New Features of Island Arc Crust Inferred from Seismic Refraction/Wide-Angle Reflection Expeditions in Japan

Takaya IwasaKI, Toshikatsu Yoshii, Naoshi Hirata and Hiroshi Sato

Earthquake Research Institute, The University of Tokyo,
Yayoi 1-1-1, Bunkyo-ku, Tokyo 113-0032, Japan
e-mail: iwasaki@eri.u-tokyo.ac.jp

Abstract. Crustal studies by deep seismic profiling within the Japanese Islands have provided important constraints on the physical properties of the island arc crust. This paper presents representative features of crustal structure in Japan through a review over previous seismic refraction/wide-angle reflection expeditions. The upper crust in the Japanese Islands has a significant heterogeneity with a P-wave velocity ranging from 5.5 to 6.1 km/s. Lateral variations in the upper crustal velocity often occur across major tectonic lines or geological boundaries. The important finding from recent modern experiments is a “middle crust” situated in a depth range of 5–15 km with a velocity of 6.2–6.4 km/s. Most of shallow microearthquakes are concentrated in the upper or middle crust. The P-wave velocity in the lower crust is in a range of 6.6–6.9 km/s although it was estimated only for several profile lines. A high velocity value exceeding 7 km/s, as reported in continental crusts, is rare in the Japanese Islands. Lower crustal reflections are observed in many regions. Probably a “reflective lower crust” as found in continental regions also exists in the island arc crust although its origin may differ. The uppermost mantle beneath the Japanese Islands is characterized by a low Pn velocity of 7.5–7.9 km/s. Recent observations of the PmP phase indicate that the Moho is not a sharp boundary with a high velocity contrast, but a transition zone from the upper mantle to the lower crustal materials. The lateral velocity change in Pn velocity is evident in NE Japan. In the backarc side, such a change occurs in a narrow zone with 20–30 km width beneath the western coast of NE Japan.

1. INTRODUCTION

The Japanese Islands are located in the subduction zone along the western rim of the Pacific Ocean (Fig. 1). These islands are geologically divided into two parts: NE Japan, presently overriding the subducted Pacific Plate, and SW Japan, presently overriding the subducted Philippine Sea Plate. The backarc basin of the Sea of Japan was formed during a period of 20–14 Ma under an extensional stress regime (e.g. Sato, 1994). In the NE Japan Arc, the stress state was changed to EW compression at 4 Ma. The stress field in SW Japan, on the other hand, has been EW compression since 2–3 Ma.

The western part of Hokkaido is considered to be an extension of the NE Japan Arc. The central part of Hokkaido is recognized as a collision zone between the NE Japan Arc and the Kuril forearc sliver, now forming the southernmost part of eastern Hokkaido.
Fig. 1. Location map of seismic refraction experiments in 1950–1978. Stars and small dots indicate shot and receiver points, respectively. A–A': Oga-Kesennuma profile. B–B': Atsumi-Noto profile. C–C': Shakotan-Erimo profile.

Seismic activity in and around the Japanese Islands is extremely high as characterized by interplate earthquakes of M~8 and intraplate earthquakes of M~7. Recent microseismic observations revealed that crustal earthquakes are almost concentrated in a depth range of 0–15 km, while deeper events are occurring on seismic planes within the subducted plates (e.g. Hasegawa et al., 1978; Ishida, 1992).

Since the first observation of a quarry blast in 1950, crustal studies with controlled seismic sources have been intensively undertaken by the Research Group of Explosion Seismology (RGES). Their activities in early stage (1950–1978) were represented by refraction experiments for elucidating large-scale seismological features of the crust and upper mantle under the Japanese Islands (Aoki et al., 1972; Yoshii and Asano, 1972; Okada et al., 1973, 1979). As stated in the next section, the most important finding of these experiments is lateral structural variation across the Japanese Islands.
Since 1979, seismic refraction/wide-angle reflection experiments have been conducted under the national project of "the Earthquake Prediction Program" (Fig. 2). The experiments in 1979–1988 were focused on complicated upper crustal structures and their relations to major faults and tectonic lines by setting rather short profile lines (50–70 km). With the increase of interesting results on lower crustal structures in the continental regions (summarized in volumes edited by Barazangi and Brown, 1986a, b), the seismic experiments after 1989 were designed to determine the entire crustal structures with longer profiles (150–200 km). Data collection techniques were improved very much in the last decade owing to the development of digital recording systems.

The refraction/wide-angle reflection surveys mentioned above have provided good constraints on seismic velocities and relatively large-scale layer geometry within the crust and upper mantle. Their resolving powers, however, are insufficient for delineating detailed structural inhomogeneities such as distribution patterns of mid-crustal reflectors and fault geometry to the deep crust. A seismic reflection
method, which has been a major tool for crustal studies in the continental regions (Barazangi and Brown, 1986a, b), had not been undertaken on the Japanese Islands until 1986 (Asano et al., 1987). The first fine crustal images by the seismic reflection method were obtained for the Hidaka collision zone, Hokkaido (Arita et al., 1998; Ito et al., 1998; Ito, 2000). They succeeded in mapping a thrust fault and lower crustal delamination associated with the arc-arc collision ongoing in central Hokkaido. These studies showed that the effectiveness of seismic reflection method even for highly complicated island arc regions.

In 1997, we started a new multidisciplinary project, "Deformation Processes of Island Arc Crust". The objective of this project is to investigate the physical properties of island arc crust through well organized expeditions of seismic refraction method, seismic reflection method and earthquake observation, and to clarify the relation between structural heterogeneity and crustal activity. This project has already provided interesting crustal images in the NE Japan Arc and Hokkaido Island for the last three years (Iwasaki et al., 2001).

2. SEISMIC STRUCTURES OBTAINED FROM EARLY EXPERIMENTS (1950–1978)

The most important finding from early experiments in 1950–1978 is the large-scale crust and upper mantle structures across the Japanese Islands (Fig. 1). Particularly, the lateral variations in Pn velocity were investigated through a number of seismic observations of underwater shots. Figure 3 shows a crustal model across the NE Japan Arc (Oga-Kesennuma Profile, see Fig. 1) by Yoshii and Asano (1972) and Okada et al. (1979). The most important feature in this model is an anomalously low Pn velocity (~7.5 km/s) under the NE Japan Arc. The Pn velocity becomes high both in the forearc and backarc sides of NE Japan. The crust of the NE Japan Arc is 30 km thick, composed of upper and lower layers with P-wave velocities of 5.9 and a 6.6 km/s, respectively. In the western part of this profile, we see remarkable crustal thinning associated with the Miocene

![Fig. 3. Velocity structure model across the NE Japan Arc from early experiments (Yoshii and Asano, 1972; Okada et al., 1979).](image-url)
opening of the Sea of Japan. The structure in Fig. 3 has been recognized as a
typical island arc crustal model for about 30 years. Further crustal studies in
central Japan (Atsumi-Noto profile, Aoki et al., 1972) and in Hokkaido (Shakotan-
Erimo profile, Okada et al., 1973) also indicate a relatively low Pn velocity of
7.5–7.9 km/s.
Upper crustal P-wave velocities obtained in the early experiments are in the
range of 5.9–6.1 km/s, from which we cannot recognize a significant lateral
heterogeneity due to their low resolving powers. The lower crustal velocity was
measured to be 6.6–6.8 km/s for several profiles. Hashizume et al. (1981)
observed a number of reflections within the crust in SW Japan. This probably
represents high reflectivity in the lower crust as found in the continental crust
(e.g. Barazangi and Brown, 1986a, b). They also observed many reflections
around the PmP phases, which were interpreted as multi-path reflections from a
Moho with irregular geometry.

3. UPPER CRUSTAL STRUCTURE

With the development of experimental techniques after 1979, more precise
and reliable knowledge is accumulated on the upper crustal features. Figure 4
shows several velocity structures obtained using modern techniques of ray-
tracing and synthetic seismograms. Figure 5 shows composite travel-time plots
of P-wave obtained from the experiments during 1979–1988 (Yoshii, 1994). The
upper crust in Japanese Islands is highly heterogeneous with a velocity ranging
from 5.5 to 6.1 km/s. Drastic velocity changes sometimes occur across major
tectonic lines. For example, more than 15% velocity change is reported across the
Akaishi tectonic line in southernmost part of central Japan (Matsu’ura et al.,
sampled the crust down to 15–20 km depths from which a “middle crust” with a
P-wave velocity of 6.2–6.4 km/s was widely found (Fig. 4). This is probably a
common feature for the Japanese Islands.

The seismic attenuation is large in the upper crust of the Japanese Islands.
Iwasaki et al. (1994, 1998) directly estimated Qp values from the wide-angle data
in NE Japan and Hokkaido. According to their results, Qp values are 100–200 in
a frequency range of 5–15 Hz, indicating high degree of structural inhomogeneity.
Layer geometry within the crust is another factor controlling observed amplitude
behaviours. In western Hokkaido, for example, the first arrival cannot be recognized
beyond an offset of 40 km even for a shot of large charge (700 kg) due to the
complicated velocity structure associated with the arc-arc collision ongoing in
central Hokkaido (RGES, 1993; Iwasaki et al., 1998).

4. LOWER CRUSTAL STRUCTURE

The lower crustal P-wave velocity obtained from the previous travel-time
analyses is ranging from 6.6 to 6.7 km/s. Their estimation errors, however, are
large because the first arrivals from the lower crust usually appear in a limited
offset range. In order to improve the accuracy of estimation, amplitude data of
Fig. 4. Representative crustal models in the Japanese Islands deduced from seismic expeditions after 1979. Locations of the individual profiles are shown in Fig. 2. (a) Crustal structure model in Hokkaido (Iwasaki et al., 1998). (b) Crustal structure model in the eastern part of NE Japan (Iwasaki et al., 1994). (c) Crustal structure model across NE Japan (Iwasaki et al., 2001). (d) Crustal structure model in the southernmost part of NE Japan (Moriya et al., 1995). (e) Crustal structure model in central Japan (Takeda, 1997). (f) Crustal structure model (Takeda, 1997). (g) Crustal structure model in and around the source region of the 1995 Kobe earthquake (Piao et al., 1996).
Fig. 4. (continued).

Fig. 5. Composite travel-time plot of 1979–1988 experiments (Yoshii, 1994). The reduction velocity is $6 \text{ km/s}$. 
Fig. 6. Examples of record sections with a number of crustal reflections. The reduction velocity is 6 km/s. Each trace is bandpass filtered (3–15 Hz), and normalized with its maximum amplitude. (a) Record section from the 1989 experiment in SW Japan. Note the reverberation from the lower crust. (b) Record section from the 1990 experiment in NE Japan. Note the reverberation from the uppermost mantle.

lower crustal reflections should be incorporated to the modelling. Such an amplitude analysis for the 1990 experiment in NE Japan showed that a relatively high velocity (6.9–7 km/s) layer is situated at the base of the lower crust (Iwasaki et al., 1994). However, a lower crustal velocity exceeding 7 km/s, as reported in shields, platforms or passive margins (Holbrook et al., 1992), has not been reported except for one case of central Japan (Takeda, 1997, see Figs. 4(e) and (f)).

Lower crustal reflections are observed in many regions of eastern Hokkaido, NE Japan, central Honshu, SW Japan and eastern Kyushu (Takeda 1997; Iwasaki et al., 1998; RGES 1999a, b, see Fig. 6). Waveforms from these reflectors are not pulssive but consists of reverberations with 2–3 sec duration time (Fig. 6). Such a feature is interpreted by a laminated lower crustal model composed of thin (0.3–1 km) alternative layers with low (6.0–6.3 km/s) and high (6.5–7 km/s) velocities.
(Takeda, 1997; Iwasaki et al., 1998). We think these features indicate “reflective lower crust” as is widely observed in continental regions.

The origin of the high reflectivity in the lower crust is not clarified yet. As a possible reason, Mooney and Meissner (1992) pointed out the magmatic intrusion and the metamorphic shearing. The former origin is plausible for the case of central Japan because the lamination pattern is found in a thermally active region. Another possible explanation is fluid within the crust. In the eastern part of NE Japan, local reflectors are situated at the upper boundary of the conductivity zone. Ogawa (1993) interpreted these reflectors to be formed by trapped fluid.

Usually, most of microearthquakes are occurring within the upper or middle crust. The very low seismic activity in the lower crust clearly indicates its ductile properties probably controlled by the thermal regime.

5. MOHO BOUNDARY AND UPPERMOST MANTLE

The Pn velocity under the Japanese Islands is estimated to be low (7.5–7.9 km/s). The amplitude of PmP phase from the recent experiments is usually not large (Fig. 6), supporting a relatively low Pn velocity. As shown in Fig. 6(b), the PmP phase is sometimes not pulsive but has a duration time of 2–3 sec. This feature indicates that the Moho is not a sharp boundary with a high velocity contrast, but has a structure corresponding to a transition zone from the upper mantle to the lower crustal materials.

The lateral variation in Pn velocity is evident across the NE Japan Arc. The old experiments indicates high Pn velocities (>8 km/s) beneath the Pacific Ocean and the Sea of Japan. This is also supported by recent ocean bottom seismographic observations (Nishizawa and Asada, 1999; Nishisaka, 2000). The intensive seismic expedition in 1997 indicates that the Pn velocity change in the backarc side occurs in a 20–30 km wide transition zone located beneath the western coast of NE Japan (Nishisaka, 2000). The physical explanation of this velocity variation is still enigmatic. A low upper mantle velocity was also found beneath active volcanoes using a tomographic method (e.g. Zhao et al., 1992). Zhao et al. (1992, 1997) interpreted this velocity lowering as the magmatic intrusion caused by the dehydration process in the subducted plate and/or ascending flow induced by the convection within the wedge mantle. Although the thermal regime by such mechanisms plays an important role for the velocity change, it may not explain sufficiently such a sharp transition zone.

6. SUBDUCTED PLATE

As described in Section 1, the subducted plates are traced by deep seismic planes. In SW Japan, the Philippine Sea Plate is situated in shallower depths of 20–70 km (Ishida, 1992). Therefore, SW·Japan is a good field to study the structure and physical properties of the subducted plate with the onshore seismological observations. Actually, the wide-angle seismic experiments in 1985 and 1988 clearly recorded reflection from the subducted plate (Yoshii, 1991; Matsu‘ura et al., 1991). Yoshii (1991) succeeded in imaging the subducted
plate by applying a normal moveout (NMO) technique of reflection seismology to the wide-angle data. Because of the high power of the dynamite source and the high quality data, we see reflections from the plate in two-way travel time (t.w.t.) of 10–15 sec (Fig. 7).

7. NEW PROJECT

Since 1997, we started a new project of "Deformation Processes of Island Arc Crust". The objective of this project is to investigate the physical properties of island arc crust through well organized expeditions of controlled source seismic survey and microseismic observation and to clarify the relation between structural heterogeneity and crustal activity.

An extensive refraction/wide-angle experiment across NE Japan in 1997 and 1998 provided new images of the volcanic arc crust (Fig. 2). A wide-angle seismic survey was carried out on both onshore and offshore profiles to elucidate the structural variation across the NE Japan Arc (Iwasaki et al., 2001). In the middle of the onshore profile, namely the backbone range of NE Japan, seismic reflection surveys were also undertaken for the precise mapping of major active fault systems. Furthermore, a very dense seismic network was operated to study microearthquake activity and 3D crustal structure by a tomographic approach (Matsubara et al., 1999).
Fig. 8. Active fault system and microseismic activity beneath the 1997 profile line across NE Japan. Fault geometry by a seismic reflection survey (Sato et al., 2001) and microearthquake distribution by a dense seismic network (Matsubara et al., 1999) are shown on the crustal structure model by Iwasaki et al. (2001). Note a good correlation between the fault and the seismicity. Most of the events are concentrated within the upper 12–15 km of the crust.

In Fig. 8, the results of seismic reflection surveys (Sato et al., 2001) and microearthquake observations (Matsubara et al., 1999) are superimposed on the crustal structure model of the refraction/wide-angle reflection profile (Iwasaki et al., 2001).

In spite of the present compressional stress regime in the surveyed area, the crustal structure obtained clearly recorded the deformation under the extensional tectonics associated with the Miocene backarc spreading. The eastern part of the profile, which has been a stable forearc block since Miocene, is characterized by a less deformed upper crust of higher P-wave velocity (6.0–6.1 km/s) and a reflective lower crust. The total crustal thickness is 32–33 km. The western part of the profile is covered with intensively deformed Tertiary sedimentary layers. The upper and lower crustal velocities are 5.8–5.9 and 6.6–6.8 km/s, respectively. The crustal thickness attains its maximum of 35 km nearby the present volcanic front, where volcanic activity has continued since Miocene. The crustal thickness decreases to 27 km at the western end of the profile. This westward crustal thinning begins at the eastern edge of the backbone range, almost coincident with the eastern limit of the Miocene faults, which was probably controlled by the crustal stretching during the backarc spreading.

The seismic reflection survey in the middle part of the profile revealed a clear image of an active fault system composed of “V-shaped” two listric planes. These fault planes become almost horizontal at a depth of 12 km, beneath which a number of reflectors are developed. It is also noted that most of the events are concentrated in the upper 12–15 km of the crust. These results strongly indicate differences in rheological properties between the upper and lower crusts. We also see a good correlation between the fault geometry and the seismic activity.
8. CONCLUSIONS

The crustal structure of the Japanese Island has been intensively investigated since 1950. With the development of experimental techniques, new features of the island arc crust have been revealed. The upper crust shows a significant heterogeneity with a P-wave velocity ranging from 5.5 to 6.1 km/s. Lateral variation of the velocity often occurs across major tectonic lines and/or geological boundaries. The recent expeditions indicate the existence of a "middle crust" whose velocity is 6.2–6.4 km/s. This is probably a common feature for the Japanese Islands.

The lower crustal P-wave velocity ranges from 6.6 to 6.9 km/s although it was constrained only for several profiles. A velocity value exceeding 7 km/s, as reported in tectonic environments of shield, platform and passive-margin (Holbrook et al., 1992), is rare in the Japanese Islands. Lower crustal reflections are observed in many regions of eastern Hokkaido, NE Japan, central Japan, SW Japan and eastern Kyushu (Iwasaki et al., 1994, 1998; Takeda, 1997; RGES, 1999a, b). Probably a "reflective lower crust" as in many continental areas is also existing in the island arc crust although its origin may differ.

The uppermost mantle beneath the Japanese Islands is characterized by a low Pn velocity of 7.5–7.9 km/s. Recent observations of the PmP phase indicate that the Moho is not a sharp boundary with a large velocity contrast, but forms a transition zone from the upper mantle to the lower crustal materials. The lateral velocity change in Pn velocity is evident in NE Japan. Particularly, in the backarc side, such a change occurs in a narrow zone with 20–30 km width beneath the western coast of NE Japan.

Acknowledgements. The authors wish to express their sincere thanks Dr. Yukio Fujinawa, National Research Institute for Earth Science and Disaster Prevention, for offering an opportunity to publish our manuscript. They also thank to Prof. Dapeng Zhao, Ehime University for his valuable comments and critically reading of the manuscript.

REFERENCES


Hashizume, M., K. Ito and T. Yoshii. Crustal structure of south-western Honshu, Japan and their


Ogawa, Y., Deep crustal resistivity structure revealed by wideband magnetotellurics-Tohoku and Hokkaido region, Ph.D. Thesis, the University of Tokyo, 1993.


Takeda, T., Detailed crustal structure in central Japan as revealed from reanalysis of wide-angle data. Master Thesis, Graduate School of Science, the University of Tokyo, 1997 (in Japanese).


