地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 78 (2003) pp. 197-203

Low-velocity zones along subducting oceanic plates—Their implications in the subduction-zone seimogenesis and a method to detect them

Yasuto Kuwahara*, Yutaka Mamada[1)] and Hisao Ito

Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology

Abstract

Subduction zone drilling into a seismogenic zone has recently been planned to understand the mechanics of large thrust earthquakes. We review studies on fault zone structures in land areas and fault mechanics studies related to the fault zones. We also point out possibilities of estimating the parameters of slip-weakening and/or rate and state dependent friction laws from a parameter of thickness of fault gouges or of fault damaged zones observed in the borehole. Two types of low velocity zone, the fault and the oceanic crust low-velocity zones (FLVZ and CLVZ), can be expected along the subduction zone plate-boundary. Delineations of FLVZ and CLVZ clarify the frictional properties of the sunduction zone plate-boundary and detailed structures of the subducting oceanic crust at deeper parts. The trapped wave observation in the subduction zone borehole is a useful tool for delineating FLVZ and CLVZ in the upper parts of the subducting slab.

Key words: low-velocity zone, subduction zone, earthquake rupture process, trapped wave, down-hole seismic observation

1. Introduction

The mechanics of large thrust earthquakes in shallow parts of subduction zones are understood as frictional sliding along upper boundary of descending slabs. Earthquake faulting is controlled by many parameters such as stress states, temperature, geometry, and mechanical properties of the slip interfaces or zones and elastic parameters of the surrounding material. Subduction zone drilling into a seismogenic zone has been recently planned to understand the mechanics of large thrust earthquakes. It would directly provide information about these parameters. However, we consider a few difficulties in understanding the mechanisms of subduction zone earthquakes through such drilling. First, although the parameters related to earthquake faulting can be elucidated by deep drilling across the seismogenic zone, the parameters measured directly in a borehole are inherently local at a borehole site. The spatial distribution of these parameters along the plate boundary is obviously necessary for an understanding of the earthquake processes. Secondly, we must know how these parameters are quantitatively related to earthquake faulting. This paper reviews previous studies to address possible ways to overcome these difficulties. We review studies on fault zone structures in land areas and fault mechanics studies related to the fault zones. We further show the feasibility of trapped wave observations with a downhole seismic array in a borehole in the subduction zone.

2. Low-velocity zones along the active faults in land areas

To understand fault zone properties in land areas, fault zone seismic waves such as fault zone head waves, direct waves propagating in the zones, and trapped waves in the zones have been analyzed (e. g.

* e-mail: y-kuwahara@aist.go.jp (AIST Tsukuba Central 7, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567 Japan)
1) Now at Disaster Prevention Research Institute, Kyoto University

Hough *et al.,* 1994; Li *et al.,* 1994, 1998, 2002; Ben-Zion and Malin, 1991; Ben-Zion, 1998; Kuwahara and Ito, 2000, Mamada *et al.,* 2002). The existence of trapped waves along fault zones indicates the existence of a fault low-velocity zone (FLVZ) that can trap seismic energy. We can estimate seismic velocity and attenuation structures in and around the low-velocity zones along the faults by analyzing the waveforms of trapped waves. Velocity and attenuation are probably related to the degree of rock damage. Fault segmentations can be also clarified using trapped waves. When hypocenters are in the FLVZ, the trapped waves can be observed; when hypocenters are located outside the zone, the trapped waves cannot be observed. Consequently, the hypocenter distribution of events that generate the trapped waves indicates the segmentation structure.

Various kinds of observations have been performed in and around a borehole penetrating the Nojima fault zone, which was ruptured during the 1995 Hyogoken-nanbu earthquake ($M_{JMA}=7.2$), at a depth of 620 m (Ito *et al.,* 1996). The observations just after drilling were core inspections, borehole logging, and vertical seismic profiling (VSP) of the borehole. Long-term seismic monitoring after drilling has been performed using a borehole seismometer array at three depth levels, and surface seismic array around the borehole (Pervukhina *et al.,* 2003). Ito *et al.* (1996) and Tanaka *et al.* (2001) elucidate lithology and physical properties such as electric resistivity, density, and seismic velocities throughout the borehole by core inspection and borehole logging. They find a fault zone with a width of a few tens of meters characterized by altered and deformed granodiorite with fault gouge, low resistivity, low density, and low velocities. They show that the fault damaged zone defined by core inspections is consistent with the FLVZ. Ito and Kuwahara (1996) and Kuwahara and Ito (2000) investigate the width of a low velocity zone of the Nojima fault using trapped wave observations of surface seismic arrays. The estimated width is about 50 m, which is consistent with the results of fault drilling.

The studies mentioned above indicate that the spatial extent of structural parameters derived from local and direct borehole observations in a fault zone can be estimated from the trapped wave analysis. On the other hand, there have been no reports of such FLVZs or damaged zones in the subduction-zone plate-boundaries. This is probably because there have been no opportunities to detect such thin fault damaged zones in subduction zones. Because many FLVZs have been found in land areas as mentioned before, it is quite natural to believe that such FLVZs also exist in the plate-boundary fault zone. If there is a borehole penetrating a subduction-zone plate-boundary, downhole seismic array observations will become possible. Analysis of the trapped waves in the subduction region by means of the downhole array would provide a new tool for delineating and monitoring the fault damaged zone along the plate boundary in the same way as land area observations.

3. Dynamics of faulting in fault low-velocity zone

It appears plausible that the presence of the FLVZ has significant effects on earthquake rupture. To date, earthquake rupture processes have usually been considered to be on a fault, which is a smooth, planar surface embedded in a uniform elastic medium. Slip-weakening and/or rate and state dependent friction laws have been introduced on such planar surfaces to evaluate fracture energies of earthquake faulting (Ida, 1972; Aki, 1979), acceleration of fault rupture propagation (Andrew, 1976 a, b; Ohnaka, 1993; Shibazaki and Matsu'ura, 1992), and relatively long-term earthquake cycles (Stuart *et al.,* 1985; Tse and Rice, 1986). In these studies, a characteristic slip distance d_0 defined in the slip-weakening model, or D_0 defined in the rate and state dependent friction laws, and/or a cohesive zone size w_0, are key parameters for the above evaluations of slip-weakening and/or rate and state dependent friction laws. We have to know how the properties of fault zone or surface are related to these parameters when fault zone properties are elucidated through drilling.

The parameter d_0 is considered to be related to the properties of the fault zone or the surface. Matsu'ura *et al.* (1992), Marone and Kilgore (1993), Yamashita and Fukuyama (1996), Kuwahara and Ito (2002) have proposed various fault zone (or surface) models describing friction laws. Basic concepts of their models are schematically illustrated in Fig. 1. Figs. 1 (a) to (d) are called roughness model, gouge layer model, damaged zone model, and plastic deformation model, respectively. The roughness model (Fig. 1 a) of Matsu'ura *et al.* (1992) describes slip-

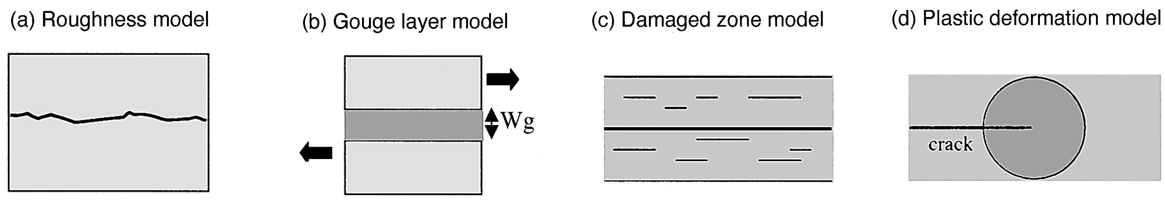

Fig. 1. Basic concepts of reviewed models of the fault zone or the fault surface to describe the friction laws. (a) Roughness model by Matsu'ura *et al.* (1992). Irregular fault surface topography control the slip-weakening behavior. (b) Gouge layer model by Marone and Kilgore (1993). Slip-weakening behavior is controlled by a thickness Wg of the gouge zone of the earthquake faults. (c) Damaged zone model by Yamashita and Fukuyama (1996). An apparent slip-weakening behavior is observed outside the fault zone, which is caused by elastic wave scattering due to cracks (parallel thin lines) in the damaged zone with a thickness W_d. (d) Plastic deformation model by Kuwahara and Ito (2002). The FLVZ with a thickness W_d is assumed to be identical to the plastic deformation zone (circular region) around the crack tip defined in fracture mechanics.

weakening frictional properties by considering a microscopic interaction between irregular fault surfaces. They successfully introduced fractal limits of fault surface topography to simulate the slip-weakening behavior observed in laboratory experiments by Ohnaka *et al.* (1987). The gouge layer model (Fig. 1 b) proposed by Marone and Kilgore (1993) is based on the physical interpretation that the characteristic slip distance D_0 is controlled by the thickness of the gouge zone of earthquake faults. The damaged zone model (Fig. 1 c) is proposed by Yamashita and Fukuyama (1996), taking account of elastic wave scattering due to cracks in the damaged zone. They show that apparent slip-weakening behavior is observed outside the fault zone. The plastic deformation model is proposed by Kuwahara and Ito (2002) by assuming that the FLVZ is identical to the plastic deformation zone around the crack tip defined in fracture mechanics. All four models seem to be candidates of a model to estimate the friction parameters from core samples or physical logging data obtained from a planned subduction zone plate-boundary drilling. It is noted that the thickness of the gouge layer or the fault damaged zone directly measured by drilling technology will in practice be an important parameter for describing models (b), (c), and (d). It may be difficult to estimate a roughness parameter, which is important for model (a), from the slip surface of a core sample, if the fault slip surface is accompanied by a fault gouge. Thus, models (b), (c), and (d) will be able to estimate friction parameters from borehole observations.

4. Oceanic crust as low-velocity zones in the descending slab

Low-velocity zones other than the fault damaged zone are likely to be found in the subduction zones (e.g. Fukao *et al.* 1983); the low-velocity zone corresponds to the descending oceanic crust. Studies on seismic velocity structures of subduction zones show that P and S wave velocities in the descending oceanic crusts are lower than those of the mantle material at depths. Thus, it should be noted that the fault zones of large earthquakes along the subduction zone plate-boundaries are considered to be formed in or on the surface of the oceanic crust low-velocity zone (CLVZ). If this is the case, the trapped waves possibly offer effective methods for imaging the descending oceanic crust of the upper parts of the oceanic plate in the subduction region.

The seismic velocity structures of subduction regions that are shallower than a few tens of kilometers have been delineated by reflection and/or refraction surveys (e.g. Iwasaki *et al.,*1989; Kodaira *et al.,* 2000; Tsuru *et al.,* 2001; Nakanishi *et al.,* 2002; Park *et al.,* 2002: Kurashimo *et al.,* 2002). The deeper parts of the velocity structure have been constrained by analyzing converted or guided seismic waves observed at land stations (e.g. Fukao *et al.* 1983; Hori, 1990; Matsuzawa *et al.* 1990). These studies also show that the CLVZs exist along the upper boundary of descending slabs from a depth of a few kilometers to a depth of more than 100 km, although the depth limit of the existence of the low-velocity zone is not clear. They suggests that deep focus earthquakes occur in the CLVZ with a thickness of about 5 km. Recent high-resolution observations of descending slabs in the Nankai (Kurashimo *et al.,* 2002) and the Sanriku (Takahashi *et al.,* 2000, Tsuru *et al.,* 2001) subdction zones suggest that there are low-velocity layers corresponding to Layer 1 or Layer 2 of the oceanic crust with a thickness of 100 m to 1 km in the upper part of the slab down to at least 15 km. Fujie *et al.* (2002) suggest that a low-velocity layer of fluid of several hundred meters in thickness exists at the plate boundary from reflection surveys in the Sanriku region and that the fluid layer is closely related to the activity of micro earthquakes. Thus, many studies have suggested that the descending oceanic crust acts as a low-velocity zone formed in the upper part of the slab. Further, the CLVZ does not consist of a single layer but of a few layers, that is, Layers 1, 2, and 3 of the oceanic crust or a fluid layer, with different low velocities.

We can expect trapped waves in the CLVZ, even if the CLVZ consists of many layers. A detailed analysis of the trapped waves will be able to clarify the detailed structure of the multi-layer CLVZs, because multi-layer low-velocity zones must strongly affect the waveforms of the trapped waves as indicated by Mamada *et al.* (2003). Thus, a new window for high-resolution mapping and monitoring of deeper parts of the subduction zone will be opened to delineate a subducting oceanic crust in the subduction zone by means of the trapped wave observations.

5. Feasibility study of trapped wave observations for CLVZ in the subduction zone

We can expect two types of low-velocity zone, the FLVZ and the CLVZ, along the subduction zone plate-boundary as reviewed in the previous sections. A feasibility test of trapped wave observations in the subduction region is possible by performing numerical calculations of synthetic seismic waves for a realistic seismic velocity structure, because the velocity structures of the suduction zones have been elucidated to some extent. Here, we examine the Nankai subduction zone, central Japan, as an example. The synthetic calculations are performed only for a model of the single layer of the CLVZ with a thickness of 5 km at present. We do not perform the calculation for a FLVZ model or a multi-layer CLVZ model because the grid sizes for the FLVZ model or the multi-layer CLVZ model are too small to get reliable numerical results from computations. Computations for both models with smaller grids will be performed in the next step.

To obtain the synthetic waveforms, we applied a 3-D staggered-grid finite-difference method with a fourth- and second-order approximation for the spatial and time derivatives, respectively, developed by Mamada *et al.* (2002, 2003). The tested CLVZ structure model is shown in Fig. 2. This model was made by simplifying the results of a refraction survey at the Nankai subduction zone obtained by Nakanishi *et al.* (2002). P and S wave velocities of each layer are shown in the figure. An earthquake source with a mechanism of down-dip compression is denoted by a star. The grid spacing of the model and a time step are 500 m and 0.025 s, respectively. A source time function is given by $(1-\cos(2\pi t/T_0))$ for $0<t<T_0$ and zero otherwise, where T_0 represents the pulse width and was set at 1 s. Attenuation parameter Q is not included in the present simulations.

Top and bottom figures in Fig. 3 show the synthetic waveforms for arrays 1 and 2, respectively, whose positions are shown in Fig. 2. Arrays 1 and 2 correspond to the trench-ward and land-ward boreholes, respectively. We show the results of radial and transverse components. The CLVZ is positioned along vertical lines between two arrows in Fig. 3. We can see many up- and down-going waves in the radial components. The down-going waves in the

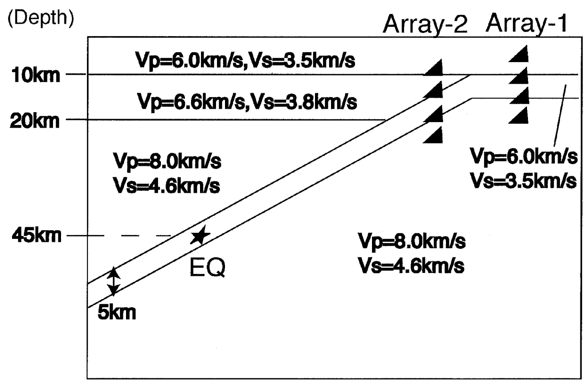

Fig. 2. CLVZ structure model tested to perform a numerical simulation in the subduction zone. An earthquake source with a mechanism of down-dip compression are denoted by a star at a depth of 45 km. The arrays 1 and 2 correspond to the trench-ward and land-ward boreholes, respectively. Other parameters for calculations are shown in the text.

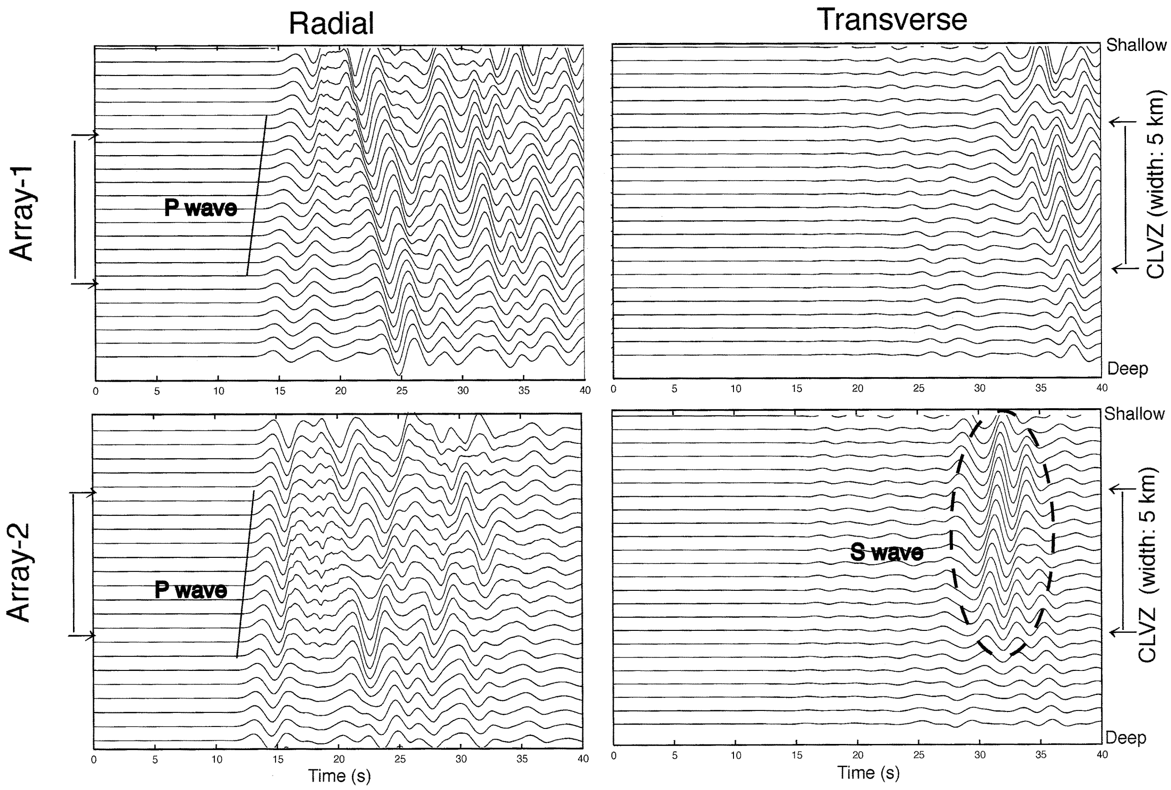

Fig. 3. Synthetic waveforms of the radial and transverse components for arrays 1 and 2. The CLVZ is positioned along vertical lines between two arrows. Amplitudes of the S waves indicated in a dashed ellipse are larger than those outside of the CLVZ.

array 1 for the shallower borehole are dominant compared to those in the array 2. It is clearly seen that the amplitudes of the S wave in the CLVZ, especially in the transverse component of the array 2, are much larger than those in the layer deeper than the CLVZ. The large amplitudes of the S wave for the array 2 are observed in the layer shallower than the CLVZ. This is because velocity contrasts of land-ward crusts with P wave velocities of 6 km/s and 6.6 km/s to the CLVZ with a velocity of 6 km/s are much smaller than the contrast between the CLVZ and the mantle with a velocity of 8 km/s. Thus, the trapped energy leaks into the layer that is shallower than the CLVZ. On the other hand, the waves trapped in the CLVZ are not clear for the array 1. This seems to be due to an effect of the leak of the trapped energy into the shallower layer before the trapped wave arrives at array 1. Relative amplitudes of trapped waves in the CLVZ to those of S waves in the deeper layer are considered to become small due to this leak of trapped energy. It should be noted that the effect of a kink of CLVZ between the arrays 1 and 2 is considered to be minor according to the results of Li and Vidale (1996), who evaluated the kink effect using numerical simulations. It is concluded that the trapped energy of the S wave is more easily detected in CLVZ for array 2 than array 1. Although we only simulate the single CLVZ model in the present paper, simulations for the FLVZ model and the multi-layer CLVZ model will be possible in the next step after improvements are made to our programming code.

6. Conclusion

We expect two types of low velocity zone along the subduction-zone plate-boundary : FLVZ and CLVZ. Delineation of the FLVZ will clarify the frictional properties of the sunduction-zone plate-boundary, taking the quantitative models describing the fault zone into account. The trapped wave observations in the subduction zone borehole will be a useful tool for delineating FLVZ and CLVZ in the upper parts of the subducting slab.

Acknowledgement

The authors wish to acknowledge the helpful comments and valuable suggestions of two anonymous reviewers to improve the manuscript.

References

Aki, K., 1979, Characterization of barriers on an earthquake fault, *J. Geophys. Res.,* **84**, 6140–6148.

Andrew, J., 1976 a, Rupture propagation with finite stress in antiplane strain, *J. Geophys. Res.,* **81**, 3575–3582.

Andrew, J., 1976 b, Rupture velocity of plane strain shear cracks., *J. Geophys. Res.,* **81**, 5679–5687.

Ben-Zion, Y., 1998, Properties of seismic fault zone waves and their utility for imaging low-velocity structures, *J. Geophys. Res.,* **103**, 12567–12585.

Ben-Zion, Y. and P. Malin, 1991, San Andreas fault zone head waves near Parkfield, California, *Science,* **251**, 1592–1594.

Fujie, G., J. Kasahara, R. Hino, R. Sato, T. Shinohara and K. Suyehira, 2002, A significant relation between seismic activity and reflection intensities in the Japan Trench region, *Geophys. Res. Lett.,* **29** (7), 10.1029/2001 GL 013764.

Fukao, Y., S. Hori and M. Ukawa, 1983, A seismological constraint on the depth of the basalt-eclogite transition in a subducting oceanic crust, *Nature,* **303**, 413–415.

Hori, S., 1990, Seismic waves guided by untransformed oceanic crust subducting in to the mantle: the case of the Kanto district, central Japan, *Tectonophysics,* **176**, 355–376.

Hough, S.E., Y. Ben-Zion and P. Leary, 1994, Fault-zone waves observed at the southern Joshua Tree earthquake rupture zone, *Bull. Seism. Soc. Am.,* **84**, 761–767.

Ida, Y., 1972, Cohesive force across the tip of a longitudinal-shear crack and Griffith's specific surface energy, *J. Geophys. Res.,* **77**, 3796–3805.

Ito, H. and Y. Kuwahara, 1996, Trapped waves along the Nojima fault from the aftershock of Kobe Earthquake, 1995, *Proceedings of VIIIth International Symposium on the Observation of the Continental Crust through Drilling,* 399–402.

Ito, H., Y. Kuwahara, T. Miyazaki, O. Nishizawa, T. Kiguchi, K. Fujimoto, T. Ohtani, H. Tanaka, T. Higuchi, S. Agar, A. Brie and H. Yamamoto, 1996, Structure and physical properties of the Nojima Fault, *Butsuri-Tansa (Geophys. Explor.),* **49**, 522–535.

Iwasaki, T., H. Shiobara, A. Nishizawa, T. Kanazawa, K. Suyehiro, N. Hirata, T. Urabe and H. Shimamura, 1989, A detailed subduction structure in the Kuril trench deduced from ocean bottom seismographic refraction studies, *Tectonophysics,* **165**, 315–336.

Kodaira, S., N. Takahasi, J.O. Park, K. Mochizuki, M. Shinohara, S. Kimura, 2000, Western Nankai Trough seismogenic zone; results from a wide-angle ocean bottom seismic survey, *J. Geophys. Res.,* **105**, 5887–5905.

Kurashimo, E., M. Tokunaga, N, Hirata, T. Iwasaki, S. Kodaira, Y. Kaneda, K. Ito, R. Nishida, S. Kimura and T. Ikawa, 2002, Geometry of the Subducting Philippine Sea Plate and the Crustal and Upper Mantle Structure beneath Eastern Shikoku Island Revealed by Seismic Refraction/Wide-angle Reflection Profiling,Journal of the Seismological Society of Japan, Second Series; *Zisin,* Second Series, **54**, 4, 489–505.

Kuwahara, Y. and H. Ito, 2000, Deep structure of the Nojima fault by trapped wave analysis, *USGS, Open-file report* 00–129, 283–289.

Kuwahara, Y. and H. Ito, 2002, Fault low velocity zones deduced by trapped waves and their relation to earthquake rupture process, *Earth Planets Space,* **54**, 1045–1048.

Li, Y.G., K. Aki, D. Adams, A. Hasemi and W. Lee, 1994, Seismic guided waves trapped in the fault zone of the Landers, California, earthquake of 1992, *J. Geophys. Res.,* **99**, 11705–11722.

Li, Y.G. and J.E. Vidale, 1996, Low-velocity fault-zone guided waves: Numerical investigations of trapped efficiency, *Bull. Seism. Soc. Am.,* **86**, 371–378.

Li, Y.G., K. Aki, J.E. Vidale, and M.G. Alvarez, 1998, A delineation of the Nojima fault ruptured in the M7.2 Kobe, Japan earthquake of 1995 using fault zone trapped waves, *J. Geophys. Res.* **103**, 7247–7263.

Li, Y.G., J.E. Vidale, S.M. Day, D.D., 2002, Oglesby and the SCEC Field Working Team, Study of the 1999 M7.1 Hector Mine, California earthquake fault plane by trapped waves, *Bull. Seismol. Soc. Am.,* **92**, 1318–1332.

Mamada, Y., Y. Kuwahara, H. Ito and H. Takenaka, 2002, 3-D finite-difference simulation of seismic fault zone waves —Application to the fault zone structure of the Mozumi-Sukenobu fault, central Japan—, *Earth Planets Space,* **54**, 1055–1058.

Mamada, Y., Y. Kuwahara, H. Ito and H. Takenaka, 2003, Discontinuity of the Mozumi-Sukenobu fault low-velocity zone, central Japan, inferred from 3D finite-difference simulation of fault zone waves excited by explosive sources, *Tectnophysics,* in press.

Marone, C. and B. Kilgore, 1993, Scaling of the critical slip distance for seismic faulting with shear strain in fault zone, *Nature,* **362**, 618–621.

Matsu'ura, M., H. Kataoka, and B. Shibazaki, 1992, Slip-dependent friction law and nucleation process in eartquake rupture in earthquake rupture, in "Earthquake Source Physics and Earthquake Precursors", ed. By T. Mikumo, K. Aki, M. Ohnaka, L.J. Ruff, and P.K.P. Spudich, Special Issure of *Tectonophysics,* **211**, 135–148.

Matsuzawa, T., T. Kono, A. Hasegawa and A. Takagi, 1990, Subducting plate boundary beneath the northeastern Japan arc estimated from SP converted waves, *Tectonophysics,* **181**, 123–133.

Nakanishi, A., N. Takahashi, J.O. Park, S. Miura, S., Kodaira, Y. Kaneda, N. Hirata, T. Iwasaki, M. Nakamura, 2002, Crustal structures across the coseismic rupture zone of the 1944 Tonankai earthquake, the central Nankai Trough seismogenic zone, *J. Geophys. Res.,* **107**, EPM2. 1–21.

Ohnaka, M., 1993, Critical size of the nucleation zone of earthquake rupture inferred from immediate foreshock activity, *J. Phys. Earth,* **41**, 45–46.

Ohnaka, M., Y. Kuwahara and K. Yamamoto, 1987, Constitutive relations between dynamic physical parameters near a tip of propagating slip zone during stick-slip shear failure, *Tectonophysics,* **144**, 109–125.

Park, J.O., T. Tsuru, S. Kodaira, P.R. Cummins, Y. Kaneda, 2002, Splay fault brabching along the Nankai subducton zone, *Science,* **297**, 1157–1160.

Pervukhina, M., Y. Kuwahara and H. Ito, 2003, A prototype of database system for seismological data - SISMO: Nojima fault area case, *Geoinformatics,* in press.

Sibazaki, B. and M. Matsu'ura, 1998, Transition process from nucleation to high-speed rupture propagation: scaling from stick-slip experiments to natural earthquakes, *Geophys. J. Int.,* **132**, 14–30.

Stuart, W.D., R.J. Archuleta and A.G. Lindh, 1985, Forecast model for moderate-earthquake near Parkfield, California, *J. Geophys. Res.,* **90**, 592–604.

Takahashi, N., S. Kodaira, T. Tsuru, J. Park, Y. Kaneda, H. Kinoshita, S. Abe, M. Nishino, R. Hino, 2000, Detailed plate boundary structure off northeast Japan coast, *Geophys. Res. Lett.,* **27**, 13, 1977–1980.

Tanaka, H., K. Fujimoto, T Ohtani and H. Ito, 2001, Structural and chemical characterization of shear zones in the freshly activated Nojima fault, Awaji island, southwest Japan, *J. Geophys. Res.,* **106**, 8789–8810.

Tse, S.T. and J.R. Rice, 1986, Crustal earthquake instability in relation to the depth variation of frictional slip properties, *J. Geophys. Res.,* **91**, 9425–9472.

Tsuru, T., J.O. Park, S. Miura, N. Takahashi, S. Kodaira, T. Higashikata, Y. Kido, and Y. Kaneda, 2001, Consideration on basal erosing along the plate boundary and interplate earthquake activity at the Japan trench subduction zone, *Butsuri-Tansa* (*Geophys. Explor.*), **54**, 21–29.

Yamashita, T. and E. Fukuyama, 1996, Apparent critical slip displacement caused by the exixtence of a fault zone, *Geophys. J. Int.,* **125**, 459–472.

(Received July 21, 2003)
(Accepted September 9, 2003)