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Crustal structure of southwest Japan, revealed by the integrated seismic experiment Southwest Japan 2002

Tanio Ito [a,*], Yuji Kojima [b], Shuichi Kodaira [c], Hiroshi Sato [d], Yoshiyuki Kaneda [c], Takaya Iwasaki [d], Eiji Kurashimo [d], Noriko Tsumura [a], Akira Fujiwara [e], Takahiro Miyauchi [a], Naoshi Hirata [d], Steven Harder [f], Kate Miller [f], Akihiro Murata [g], Satoshi Yamakita [h], Masazumi Onishi [i], Susumu Abe [i], Takeshi Sato [c], Takeshi Ikawa [i]

[a] Department of Earth Sciences, Graduate School of Science, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[b] Daiwa Exploration & Consulting Co., Ltd, 2-2-11 Furuishiba, Koto-ku, Tokyo 135-0045, Japan
[c] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-machi, Yokosuka 237-0061, Japan
[d] Earthquake Research Institute, University of Tokyo, 1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[e] Geosys Inc., 1-5-18 Otsuka, Bunkyo-ku, Tokyo 112-0012, Japan
[f] Department of Geological Sciences, University of Texas, El Paso, 500 W University Ave, El Paso, Texas 79968-0555, USA
[g] Faculty of Integrated Arts and Sciences, Tokushima University, 1-1 Minami Josanjima, Tokushima 770-8502, Japan
[h] Faculty of Education and Culture, Miyazaki University, 1-1 Gakuenkibanadai-nishi, Miyazaki 889-2192, Japan
[i] JGI, Inc., 1-5-21 Otsuka, Bunkyo-ku, Tokyo 112-0012, Japan

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ABSTRACT

A multi-purpose seismic experiment named the 2002 integrated seismic experiment Southwest Japan was conducted in 2002 along a more-than-240-km-long line across southwest Japan from the Pacific coast to the Japan Sea coast. Its profile provides the first crustal-scale cross section across the Japanese island arc, which highlights a number of significant points related to the structural development of the arc. Major outstanding points are that the Japanese island arc is composed of two completely different crusts juxtaposed by the Median Tectonic Line (MTL), and that the MTL started its activity associated with lower crustal thinning and formation of an upper crustal-scale half-graben in Late Cretaceous.

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1. Introduction

Southwest Japan is an island arc system with the Nankai trough as a trench and the Japan Sea as a back-arc sea (Hashimoto, 1991). The Philippine Sea (PHS) plate is subducting beneath southwest Japan, which belongs to the Eurasian plate (Fig. 1). The basement of southwest Japan is composed mainly of late Paleozoic to Neogene accretionary complexes, but the deep structure is unknown due to paucity of available seismic reflection data. Yoshikawa et al. (1987) obtained the first seismic reflection profile of the Median Tectonic Line (MTL), the most significant fault in Japan, which divides the Japanese island arc into the Inner (Japan Sea-side) and the Outer (Pacific-side) zones. That study dispelled the traditional idea that the MTL dips at a high angle, and demonstrated clearly a gentle northward dip down to about 2-km depth. Since that pioneering work, a number of influential seismic reflection experiments across the MTL have improved dramatically our knowledge of the crustal structure of the Japanese island arc (e.g., Yoshikawa et al., 1992; Ito et al., 1996; Kawamura et al., 2003.).

Based on these groundbreaking experiments conducted since the late 1980s, a multi-purpose seismic experiment was designed along the more-than-240-km-long line across southwest Japan from the Pacific coast of Shikoku to the Japan Sea coast of Chugoku (Fig. 1). The experiment, named the 2002 integrated seismic experiment Southwest Japan (hereafter Southwest Japan 2002), was conducted in 2002 as a collaborative project involving the Earthquake Research Institute (ERI) of the University of Tokyo, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Chiba University, and the University of Texas, El Paso (Iwasaki, 2006). One of the major goals of the experiment was to obtain a crustal profile of southwest Japanese island arc with the subducting PHS Plate. The southern end of the profile connects with another profile obtained by the JAMSTEC experiment in 1999 (Kodaira et al., 2002). Important information in the experiment Tottori 2001 (Tottori Prefecture, 2002) can be also

* Corresponding author.
E-mail address: tito@earth.s.chiba-u.ac.jp (T. Ito).

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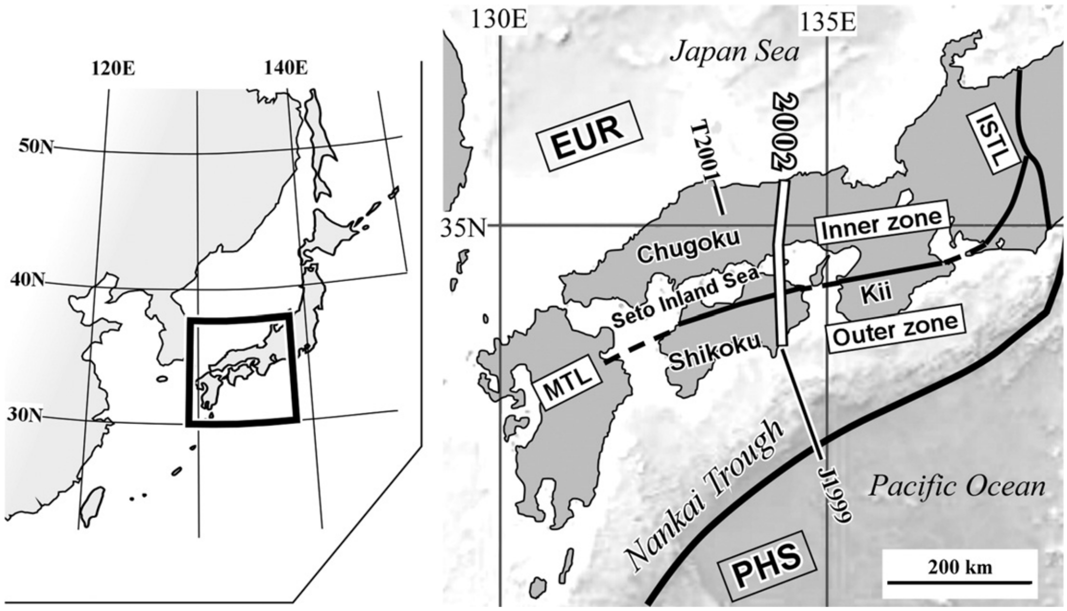

Fig. 1. Seismic line of Southwest Japan 2002 indicated by the outline letter 2002. Seismic line of JAMSTEC experiment in 1999, J1999. Seismic line of Tottori Prefecture in 2001, T2001. MTL, Median Tectonic Line. ISTL, Itoigawa–Shizuoka Tectonic Line. EUR, Eurasian plate. PHS, Philippine Sea plate.

projected onto the profile. Thus a whole crustal-scale cross section can be constructed from the Nankai trough to the Japan Sea coast crossing southwest Japan.

In this paper we present the results and interpretations of Southwest Japan 2002, and discuss their significance.

2. Geologic setting

The seismic line of Southwest Japan 2002 runs from the Muroto Peninsula across the Seto Inland Sea to the Japan Sea coast, transecting the Inner and the Outer zones which are juxtaposed at the MTL. The surface geology is shown in Fig. 2.

2.1. Outer zone

The Outer zone is characterized by an along-arc zonal arrangement of geological belts, namely the Sambagawa, the Chichibu, the Northern Shimanto, and the Southern Shimanto belts from north to south, which have different ages and lithologies. The Sambagawa belt is composed mainly of the high P/T Sambagawa metamorphic rocks (pelitic, and psammitic schists, and greenschist) derived probably from a Jurassic to Cretaceous accretionary complex. The Chichibu belt is composed of the Chichibu supergroup whose main constituent is a Jurassic accretionary complex. Between the Sambagawa and the Chichibu belts, occur the Mikabu green rocks of gabbro-peridotite complex with middle Jurassic to early Cretaceous chert (Faure et al., 1991; Sakakibara et al., 1993). The Northern Shimanto and the Southern Shimanto belts consist of the Cretaceous to early Paleogene Northern Shimanto and the middle Paleogene to the early Miocene Southern Shimanto groups, respectively. Both groups are made up of accretionary complexes with coherent and mélange units. The coherent unit consists mainly of alternating beds of sandstone and mudstone, and subordinately of chert and green rock beds. In contrast, the mélange unit consists mostly of muddy matrix dominant mélange with the fragments of abundant chert and green rocks. Both units are structurally repeated in an alternating sequence by north-dipping thrusts and form an accretionary structure. An Albian to Cenomanian coherent, a Santonian to Campanian mélange, a Campanian to Maastrichtian coherent, and a Maastrichtian to Paleocene mélange units are arranged structurally downward in the northern Shimanto group. In the southern Shimanto group, an Eocene to Oligocene coherent and an Oligocene to early Miocene mélange units are arranged structurally downward (Muramatsu, 1986; Yamakita's unpublished data).

Most of these belts are bounded by major north-dipping boundary faults: the Butsuzo Tectonic Line (BTL) along which the shallower Chichibu supergroup and the deeper Sambagawa metamorphic rocks are thrust over the Northern Shimanto group; and the Aki Fault (AF) along which the Northern Shimanto group is thrust over the Southern Shimanto group. The Southern Shimanto group is thought to structurally overlie a middle Miocene to the present accretionary complex along a fault whose surface trace runs off Shikoku. The surface geology suggests that the Sambagawa metamorphic rocks are gently folded and form a broad anticlinorium, and that Chichibu supergroup overlies both the Sambagawa metamorphic rocks and the Northern Shimanto group forming a broad syncline.

2.2. MTL

The sense of lateral motion along the MTL has changed repeatedly in response to plate tectonic setting since its birth in about 100Ma (Takagi and Shibata, 2000). The net displacement probably reached several hundreds of kilometers in a left-lateral sense (Yamakita and Otoh, 2000). Recent seismic profiling studies have revealed that the MTL dips northward at about 40° down to about 10km depth (Ito et al., 1996; Kawamura et al., 2003). As the deeper structure of the MTL has not been revealed yet, still the MTL as a whole is generally believed to be vertical or subvertical as proposed by Fitch (1972).

2.3. Inner zone

The Inner zone is composed of the Ryoke belt in the Seto Inland Sea area, and the nappe group in Chugoku (Hayasaka, 1987; Isozaki and Maruyama, 1991; Ishiwatari, 1991).

The Ryoke belt is composed of the Ryoke metamorphic rocks and Cretaceous granitic rocks. The Ryoke metamorphic rocks are originally derived mainly from alternating beds of sandstone and mudstone with chert, which constitute a Jurassic accretionary complex. They

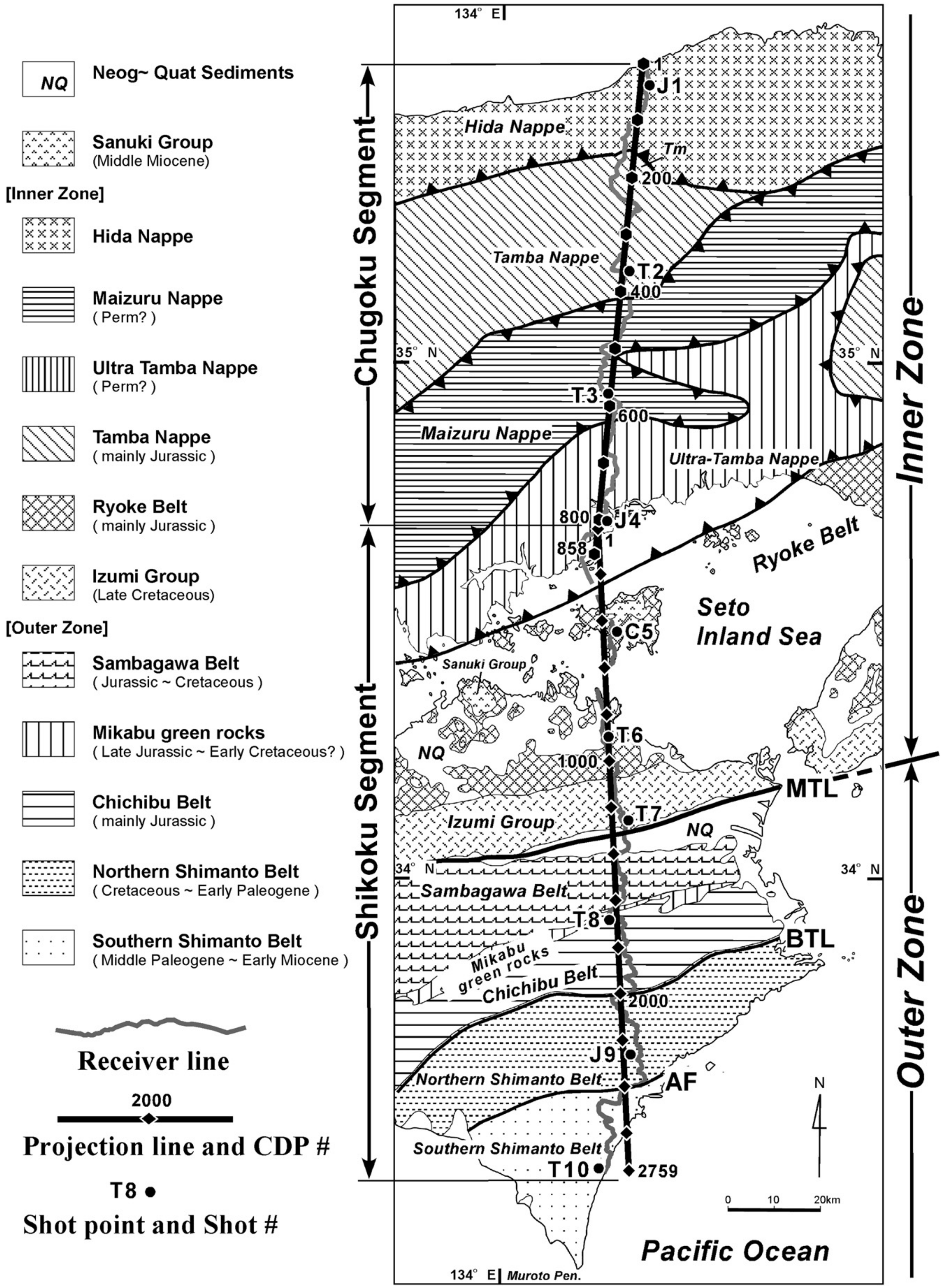
NQ
Neog~ Quat Sediments
Sanuki Group
(Middle Miocene)
[Inner Zone]
Hida Nappe
Maizuru Nappe
(Perm?)
Ultra Tamba Nappe
(Perm?)
Tamba Nappe
(mainly Jurassic)
Ryoke Belt
(mainly Jurassic)
Izumi Group
(Late Cretaceous)
[Outer Zone]
Sambagawa Belt
(Jurassic ~ Cretaceous)
Mikabu green rocks
(Late Jurassic ~ Early Cretaceous?)
Chichibu Belt
(mainly Jurassic)
Northern Shimanto Belt
(Cretaceous ~ Early Paleogene)
Southern Shimanto Belt
(Middle Paleogene ~ Early Miocene)
Receiver line
2000
Projection line and CDP #
T8
Shot point and Shot #
Chugoku Segment
Shikoku Segment
Inner Zone
Outer Zone
134° E
35° N
34° N
Hida Nappe
Tm
Tamba Nappe
Maizuru Nappe
Ultra-Tamba Nappe
Ryoke Belt
Seto
Inland Sea
Sanuki Group
NQ
Izumi Group
Sambagawa Belt
Mikabu
green rocks
Chichibu Belt
Northern Shimanto Belt
Southern Shimanto Belt
Pacific Ocean
Muroto Pen.
MTL
BTL
AF
J1
T2
T3
J4
C5
T6
T7
T8
J9
T10
1
200
400
600
800
858
1000
2000
2759
N
0
10
20km

Table 1
Receiving and CDP systems.

		Chugoku Segment	Shikoku Segment	
			Seto Inland Sea	Shikoku
Receiver Type		Off-line Geophone (L-22D 2.2 Hz)	On-line Geophone (GS-11D 4.5 Hz) On-line Hydrophone (P-350 10 Hz)	Off-line Geophone (Texan 4.5 Hz)
Receiver Interval		250 m (average)	50 m (partly 25 m)	120 m (average)
Sampling Rate		4 ms		
Total No. of Receivers		409	1108	805
CDP	No.	1 to 858	1 to 2759	
	Interval	125 m	50 m	

Table 2
Dynamite shot data.

Segment	Shot point	Size	Segment	Shot point	Size
Chugoku	J1	500 kg	Shikoku	T6	100 kg
	T2	100 kg		T7	50 kg
	T3	300 kg		T8	300 kg
	J4	500 kg		J9	500 kg
Shikoku	C5	100 kg		T10	100 kg

were formed under low P/T metamorphic conditions due to the huge intrusion of Cretaceous granitic rocks. The late Late Cretaceous Izumi group unconformably overlies the southernmost border of the Ryoke belt along the MTL. The group was deposited within a pull-apart basin associated with left-lateral activity of the MTL in Late Cretaceous (Miyata, 1990; Miyata and Iwamoto, 1994).

The four nappes in Chugoku have low-angle basal contacts. In the southern half of Chugoku, in structurally ascending order, are the Tamba nappe chiefly a Late Triassic to Jurassic accretionary complex; the Ultra-Tamba nappe chiefly a Permian accretionary complex; and the Maizuru nappe, probably composed of Permian island arc materials with oceanic components. The Tamba nappe is composed mainly of alternating beds of sandstone and mudstone with chert, which correspond to the metamorphosed strata of the Ryoke belt. The Ultra-Tamba nappe consists chiefly of the alternating beds of sandstone and mudstone, sandstone, chert and limestone. On the contrary, the Maizuru nappe is formed mainly of a complex of gabbro and granitic rocks, and shallow marine sediments. The Hida nappe, probably a fragment of the Eurasian continental crust is thrust over the Tamba nappe in northernmost of Chugoku. Neogene volcaniclastic rocks occur in the coastal area of the Japan Sea as the syn-rift sediments associated with the opening of the Japan Sea. There is no geological information beneath the Tamba nappe.

Subaerial high-Mg andesitic lava and pyroclastics of the middle Miocene Sanuki group occur in and around the Seto Inland Sea area. This andesitic volcanism formed the Setouchi volcanic belt (Tatsumi, 2001).

3. Seismic profile across southwest Japan

3.1. Framework of Southwest Japan 2002

The receiver line is composed of two segments, referred to below as the Chugoku and the Shikoku segments (Table 1). The Chugoku segment transects Chugoku from the Japan Sea coast to the Seto Inland Sea coast, whereas the Shikoku segment extends from the Seto Inland Sea and Shikoku (Fig. 2). The former crosses gently-sloping hilly areas in central Chugoku, whereas the latter crosses rugged mountainous areas in the southern half of Shikoku. The receiver interval of the Chugoku segment is 250m on average. The receiver interval of the Shikoku segment is smaller: (i) 50m on islands and in coastal areas, (ii) 25m in the Seto Inland Sea, and (iii) 120m on average in Shikoku. In total, 2212 receivers were used along the 245-km-long line.

The receiver line is somewhat crooked in hilly and rugged mountainous areas, and straight across the Seto Inland Sea. It was impractical to use conventional seismic reflection vibrators and instead ten dynamite shots of 50–500kg were detonated at intervals of about 30km with all receivers active (Table 2).

3.2. Integrated profile

Seismic data processing was conducted according to the flow chart illustrated in Fig. 3. For the left-hand processing sequence, normal move-out (NMO) correction and frequency domain-type (FD-type) time migration were applied to each shot gather, not as well as usual common-depth-point (CDP) stacking method. Then, a single-fold seismic profile along the projection line (CDP line) was created by selecting seismic traces (usually deleting far-offset traces) as an alternative to CDP stacking, which did not work properly due to the sparse shot interval. Single-fold seismic profiles were paneled together and integrated into a reflection image of the whole profile. Finally, the integrated seismic section was converted to the depth domain. In order to enhance reflection events appearing on the seismic section, a 3–20Hz bandpass filter and F-X prediction filter were applied before and after NMO correction, respectively. It has already been demonstrated that a single-fold profile such as that created here is adequate to reveal clear subsurface images of major boundary faults (Kawamura et al., 2003). The right-hand processing sequence also involved refraction analyses (Kurashimo et al., 2003); the data from the refraction analyses were very useful for the reflection analyses in the left-hand processing sequence.

The integrated profile of the Southwest Japan 2002 is presented in Fig. 4 as a time migrated section and in Fig. 5 as a depth section. Conventional CDP numbers for this method are defined along the projection line at intervals of 125m for the Chugoku segment, and of 50m for the Shikoku segment (Fig. 2). The processing method has been in detail reported for the Shikoku segment in another paper (Sato et al., 2005). It is noteworthy that both profiles are characterized by a contrast between highly reflective domains and poorly reflective ones. As there are no marked contrast differences between the time and the depth sections, we limit the analyses that follow to the depth section. Close inspection of Fig. 5 reveals the following observations: 1) Reflective domains composed of dense laminations are generally elongated parallel to their laminations; 2) Reflective domains tend to be aligned to form a reflective zone; 3) Most of the lower portions of the reflective domains change gradually into poorly reflective domains. For later interpretation, the prominent upper boundaries of the reflective domains are indicated in Fig. 6; where these domains exhibit clear and continuous lower boundaries, those are also indicated.

4. Interpretation

Three kinds of supplementary data are very useful to interpret Fig. 6 — surface geology, seismic refraction, and conventional seismic

Fig. 2. Receiver and projection lines of Southwest Japan 2002 and the surface geology along the lines. The surface geology of Shikoku and Seto Inland Sea is simplified after Geological Survey of Japan (1992). The surface geology of Chugoku is compiled mainly from Isozaki and Maruyama (1991) and Ishiwatari (1991). Cretaceous to Paleogene granitic rocks and welded tuff, and Paleogene to Recent sedimentary rocks in Chugoku are omitted for better display of the nappe structure. MTL, Median Tectonic Line. BTL, Butsuzo Tectonic Line. AF, Aki Fault.

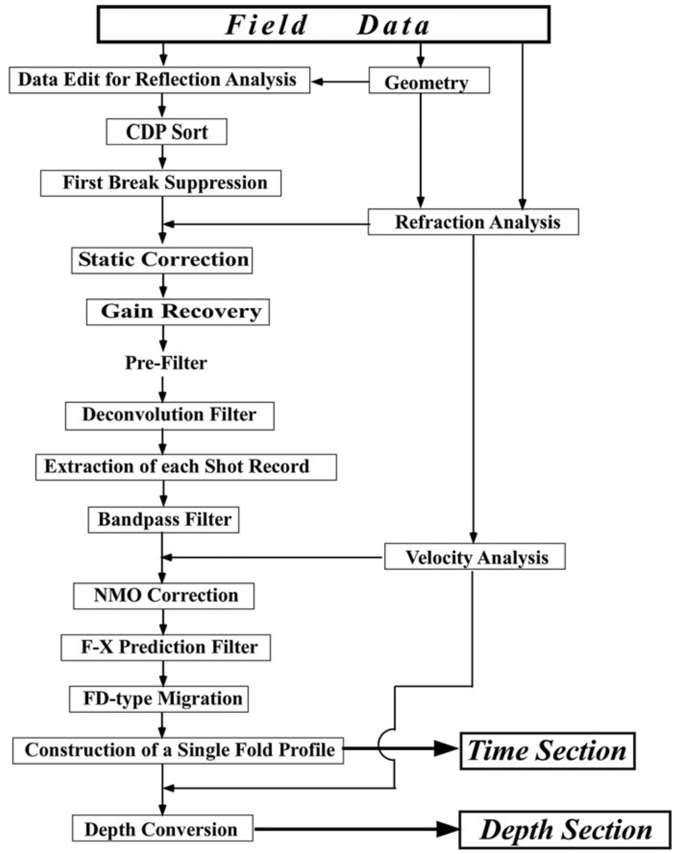

Fig. 3. Flow chart of processing in this study.

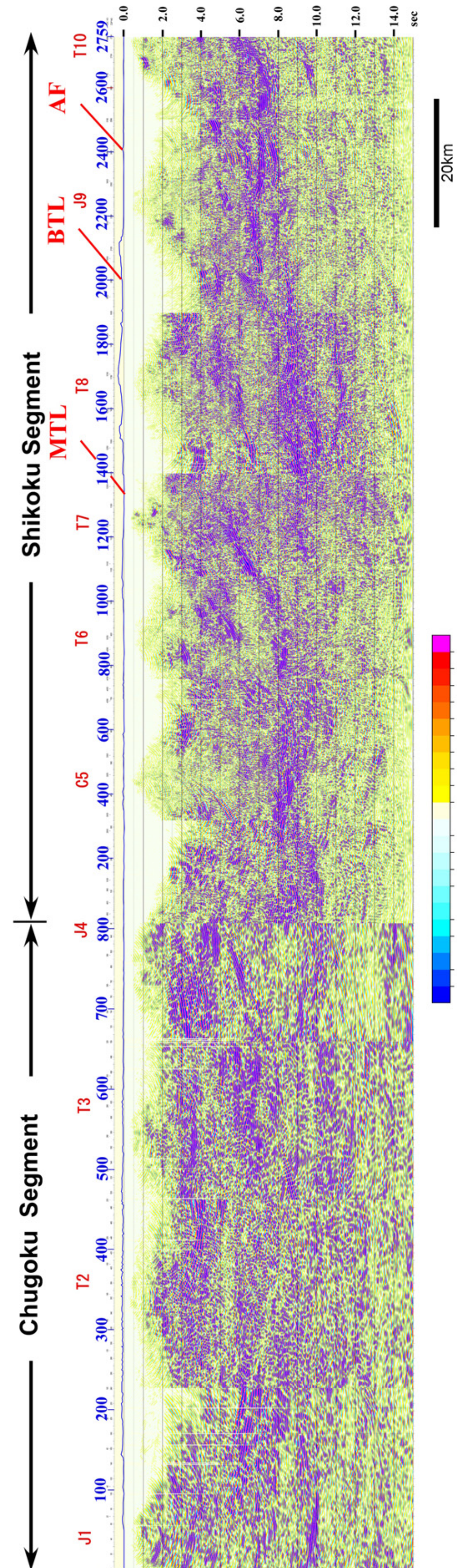

Fig. 4. Time migrated section along the projection line of Southwest Japan 2002. Red numbers, such as J1, indicate shot points in Fig. 2. Abbreviations of fault names are the same as those in Fig. 2.

reflection. The surface geology is illustrated in Fig. 2, the seismic refraction data were presented by Kurashimo et al. (2003), and conventional seismic reflection data were collected by Ito et al. (1996) that focused on the MTL very close to the projection line of Southwest Japan 2002 and by Matsuoka (2000) for the BTL in west Kii, about 100km east of the seismic line. A comparison between the reflections illustrated in Fig. 6 and the velocity structure (Kurashimo et al., 2003) is presented in Fig. 7.

4.1. Southern half of the Shikoku segment (south of the MTL)

The basic interpretation for the southern half of the Shikoku segment – south of the MTL – was performed for the Outer zone by Sato et al. (2005) using the results of Ito et al. (1996), Matsuoka (2000), and Kawamura et al. (2003). We briefly review Sato et al.'s (2005) three key results.

1) The R1, the R2 and the R4 reflections correspond to the MTL, the deeper part of the BTL, the deeper part of the AF, respectively;
2) The reflective zone between the R1 and the R2 reflections corresponds to the Sambagawa metamorphic rocks, which outcrop at the surface;
3) Highly reflective zones and poorly reflective ones correspond generally to coherent and mélange units, respectively based on correlations with outcrops (Matsuoka, 2000).

In view of the arrangement of coherent and mélange units in the Northern and Southern Shimanto groups, result 3) above implies that the reflective zones below the R2 and the R3 reflections correspond to the Albian to Cenomanian coherent unit (CU1), and the Campanian to Maastrichtian coherent unit (CU2) in the North Shimanto group,

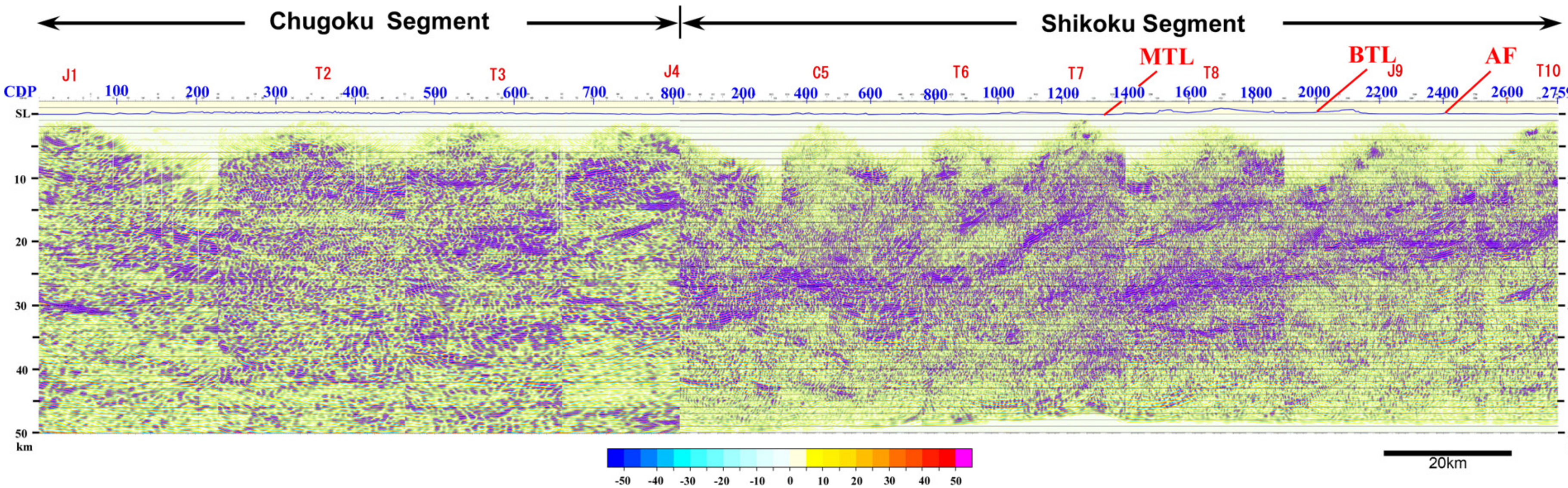

Fig. 5. Depth section along the projection line of Southwest Japan 2002. Red numbers, such as J1, indicate shot points from Fig. 2. Abbreviations of fault names are the same as those in Fig. 2.

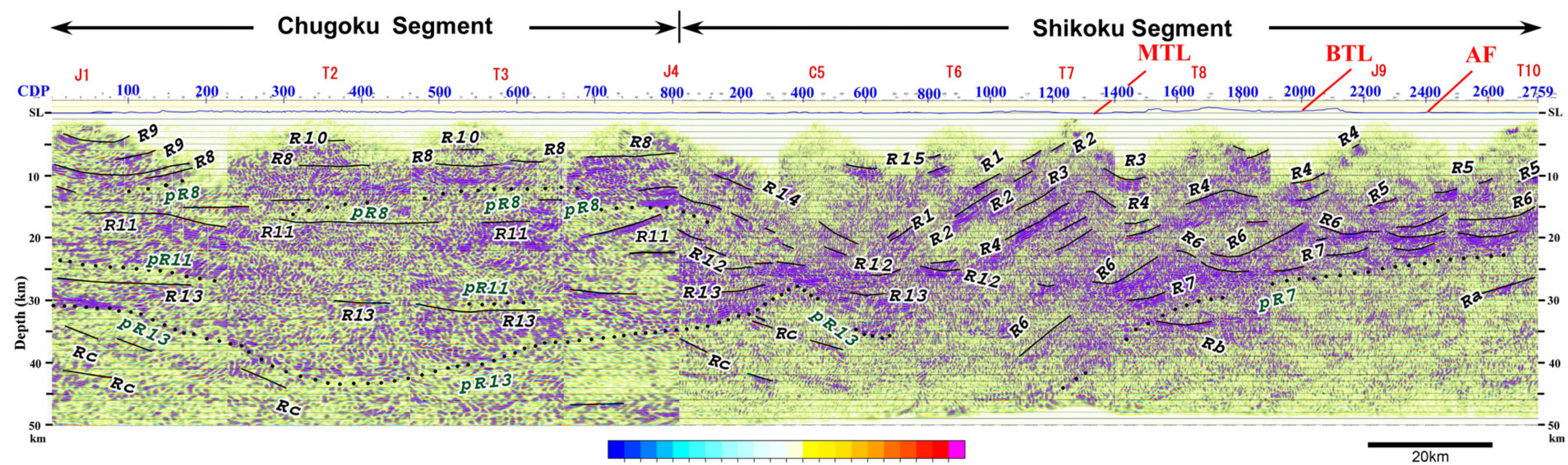

Fig. 6. Predominant reflective domains in the depth section (Fig. 5). Prominent upper boundaries of reflective domains are manually drawn as a solid line labeled as Ri, where a suffix i indicates a reflective zone. In case that a reflective zone has clear and continuous lower boundaries, the boundaries are indicated to be a dotted line labeled as pRi in the same manner as Ri. Beneath pR7, small but visible reflective domains are labeled Ra and Rb. Beneath pR13, a group of sparse south-dipping events is labeled Rc.

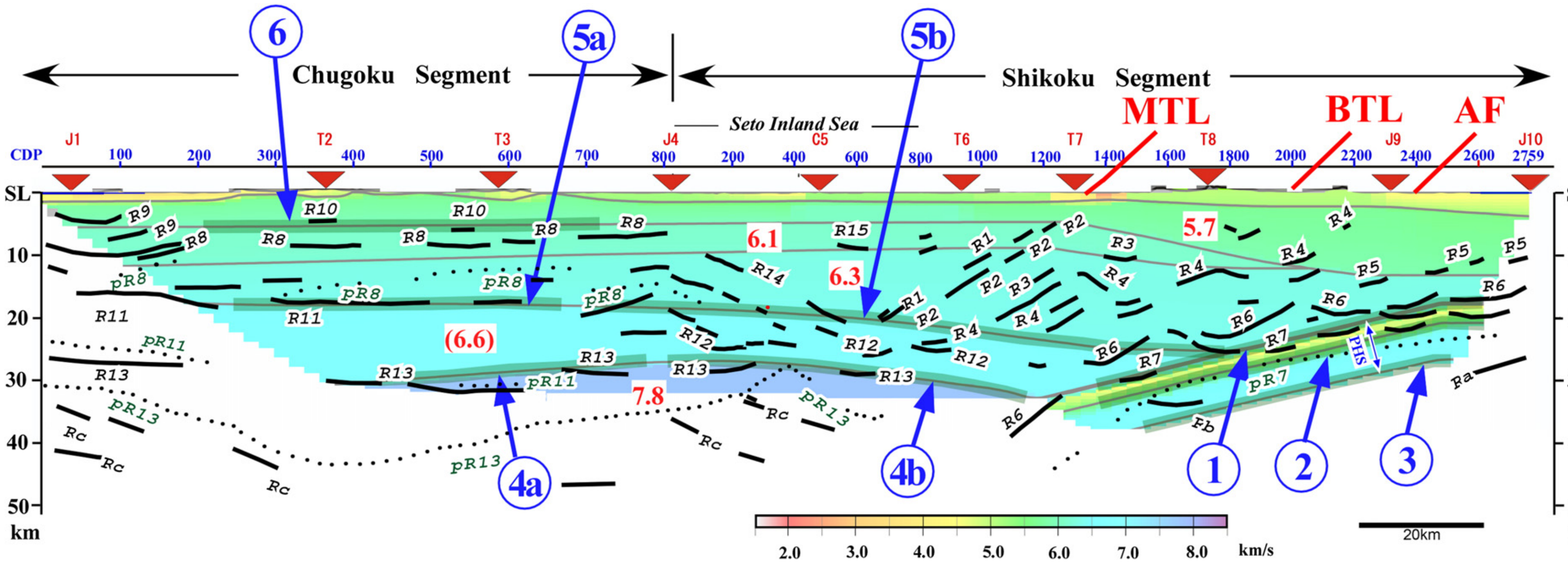

Fig. 7. P-wave structure (in km/s) estimated by Kurashimo et al. (2003) and upper and lower boundaries of predominant reflective domains from Fig. 6. PHS, oceanic crust of PHS plate. Only regions constrained by rays corresponding to picked arrivals have been colored. PHS, oceanic crust of the PHS plate estimated by Kurashimo et al. (2003). 1 to 6 are boundaries for the interpretational work.1 is very well constrained by wide-angle reflections from several shots. 2 is fairy well constrained by wide-angle reflections from a single shot. 3 is not so well constrained, because it is only drawn extrapolating from Kodaira et al. (2002). 4a is well constrained by reflected (PmP) waves. 4b is very well constrained by both refracted (Pn) and reflected (PmP) waves. 5a is well constrained by strong wide-angle reflections from a single shot, but 5b is fairy well by week ones. 6 is very well constrained by both refractions and wide-angle reflections.

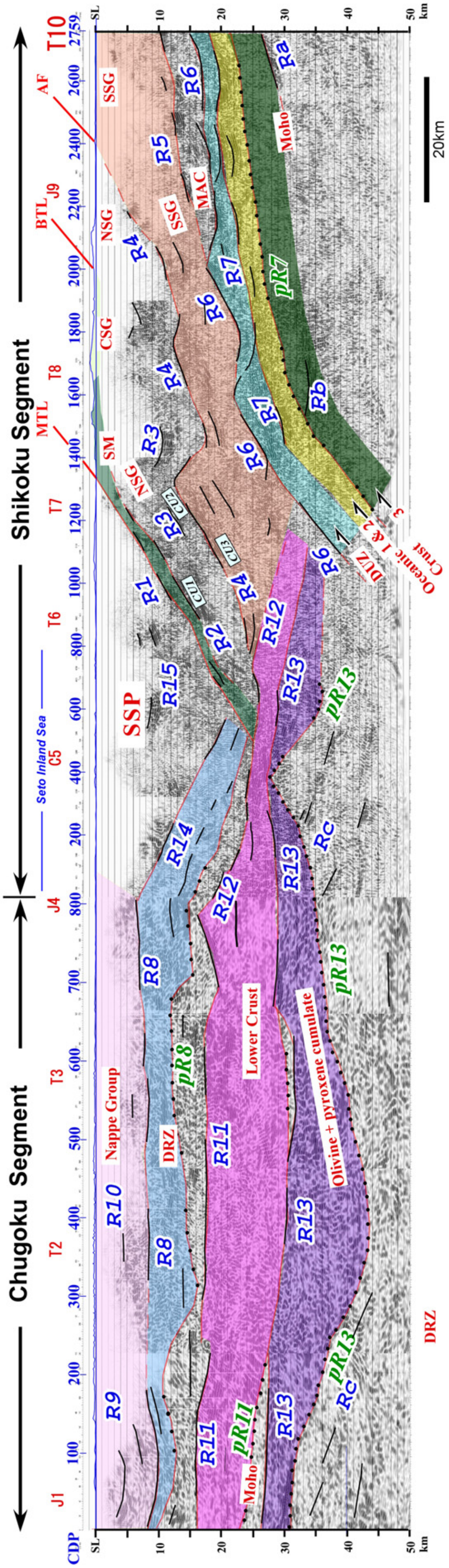

Fig. 8. Interpretation of depth section along the projection line of Southwest Japan 2002. Labels for reflectors are the same as those in Fig. 6. SSP, Seto Subsurface Prism. DRZ, Densely reflective zone. SM, Sambagawa metamorphic rocks. CSG, Chichibu supergroup. NSG, Northern Shimanto group. SSG, Southern Shimanto group. MAC, Middle Miocene to the present accretionary complex. DUZ, Duplexing-underplating zone. CU1 and CU2, Albian to Cenomanian, and Campanian to Maastrichtian coherent units in the Northern Shimanto group. CU3, Eocene to Oligocene coherent unit in the Southern Shimanto group.

respectively, and the reflective zone below the R4 reflections to the Eocene to Oligocene coherent unit (CU3) in the Southern Shimanto group. The R5 reflections may indicate the upper boundary of the middle Miocene to the present accretionary complex. These interpretations are illustrated in Fig. 8.

As illustrated in Fig. 7, the R7 reflections almost correspond to the very well constrained boundary 1 of the upper surface of the subducting Philippine Sea (PHS) plate, where as the pR7 reflections correspond approximately to the rather well constrained boundary 2 at the base of low-velocity layer in the PHS. Thus it is reasonable to suggest that the densely reflective zone between the R7 and the pR7 reflections coincides with the layers 1 and 2 of oceanic crust of the PHS Plate. Layer 3 of the oceanic crust appears to correlate with the poorly reflective domain beneath the pR7 reflections. The prominent reflection Ra below the poorly reflective domain may be the Moho of the oceanic crust. Considering that the boundary 3 as the Moho in Fig. 7 is not so well constrained, the discrepancy between the Ra and boundary 3 is not serious. As the reflective zone below the R6 reflections has a wavy character, it likely correlates with the duplexing–underplating zone. Judging from the trace of pR7 reflections, the dip of the subducting PHS plate steepens rather abruptly at about CDP1500 of the Shikoku segment as shown in Fig. 8. What structure corresponds to the Rb reflection remains unknown.

4.2. Lower crust

The lower crust is defined between the well constrained boundaries 5a and 4a in Chugoku (Fig. 7), where 5a marks an increase in Vp from 6.3km/s to 6.6km/s, and 4a from 6.6km/s to 7.8km/s. As the R11 reflections correspond to boundary 5a, they correspond to the upper boundary of the lower crust. The lower boundary of the lower crust, 4a, is located close to the R13 and the pR11 reflections. The reflective domains between the R11 and the pR11 reflections are thought to represent "lower crustal laminations", in which case the Moho corresponds to the pR11 reflections, and to the R13 reflections in those areas where the pR3 reflections are not observed. The reflective domains, "lower crustal laminations" extend southward between the R12 and the R13 reflections. Therefore we interpret that the lower crust is defined between these reflections beneath the Seto Inland Sea area. Whereas the R13 reflections almost certainly coincide with the very well constrained boundary 4b, the R12 reflections are not equivalent to boundary 5b. However this discrepancy between R12 reflections and boundary 5b may be ignored because boundary 5b is not well constrained. The southern extensions of the R12 and the R13 reflections are poorly defined in the range CDP800 to 1300 of the Shikoku segment.

4.3. Upper crust of the Chugoku segment

It is difficult to analyze the nappe structure seen in surface geology in Chugoku in the reflection data, because reflection information is poorly available in the upper several kilometers in our single-fold data set. However the following statements can be made:

1) The upward extension of the R9 reflections reaches the surface at CDP200 where the base of the Hida nappe is observed (Fig. 2). This suggests that the R9 reflections mark the base of the Hida nappe at depth.
2) The subhorizontal R10 reflections beneath Shots T2 and T3 coincide with the very well constrained boundary 6 between Vp of 5.7km/s and 6.1km/s (Fig. 7) implying that the reflections correspond to a major subhorizontal fault within the nappe structure, which superimposes different geologic bodies. The nappe structure may also continue down to the subhorizontal R8 reflections at about 8km depth.

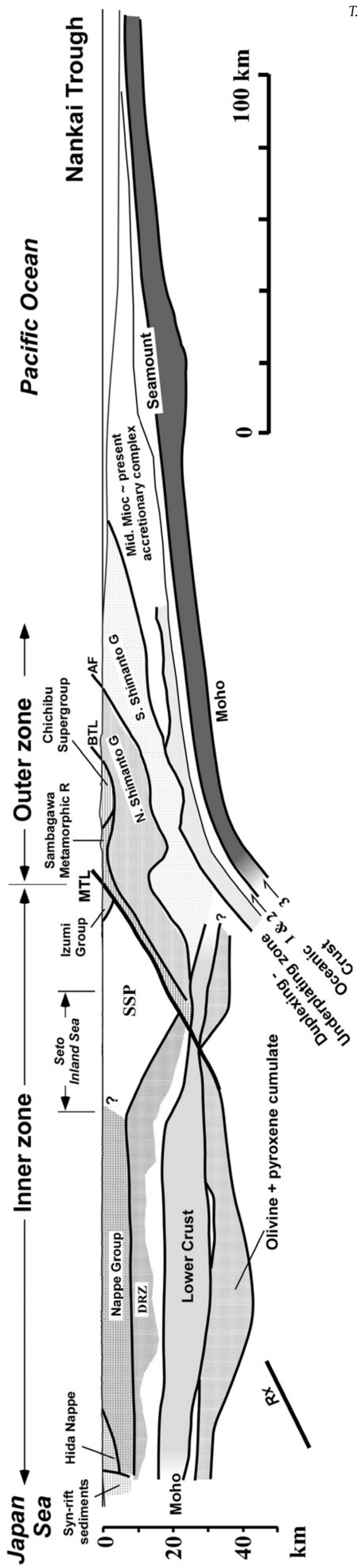

Fig. 9. Cross section across southwest Japan and PHS plate.

The densely reflective zone (DRZ) between the R8 and the pR8 reflections varies in thickness between 2km and 7km, because its lower boundary is wavy. Poorly reflective domains occur between the pR8 and the R11 reflections. No clear geologic interpretation is currently possible for the DRZ and poorly reflective domains that underlie it.

4.4. Upper crust of the northern half of the Shikoku segment (north of the MTL)

Between CDP 800 of the Chugoku segment and CDP1300 of the Shikoku segment lies the "Seto Subsurface Prism" (SSP) which is bounded by the R14 reflections of the upper surface of the DRZ to the north, and by the MTL to the south. Near the surface, the SSP is composed mainly of the Cretaceous granitic rocks and the metamorphosed late Triassic to Jurassic accretionary complex of the Ryoke belt. Its seismic images are characterized by short reflectors (R15) at shallower depths, and by poorly reflective domains in the deeper portions.

4.5. Upper mantle

Thick and wide reflective domains extend from the Moho down to the pR13 reflections. These domains can be divided into northern and the southern portions at CDP400 of the Shikoku segment, close to the lower termination of the MTL. The northern domain exhibits a downward-convex shape in cross section, whose thickness reaches 12km beneath the central Chugoku. In contrast, the southern domain is both thinner and narrower. The southern domain becomes indistinct south of CDP800 of the Shikoku segment. Both domains thin out at their meeting point, CDP400 of the Shikoku segment.

Takahashi (1978) and Arai et al. (2000) suggested that olivine-pyroxene cumulate is extensive beneath Chugoku. As this lithology is commonly expressed as reflective domains due to its internal layering, it is likely that the reflective domains beneath the Moho represent olivine-pyroxene cumulate.

The upper mantle outside the reflective domains is not transparent but rather contains short reflectors, such as the Rc reflections in Fig. 6. The reflector Rx, which is substantially more prominent than the Rc, is found in Tottori2001. The reflector is projected onto Fig. 9. There are as yet no well constrained interpretations of these reflectors.

5. Conclusions

Fig. 9 is drawn based on the interpretation illustrated in Fig. 8, the results of the JAMSTEC1999 (Kodaira et al., 2002), ODP Leg 190 (Moore et al., 2001), and Tottori2001 (Tottori Prefecture, 2002) experiments, and the surface geology. It represents the first crustal-scale cross section across southwest Japan, from the Nankai trough to the Japan Sea coast.

5.1. Outer zone

The Outer zone is, as a whole, characterized by a north-dipping arrangement of the accretionary complexes as indicated in surface geology. The boundary faults, however, do not extend directly downward, but appear to undulate. It can be seen from Fig. 8 that the AF undulates twice with a wavelength of about 20km. On the other hand, the structure of the BTL remains obscured, particularly at shallow depths, because reflection information is poorly available in the upper several kilometers referred to above. Thus the shallower structure of the BTL can only be expressed roughly as a gentle undulation associated with an anticline in the Sambagawa metamorphic rocks and a syncline in the Chichibu supergroup, considering the shallow structure revealed by the conventional seismic reflection study in Kii (Matsuoka, 2000). The cross sections by Murata (1982) and Isozaki and Maruyama (1991) are also referred. It is difficult to determine whether the undulation of the AF is related to that of the shallow structure of the BTL.

A lower crust similar to the laminated lower crust of the Inner zone is seen only in the region less than 40km southward from the lower termination of the MTL. The relationship among the duplexing–underplating zone, the accretionary complexes, and the lower crust is not clear below 30km depth, although the duplexing–underplating zone may overlie the PHS plate there.

5.2. Subducting PHS plate

The PHS plate dips very gently at about 6° from the Nankai trough to the central Shikoku, changing to a steeper angle of about 30° further north. As the change in dip occurs rather abruptly, the PHS plate appears to be bent beneath central Shikoku. A subducting seamount occurs on the PHS plate off the Muroto peninsula (Kodaira et al., 2000).

5.3. Mtl

The MTL cuts the whole upper crust to 24km depth dipping almost straightly northward at about 30 to 40°. Then it reaches the thinnest (about 3km thick) part in the lower crust, where the Moho shoals to 27km depth. This strongly suggests that the MTL cuts the entire crust, juxtaposing the two completely different crusts of the Inner and the Outer zones.

5.4. Upper crust of the Inner zone

The upper crust of the Inner zone consists of the two parts; that beneath Chugoku, and that underlying the Seto Inland Sea area. The former is characterized by subhorizontal structure beneath the surficial nappes and the latter by the poorly reflective domain, the SSP. The DRZ subhorizontally underlies the nappe group in Chugoku, and dips southward beneath the SSP in the Seto Inland Sea area.

5.5. Lower crust of the Inner zone

The lower crust of the Inner zone is characterized by a very gentle Moho depression located in central Chugoku at about 30km depth. Its thickness is 12–15km on average in main part of Chugoku, whereas it abruptly decreases to 4km beneath the SSP (Fig. 9).

5.6. Upper mantle

Thick and wide reflective domains, which infer to represent olivine-pyroxene cumulate, occur just below the Moho in both the Inner and the Outer zones. The domains are thicker in the north than in the south, but both portions thin towards their meeting point, which corresponds to the lower termination of the MTL.

6. Discussion

The present results are still not so sufficient to fully understand the structural development of the Japanese island arc, in comparison for example with the huge number of geological and geophysical data collected along the west margin of the North America and summarized by Fuis (1998) and Fuis et al. (2008). However our first crustal-scale cross section, Fig. 9, highlights a number of significant points related to the structural development of the Japanese island arc.

6.1. Growth of the lower crust

A horizontally laminated reflective lower crust has developed in the Inner zone, but exists only in the northern part in the Outer zone. This contrast between the Inner and Outer zones may be related to differences in volcanic activity. Volcanic activity was predominant in Cretaceous to Paleogene in the Inner zone. Since then the activity has been continued sporadically in the Inner zone. The thick olivine-pyroxene cumulate may have been formed by these volcanic activities. In contrast volcanic activity has been poor in spatially and temporally restricted in the Outer zone except in the Seto Inland Sea area in middle Miocene.

6.2. Formation of the horizontal structure of the Inner zone

Most geologic bodies outcropping at the surface in the Inner zone are derived from the accretionary complexes that would have originally dipped towards the continent as they do in the Outer zone. However the dips had become subhorizontal by late Late Cretaceous, judging from that the late Late Cretaceous welded tuff widely covered almost horizontally. This motivates an unsolved question; what kind of event and deformation made such the subhorizontal structure? This is a further problem essential to the structural development of the Inner zone.

6.3. SSP and the birth of the MTL

The existence of the SSP was not anticipated from the surface geology around the MTL. Although the geologic constituents and structure of the SSP remain unknown, the SSP may have been formed from material infilling an upper crustal-scale half-graben during transtension along the MTL. The interpretation is motivated by 1) the change in attitude of the DRZ from subhorizontal in Chugoku to south-dipping beneath the SSP, where the DRZ is cut by the north-dipping MTL, and 2) abrupt thinning of the lower crust beneath the SSP. As the Ryoke belt occupying the upper part of the SSP is unconformably covered by the late Late Cretaceous Izumi group, the SSP is inferred to have been essentially established by that time. This is compatible with the suggestion that the first phase of MTL activity involved a normal dip slip together with a left-lateral motion from early Late Cretaceous until Paleocene (Otoh and Yamakita, 1995).

In summary, the birth of the MTL was characterized by lower crustal thinning and dissection of the entire crust of the Inner zone. At that time, there was no lower crust beneath the Outer zone as discussed below in 6.4. The MTL juxtaposed two completely different crusts in the first phase of its activity. These characteristics may be one of the main reasons why only the MTL has repeatedly reactivated in the major boundary faults and changed its sense of motion since its birth in a passive response to change of plate tectonic conditions. More research on the SSP is expected to yield new information on the birth and evolution of the MTL.

6.4. Uplift of the high P/T Sambagawa metamorphic rocks

Most of the high P/T Sambagawa metamorphic rocks were metamorphosed at about 10kbar corresponding to depths of about 30 to 40km, although some including the eclogite reached 20kbar corresponding to depths of 60 to 70km (Aoya et al., 2003). What path enabled uplift of the Sambagawa metamorphic rocks from such great depths to the surface? Although the lower crust of the Outer zone has not been fully developed yet, the lower crust and its underlying olivine-pyroxene cumulate might have acted as obstructions to the ascending metamorphic rocks. Conversely, as the first arrival of the Sambagawa metamorphic rocks at the surface was in late Paleocene (Oyaizu and Kiminami, 2004), the lower crust and the olivine-pyroxene cumulate might have formed after that time. The middle Miocene volcanic activity in the Seto Inland Sea area possibly contributed to the formation of the lower crust of the Outer zone. The mechanism of uplift of the high P/T Sambagawa metamorphic rocks remains one of the major outstanding problems in the structural development of the Japanese islands.

6.5. Bending of the subducting PHS plate

The bending of the PHS plate seems to be associated with the presence of the lower crust. A similar phenomenon is recognized in the west margin of the North America as follows (Fuis, 1998). Where only upper crustal materials overlie the subducting plate, the dip of the plate is less than 10°, whereas beneath geologic bodies whose velocity corresponds to those of lower crust, the subducting plate steepens to dips of more than 20°. The existence of a lower crust is probably one essential factor controlling the dip of the subducting plate.

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