep CMP seismic reflection profiles (Ikawa *et al.*, 2001) and seismic activity (Umino *et al.*, 1999), the deeper extension of the Nagamachi-Rifu fault shows moderate dip angle (45 degrees) in the upper crust and decreases its angle to 30 degrees near the bottom of seismogenic layer.

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