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Seismological and geological characterization of the crust in the southern part of northern Fossa Magna, central Japan

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The northern Fossa Magna (NMF) is a Miocene rift basin formed in the final stages of the opening of the Sea of Japan. The northern part of Itoigawa-Shizuoka Tectonic Line (ISTL) bounds the western part of the NMF and forms an active fault system that displays one of the largest slip rates in the Japanese islands. Reflection and refraction/wide-angle reflection profiling and earthquake observations by a dense array were undertaken across the northern part of ISTL in order to delineate structures in the crust, and deep geometry of the active fault systems. The ISTL active fault system at depth (ca. 2 km) shows east-dipping low-angle in Omachi and Matsumoto and is extended beneath the Central Uplift Zone and Komoro basin keeping the same dip-angle down to ca. 15 km. The upper part of the crust beneath the Central Uplift Zone is marked by the high Vp and high resistivity zone. Beneath the folded zone of the NMF, the middle to lower crust shows low Vp, low resistivity and more reflective features. The balanced geologic cross-section based on the reflection profiles suggests that the shortening deformation since the late Neogene was produced by the basin inversion of the Miocene low-angle normal fault.

Key words: Crustal structure, geologic structure, active fault, Itoigawa-Shizuoka tectonic line, northern Fossa Magna, seismic reflection profile, seismic refraction profile, central Japan.

1. Introduction

To construct a realistic model to explain crutal deformation processes in the short term (<100 years) to long term is important for a better understanding of the occurrence of crustal devastative earthquakes and seismic hazards. Geodetic measurements, including triangulation for nearly 100 years and GPS measurements, suggest that strain accumulation has occurred around the northern part of the Itoigawa-Shizuoka tectonic Line (ISTL) active fault system and northern Fossa Magna, central Japan (Fig. 1; Sagiya *et al.*, 2002). Also, on the evidence of paleo-seismology (Okumura, 2001), the ISTL active fault system poses the highest seismic risk and shows one of the largest slip rates (4–9 mm/yr) among active onshore faults (e.g. Ikeda *et al.*, 2002). Based on such features, the northern part of the ISTL active fault system provides an excellent opportunity to reveal on-going crustal deformation mechanisms and processes, and was determined as a target area for the research project on "Slip and Flow Processes in and below the Seismogenic Region".

Revealing the crustal architecture of the target area is an important key to construct the numerical model for crustal deformation. For this purpose, multi-disciplinary research to reveal the crustal structure has been carried out, including seismic reflection profiling (Sato *et al.*, 2004a), seismic refraction/wide-angle reflection profiling (Imai *et al.*, 2004; Takeda *et al.*, 2004), seismic tomography (Kurashimo and Hirata, 2004), receiver function analysis (Yoshimoto *et al.*, 2004; Abe *et al.*, 2004), and resistivity structure by magnetotelluric (MT) method (Ogawa *et al.*, 2002) across the northern part of the ISTL active fault system. In this paper, we try to synthesize the crustal structure of the northern Fossa Magna region and deep geometry of the ISTL active fault system based on the above-mentioned results and other related seismic profiles (Matsuta *et al.*, 2004; Ikeda *et al.*, 2004; Elouai *et al.*, 2004).

2. Geological Setting

The northern part of the ISTL is defined as the western boundary fault of the Neogene sedimentary basin, named Fossa Magna. The tectonic line, which separates the pre-Tertiary basement of the NE Japan from SW Japan, is the Tanakura Shear Zone (e.g. Otsuki, 1975; Fig. 1). The ISTL produced a certain displacement in pre-Tertiary basement,

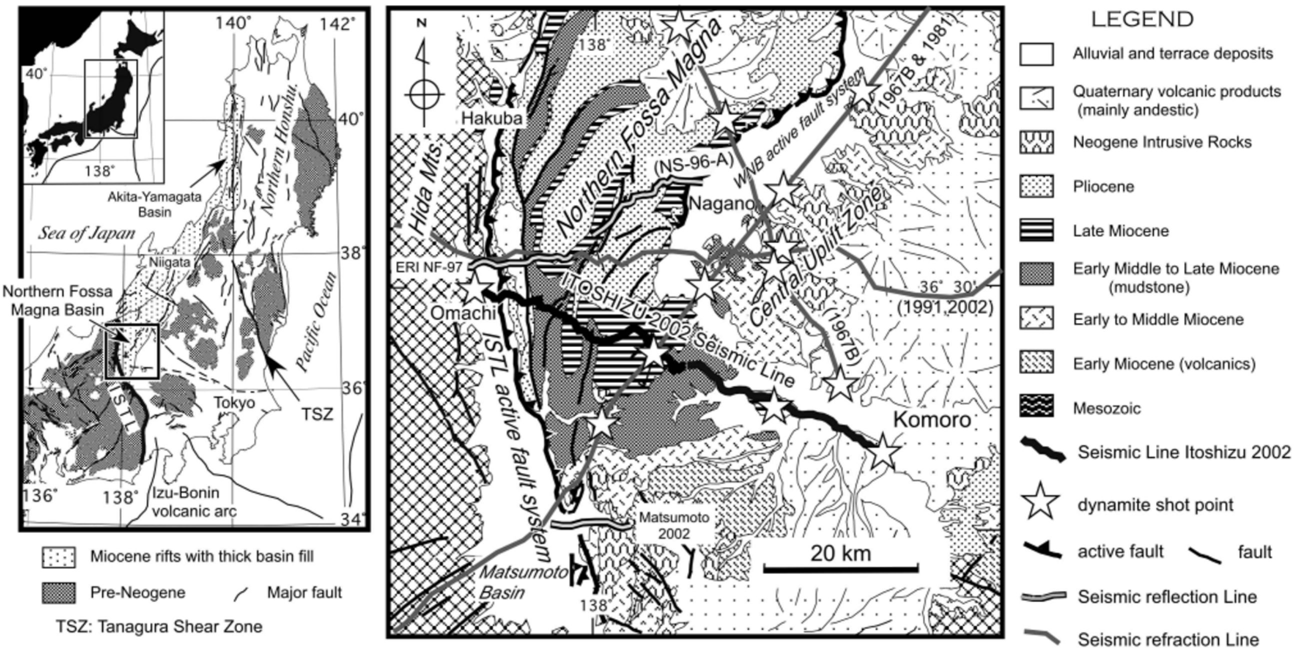

Fig. 1. Geologic map of the northern Fossa Magna (Geological Survey of Japan, 1992) and location of seismic lines.

which belongs to the geologic belts in SW Japan. However, due to a thick Neogene sedimentary cover, the tectonic movement of ISTL in Pre-Neogene is poorly understood. Judging from the basin fill, the formation of the northern part of the ISTL and northern Fossa Magna is closely related to the formation of the Sea of Japan and northern Honshu rift system (Sato *et al.*, 2004a). In the southern Fossa Magna region, the fore-arc sediments of Honshu arc and the sediments deposited on the Izu-Bonin arc are strongly deformed by the collision of the two arcs. The southern ISTL was produced by this collision processes (Kano *et al.*, 1990) and its nature and geometry is very different from the northern one. The northern part of the ISTL has an east-dipping fault plane, yet the southern part shows a west-dipping fault plane. Therefore, the ISTL should not be considered as a single fault system, it consists of two fault systems different in origin and deep geometry.

The northern Fossa Magna was formed as a rift basin located in the southern end of the northern Honshu rift system. In the northern part of the basin, more than 6 km of marine sediments have accumulated (Kato, 1992). The Neogene basin fill is strongly folded with NE trending axial trace (Fig. 1). The Central Uplift Zone trends parallel to the northern Fossa Magna basin and consists of gently dipping lower Miocene submarine mudstone and volcanic rocks. A negative Bouguer gravity anomaly zone 25 km in width is formed east of, and parallel to, the Central Uplift Zone (Hiroshima *et al.*, 1994). However, due to the cover of Quaternary volcanic products, the age of the infill of this basin is uncertain.

The central part of the ISTL forms active fault systems with high slip-rate of 4–9 mm/y (Matsuta *et al.*, 2004; Ikeda *et al.*, 2004). However, the northernmost part of ISTL, north of Hakuba, shows no evidence of late Quaternary faulting (Togo *et al.*, 1996). In other words, along the northernmost part of ISTL, there is no evidence suggesting that this fault is a plate boundary between Eurasia and North American plates (e.g. Nakamura, 1983) at least since late Quaternary.

3. Velocity Structure Obtained from Refraction/ Wide-Angle Reflection Profiling

Since the 1960's, several seismic experiments have been carried out in the northern Fossa Magna region, including Asano *et al.* (1969), Ikami *et al.* (1986), Sakai *et al.* (1996) and Takeda (1997). The previous data were reprocessed by Takeda *et al.* (2004). In this project, the seismic reflection (Sato *et al.*, 2004a), refraction/wide-angle reflection (Imai *et al.*, 2004) data were acquired across the ISTL active fault system with a 68-km-long seismic line (Itoshizu 2002; Fig. 1). The obtained P-wave velocity model by Imai *et al.* (2004) using a 2-D ray tracing method (Iwasaki, 1988) is shown in Fig. 2. The most prominent feature is the "Central Uplift Zone", flanked on the west and east by sedimentary basins. Low velocity layers below the ISTL active fault, extend beneath the Central Uplift Zone, showing a thin wedge-shaped geometry. The upper interface of the low velocity zone is interpreted as the deeper extension of the ISTL active fault at least just beneath the Central Uplift Zone. The connectivity of the probable deeper extension of the ISTL active fault and the thin low velocity layer beneath the eastern flank of the Central Uplift Zone is obscure.

The main geologic structure such as the northern Fossa Magna basin, Central Uplift Zone and the Komoro basin is clearly indicated by several seismic lines in northern Fossa Magna area (Takeda *et al.*, 2004). The depth of the base of Neogene basin fill in the northern Fossa Magna increases to the northeastward.

4. Fault Geometry Based on the Seismic Reflection Profiles

The common mid-point (CMP) seismic reflection profiling was carried out at several seismic lines across the ISTL

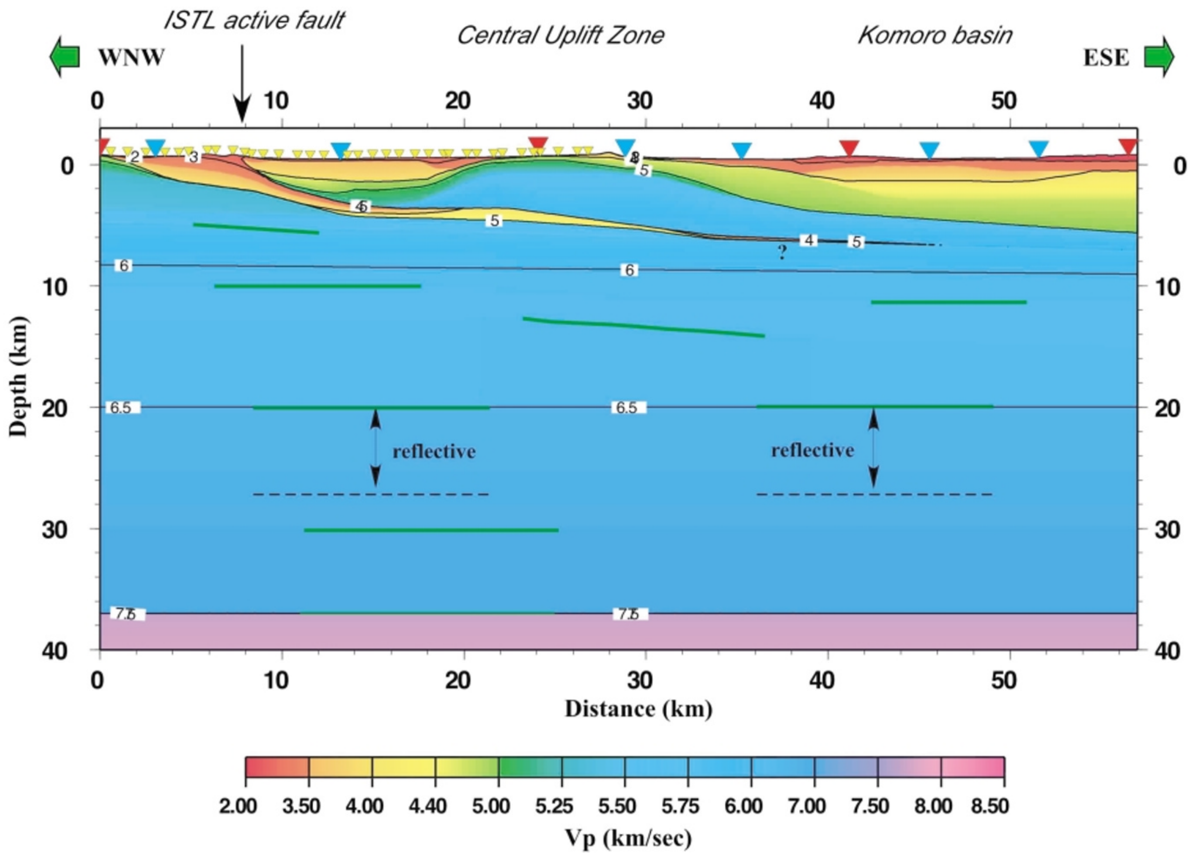

Fig. 2. P-wave velocity structure by ray-tracing method along Itoshizu 2002 seismic line (Sato *et al.*, 2004a) after Imai *et al.* (2004). Red triangles: locations of explosive sources, blue triangles: locations of high energy shots (a large number of sweeps) by vibroseis trucks, yellow triangles: locations of vibroseis shot points used in this analysis. Green lines represent the reflectors clearly observed on the shot gathers by explosive sources.

active fault system. The representative line is the Itoshizu 2002 (Sato *et al.*, 2004a; Fig. 1). Seismic data were acquired using four vibroseis trucks and explosive sources. Resultant depth converted seismic sections and its geologic interpretation are shown in Fig. 3. The obtained seismic profiles, including a shallow high-resolution profile along the same seismic line (Matsuta *et al.*, 2004), suggest that the ISTL active fault forms an emergent thrust with a dip-angle of 30 degrees to the east at the shallow depth (< 2 km). The deeper extension of this fault can be traced in the Miocene basin fill with low-angle and possibly traced beneath the Central Uplifted Zone (Sato *et al.*, 2004a; Fig. 3 suggested by arrows Y). The boundary between Cretaceous granitic rocks and Neogene sediments is clearly recognized by strong continuous reflections and can be traced down to 3 km at a distance of 6 km from the western end (Fig. 3, X). The boundary between the Cretaceous and Neogene and the extension of the ISTL active fault are estimated to merge beneath the Central Uplift Zone. Based on our velocity model and seismic reflection profile and available geologic data (e.g. Kato, 1980; Kato and Sato, 1983; Kato and Akabane, 1986; Kato *et al.*, 1989; Arai, 2000), the seismic section of Itoshizu 2002 is interpreted as shown in Fig. 3. The low-angle fault geometry of the ISTL active fault system at the depth more than 2-km is also demonstrated by seismic reflection profile in Matsumoto (Matsumoto 2002 in Fig. 1; Ikeda *et al.*, 2004). This geometry well accords to the velocity structure obtained by the reprocessing of refraction data of the 1987 seismic line (Fig. 1, Takeda *et al.*, 2004). The similar geometry of the ISTL active fault system is also presented in ERI NF 97 seismic line, located north of the Itoshizu 2002 seismic line (Fig. 1; Elouai *et al.*, 2004).

5. Relationship between Velocity Structure, Fault Geometry and Other Geophysical Features

Along the Itoshizu 2002 seismic lines, earthquakes were recorded for two months by a dense array of temporary seismic stations. Based on these data, the crustal structure was investigated by seismic tomography (Kurashimo and Hirata, 2004) and receiver function analysis (Abe *et al.*, 2004). Resistivity structure along the same profile was also obtained by the magnetotelluric method (Ogawa *et al.*, 2002).

According to the receiver function analysis using CCP (common-conversion-point) stacking and prestack migration of teleseismic P-SV converted wave, two P-S converted interfaces are identified at a depth of 17–18 km and 38–40 km. The later phase with positive polarity can be interpreted as the P-S conversion from the Moho (Abe *et al.*, 2004). Figure 4 is a shot record of the explosive source at the western end of the Itoshizu 2002 seismic line. The coherent reflections can be recognized from 6 to 13 sec (TWT: two-way travel time), suggesting that the laminated lower crust extends up to 13 sec (TWT). From these observations, it is highly probable that the Moho-depth is located at about 40 km.

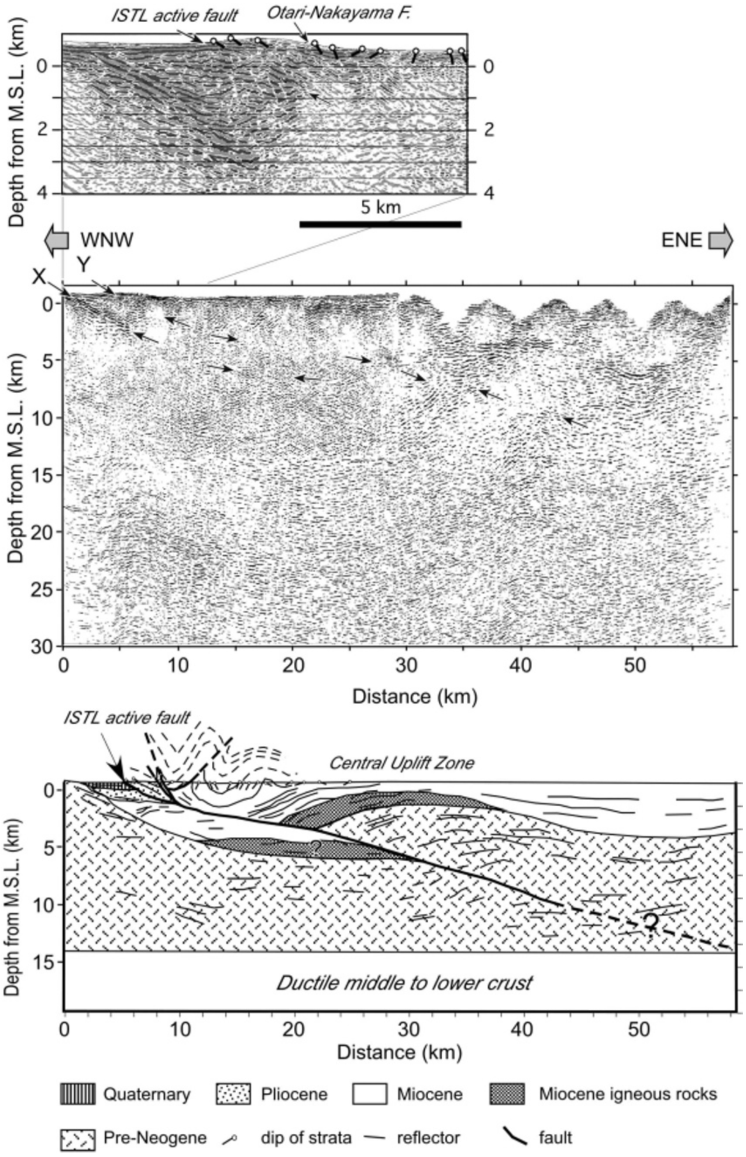

Fig. 3. Stacked, migrated, depth converted seismic sections of Itoshizu 2002 and its geologic interpretation after Sato *et al*. (2004a). X: base of Neogene, Y: deeper extension of the ISTL active fault.

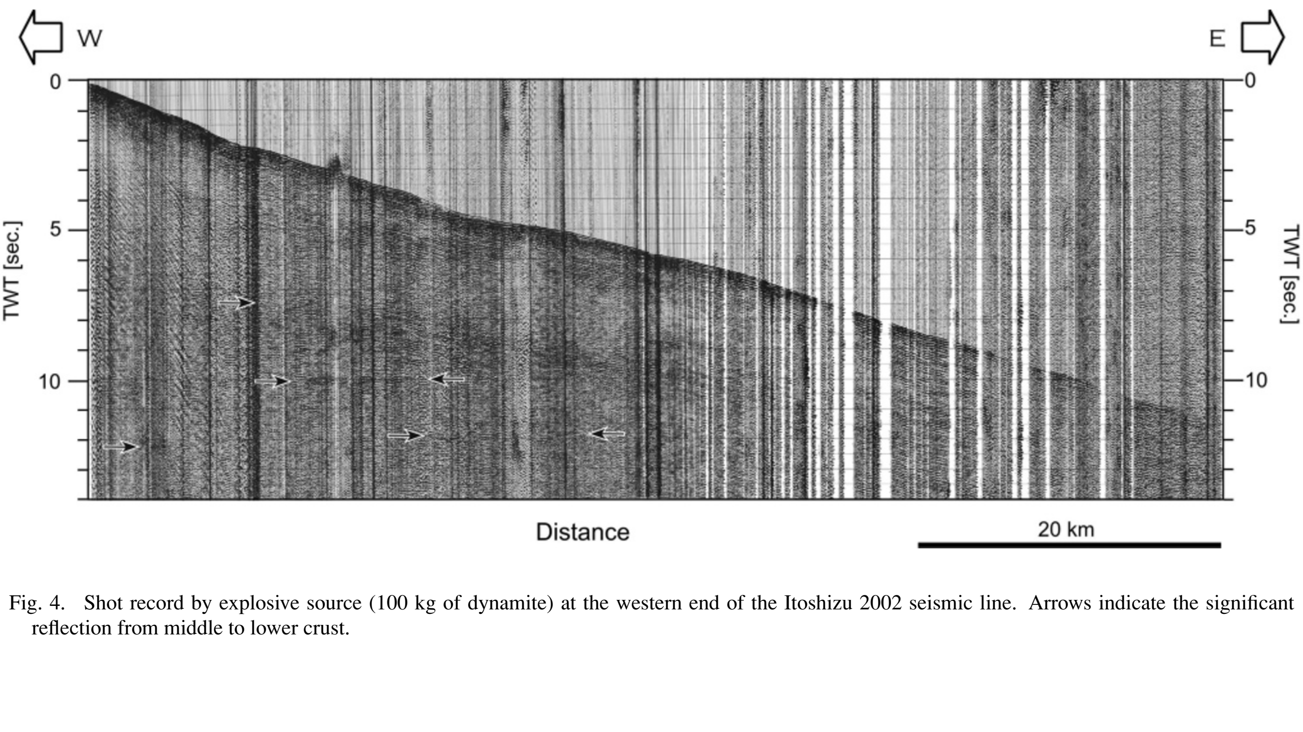

Fig. 4. Shot record by explosive source (100 kg of dynamite) at the western end of the Itoshizu 2002 seismic line. Arrows indicate the significant reflection from middle to lower crust.

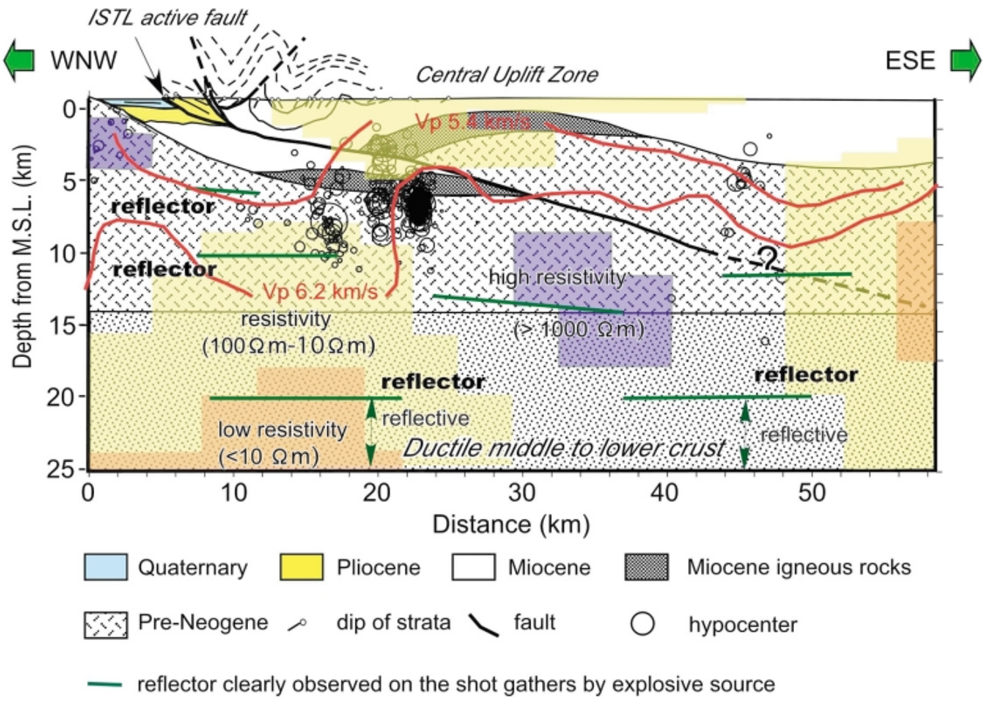

Fig. 5. Geologic cross-section along the Itoshizu 2002 seismic line (Sato *et al.*, 2004a) with the resistivity structure (Ogawa *et al.*, 2002), the hypocentral distribution (Sakai, 2004) and P-wave velocity structure obtained by seismic tomography (Kurashimo and Hirata, 2004). The location of deep reflectors is after Imai *et al*. (2004).

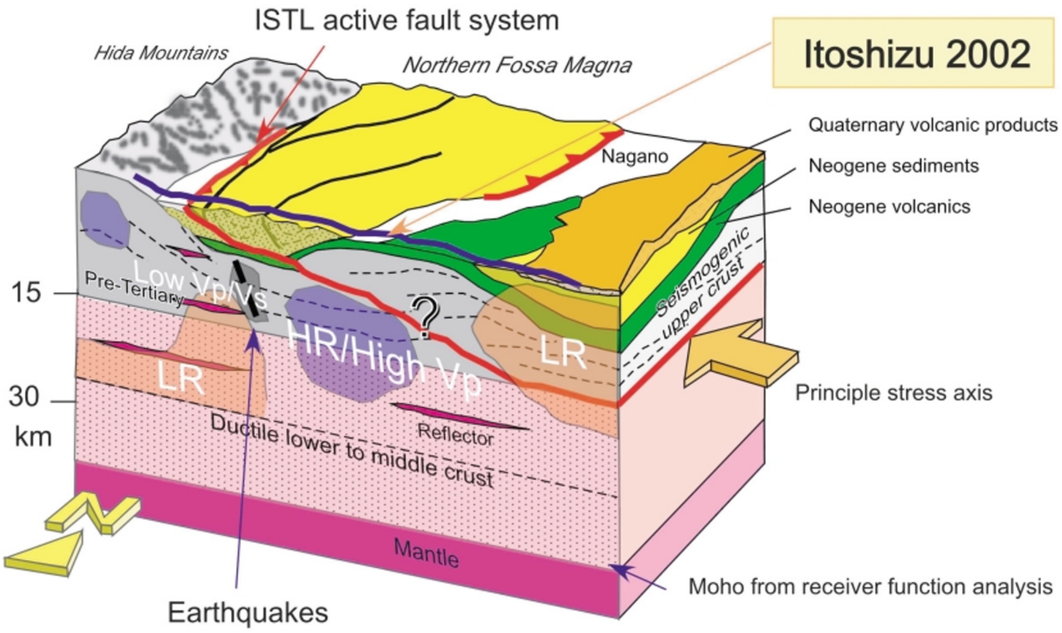

Fig. 6. Schematic illustration showing the crustal structure around the southern part of the northern Fossa Magna.

The resistivity structure along the Itoshizu 2002 (Ogawa *et al*., 2002), the relocated, hypocentral distribution (Sakai, 2004) and the reflectors observed on the shot gathers by explosive sources (Imai *et al*., 2004) are superposed on the geologic cross-section (Fig. 5). The high resistivity area beneath the Central Uplift Zone (∼20 km) is almost coincidence with the high velocity area obtained by seismic tomography analysis (Kurashimo and Hirata, 2004). The basement beneath the folded zone of the northern Fossa Magna basin is marked by the low resistivity (Ogawa *et al*., 2002), low Vp (Kurashimo and Hirata, 2004; Takeda *et al*., 2004), low to moderate Vp/Vs (Kurashimo and Hirata, 2004) and distribution of the clear reflectors (e.g. Fig. 3). Kurashimo and Hirata (2004) suggested the existence of aqueous fluid pores with high aspect rations in this zone.

Using the obtained velocity structure by refraction analysis, hypocentral distribution of micro-earthquakes were redetermined and projected on the Itoshizu 2002 seismic line (Sakai, 2004; Fig. 5). Most of micro-earthquakes occur in the footwall of the ISTL active fault system. As suggested

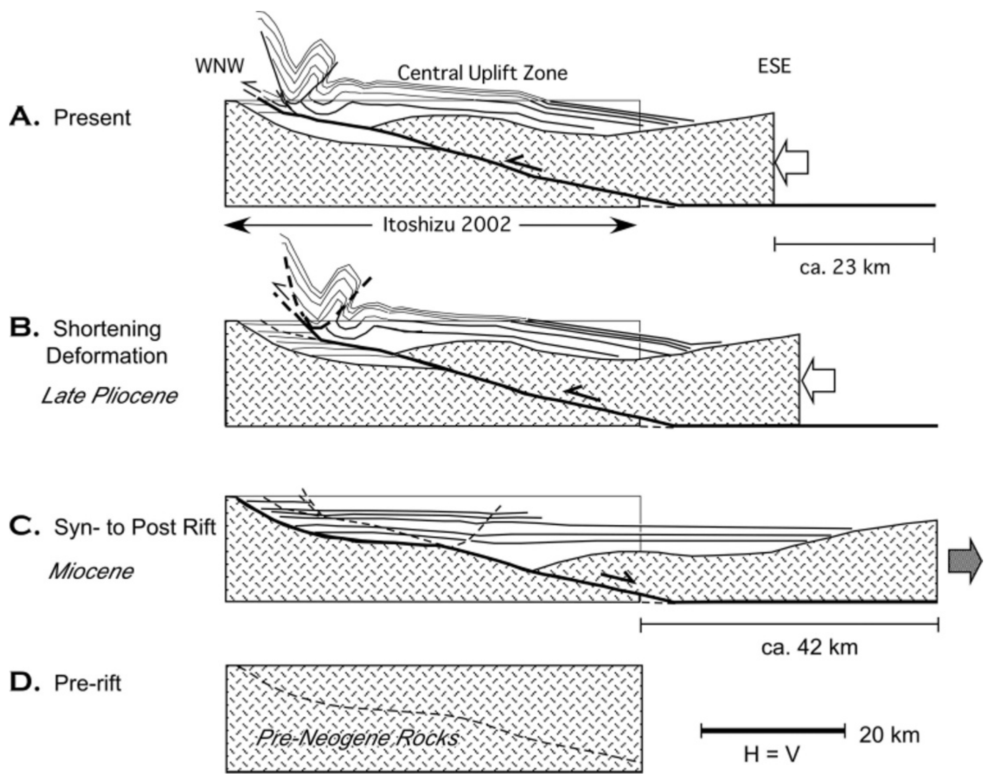

Fig. 7. Schematic diagram showing the evolution of the northern Fossa Magna after Sato *et al*. (2004a).

by Ogawa *et al*. (2002), the hypocentral distribution has tendency to concentrate between low and high resistivity area. The focal mechanisms of these earthquakes are strike-slip with WNW trending P-axis (Sakai, 2004). Including the northern Fossa Magna region, the most of the focal mechanisms in the back-arc side of the southern part of the northern Honshu shows the strike-slip type with WNW trending P-axis (Kosuga, 1999). However, active faults distributed in this region are dominated in reverse faults. This incompatibility suggests that the stress condition which generates large earthquakes associated with faulting along the pre-existing active-seismogenic source fault probably differ from the one of micro-earthquakes in steady state and/or stress build up processes.

The observed micro-earthquakes in the footwall, forming the NNW trending zone (Sakai, 2004), are possibly produced by slip of preexisting NNW trending fault system and/or triggered by migration of fluid to less permeable (more resistive) crust (e.g. Ogawa *et al*., 2001). However, we cannot find evidence showing the large vertical displacement along the estimated high-angle fault beneath the surface trace of the ISTL (Imai *et al*., 2004). It is reasonable to release the strike-slip components by slip on such high-angle fault. However, it seems to be very difficult to release the significant amount of WNW- trending strain by NNW-trending high-angle fault. Thus, we interpreted that the deeper extension of the ISTL active fault does not connect to this high angle-fault (Fig. 6).

6. Tectonic Model for the Evolution of Northern Fossa Magna Basin

The basin formation and subsequent inversion processes in the northern Fossa Magna basin can be explained using a simple model based on fault reactivation along the ISTL (Sato and Ikeda, 1999a; Sato *et al*., 2004a; Fig. 7). In this reconstruction ca. 42 km of Miocene extension is estimated (Fig. 7, C and D). The total amount of shortening since the late Neogene is estimated to be ca. 23 km. If the shortening started at 6–4 Ma, the averaged slip rate is calculated as 4–6 mm/y under a constant slip rate. This value is similar to the rate obtained by drilling and very shallow seismic reflection profiling across the toe of the thrust in northern part of the ISTL active fault system from the late Quaternary (4.7 mm/y; Matsuta *et al*., 2001).

In the northernmost part of the ISTL, the faulting has terminated since late Quaternary. In the northern part of northern Fossa Magna, the late Quaternary horizontal shortening accommodated along the western Nagano basin active fault system (Fig. 1). The shift of the location of late Quaternary faulting from the western end (ISTL active fault system) to the eastern end of the Northern Fossa Magna basin (western Nagano basin active fault system) is easily understood as the shortening deformation processes of the basin fill caused by the thrusting of the east-dipping master fault beneath the Central Uplift Zone (Elouai *et al*., 2004; Takeda *et al*., 2004).

7. Conclusions

The northern part of ISTL was formed as a low-angle normal fault in Miocene, bounding the western margin of the northern Fossa Magna rift basin. Due to the shortening deformation since late Neogene, the present ISTL active fault system was developed in the basin fill by basin inversion processes.

Low Vp, low Vp/Vs and low resistivity are observed beneath the folded zone of the northern Fossa Magna. Such crustal structure has potential to give significant amounts of control for seismicity and crustal deformation processes.

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