Approach for the Realisation of Sea Bottom Crustal Deformation Observations Targets and Tactics in Waters around Japan

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The Japan Hydrographic Department (JHD), has been pursuing two approaches using acoustic geodetic techniques to observe the crustal deformations on the deep sea floor to understand the mechanisms of major interplate earthquakes at subduction plate boundaries. One is the repeated acoustic ranging between two stations on the sea floor. The other is the linkage of GPS precise positioning of a sea surface platform and acoustic ranging between the sea surface and sea bottom transducers. The applicability of both methods to detect the plate motions of oceanic crust has already been demonstrated, through sea trials. In the JHD, there is a plan to realise operational surveys for the detection of sea bottom crustal deformations.

Introduction

Around Japan, thrust-type major earthquakes have occurred repeatedly beneath the deep ocean floor at the seismic coupling zone between the descending ocean-

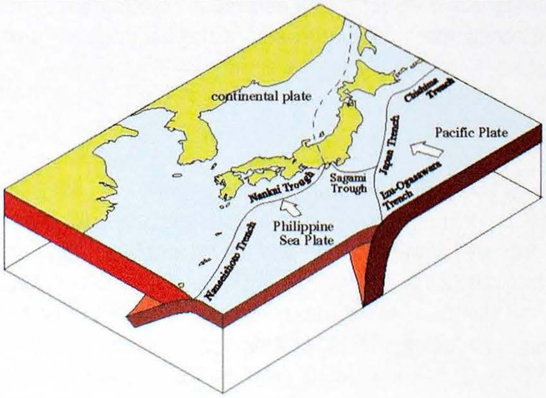

Figure 1: *Plates in the Japanese archipelago and surrounding area. Arrows in the figure show the relative motion of each plate in relation to the land plate. One theory holds that a plate boundary exists along the eastern margin of the Sea of Japan (Japan Sea) (broken line in figure). After Earthquake Research Committee (1998)*

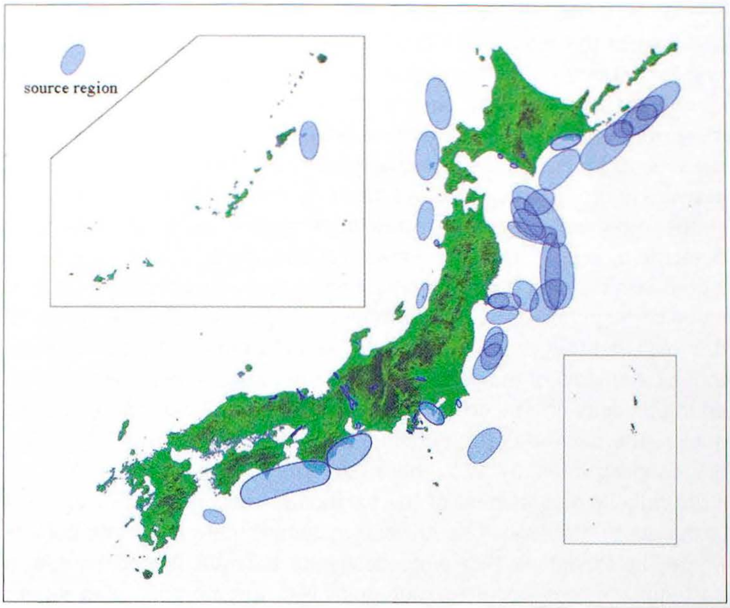

Figure 2: *The source region of the primary destructive earthquakes in the Japanese archipelago and surrounding areas (1885-1995, depths of 100 km or less). After Earthquake Research Committee (1998)*

ic plate and the overhanging continental crust. Along the Chishima Trench, Japan Trench and the Nankai Trough, zonal areas were covered by many source regions of major earthquakes between the trench axes and the land (Figure 1 and 2). For people living in the coastal areas, a surge of tsunami generated by a major earthquake occurring at the deep sea bottom is one of the most fearful natural hazards, in that they are given no information about what will happen in the ocean bottom crust.

The understanding of the mechanism of earthquakes and the prediction of earthquake occurrence has been an important subject of study for a long time in Japan. The mechanism of an earthquake source is considered to be the rupture process slipping on the underground fault surface. The solid earth, an opaque body, usually hides the natures of earthquake sources. Therefore, we estimate these processes through the records of seismic tremors radiated from the earthquake sources. For that purpose, large networks of seismographs have been established on the land in Japan. However, there is a question to be answered. When does the crust body transfer from the static state to the dynamic rupturing state on fault surfaces? In order to obtain a solution, it is important to understand the mechanism of earthquake generation. It is very difficult to obtain the mechanical situation of the crust directly. On the other hand, the changes of mechanical situation of the crust body may be estimated, to some degree, by observations of crustal deformations. Then, it is indispensable to observe and to record the details of crustal deformations in order to understand the mechanism of earthquake generation.

Space geodetic techniques have already achieved the monitoring of crustal deformations on land not only with high spatial and temporal resolutions but also with centimetre-level high accuracy. Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) have already revealed the present steady plate motions. Moreover, especially in Japan, the large network of Global Positioning System (GPS) continuous observation stations (GEONET) has been producing results contributing enormously to the widening of our understanding of the complicated crustal processes (e.g. Miyazaki and Hatanaka, 1997). Also, there has been considerable success in the high performance of remote sensing from airborne vehicles with the SAR (Synthetic Aperture Radar) technique (Massonnet, et al 1993). However, these space techniques are limited to land only and we may recognise that 70 % of solid earth surface is veiled by sea water.

Observation of Crustal Deformations at Sea Bottom

It is known that there exists a cycle of major interplate earthquake recurrence at the subduction plate boundary around Japan (Thatcher, 1984; Sato and Matsu'ura, 1992). A typical process is as follows. During most of a period, the crust is practically quiet, while a tectonic loading process progresses steadily within the zone of typically a few hundred kilometers width through the coupling of two plates. In some areas, the seismic coupling is complete at the plate boundary and almost all the relative plate motion is consumed by the elastic/viscoelastic deformation of crust. In other areas, the couplings are not complete and part of the relative motions may be consumed by many small slips or creeping on the plate boundary. The intensity of seismic coupling is dependent on the physical properties of the plate boundary, while it is impossible for us to observe these properties in the sites. When the accumulated stresses stemming from tectonic loading become greater than a critical value, the environment may be ready to start a dynamic rupture process. In some cases, the dynamic rupture may grow up to be a major earthquake of magnitude 8 or greater. In other cases, it may become a silent phenomenon to release the strain energy gently within a few hours or a few days without radiating dynamic tremors of ground, which may not be detected by the seismograph network (Kawasaki et al. 1995). After the occurrence of a major earthquake, a post-seismic slow deformation usually follows for a few years to pursue the gravitationally balanced condition through the viscous deformations of solid earth (Heki et al. 1997).

It is believed that the observation of sea bottom crustal deformations will promote an understanding on the mechanisms of major interplate earthquakes. The focuses will be on the following points. The first is on the process of pre-, co- and post-seismic crustal deformations associated with a major interplate earthquake. The second is the detection of silent earthquakes. The third is on the non homogeneity of seismic coupling intensity. With the investigation of sea floor crustal dynamics, it is hoped to contribute to more reliable assessment of the earthquake occurrence probability at the plate boundary.

In the south offshore of southwestern Japan, there is a plate boundary along the Suruga-Nankai Trough, where the Philippine Sea plate descends beneath the continental plate. At this plate boundary, major earthquakes have occurred repeatedly with a recurrence interval of about 100-200 years (Ando, 1975). The plate convergence rate is estimated at 3-5 cm/year. A conspicuous feature for this region is a current low seismic activity compared with the Japan Trench area. One speculation is that the coupling of a continental plate and an oceanic plate is almost complete. Then most relative motions are consumed by the deformation of the continental plate in the zone of about 100 kilometer width, which corresponds to the overlapping zone of the descending oceanic plate and continental plate (Ito et al., 1999). If this is right, it is expected that small relative motion will be observed between the coast and ocean bottom on the landward side of the Nankai Trough plate boundary.

On the other hand, the Japan Trench plate boundary, along which the Pacific oceanic plate descending beneath the continental plate, has different features with respect to crustal activities. The convergence rate is estimated 8 cm/year. Hino et al. (1996) investigated the non homogeneous distribution of seismic events along the Japan Trench. As well, the extrapolation of crustal deformations observed on land indicate the lack of homogeneity of plate coupling intensity (Ito et al., 2000; Nishimura et al. 2000). Although major earthquakes have occurred repeatedly in the vicinity of the Japan Trench, the distributions of source area and the recurrence time seem less systematic than those at the Nankai Trough. These features may be explained by the strong lack of homogeneity of plate coupling intensity between the descending oceanic plate and the overriding continental plate. The observation of sea bottom crustal deformation is expected to illustrate the lack of homogeneity effectively.

Development of Acoustic Techniques for Sea Bottom Geodesy

Contrasting to the advances of space geodetic techniques, due mainly to progress of remote sensing technology and communication technology with radio waves and/or optical signals, the geodetic techniques on the sea floor have not reached the level that they have on land. Methodological studies have been promoted at several institutes. In the Japan Hydrographic Department (JHD), based on the concept of developing acoustic techniques analogous with the geodetic technique with radio waves and optical signals, a programme has been initiated to develop the instruments at the beginning of 1990s.

Direct Path Acoustic Ranging between Two Sea Bottom Stations

The first approach of the JHD was the repeat of acoustic ranging between two sea bottom stations. In this paper, the method is called the Direct path acoustic ranging (DPAR) method. This approach is rather simple; the travel time of an acoustic pulse between two transducers placed on the sea floor is repeatedly measured. By drawing a graph of the travel time versus measurement time, it is intended to estimate the change of geometric range between two transducers to reveal the movement of sea bottom crust.

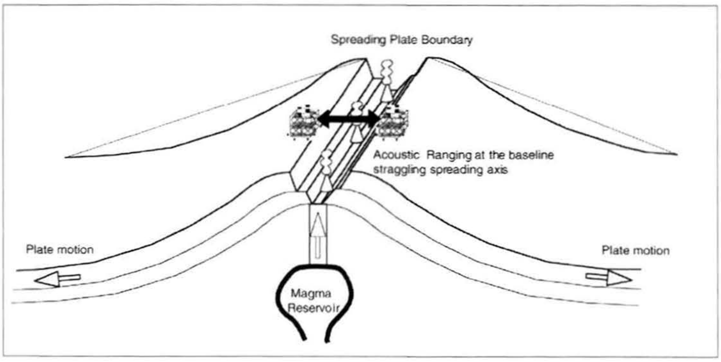

Figure 3: *Schamatic Image of the observation of dynamic spreading process wth direct path acoustic ranging at the baseline straggling over the spreading plate boundary*

One advantage of the DPAR method is that the environment of deep sea water, temperature and salinity, on which sound speed is dependent, is so stable compared with shallow sea water that the unpredictable influence on sound speed change can be reduced. Although the environment changes slightly even in deep sea water, it is possible to estimate and remove that influence by monitoring at several points of temperature with high temporal resolution enough to trace and clarify the process of environment changes.

By using the advantages of the DPAR method, Nagaya et al. (1999), Fujimoto et al. (1999) and Chadwell et al. (1999) have succeeded in a monitoring of range-changes at the baseline straddling the spreading plate boundary.

According to Nagaya et al. (1999), with an acoustic ranging system comprising twin units developed by JHD, which is called SeaFAR, propagation times of acoustic signals between two units can be measured repeatedly every hour with a resolution of two microseconds. In July 1997 two units were deployed on the sea floor at 2,600 metres depth across an axial trough at 18° 25' S on the Southern East Pacific Rise (SEPR) with the support of the manned submersible SHINKAI6500 and her mother ship YOKOSUKA (Figure

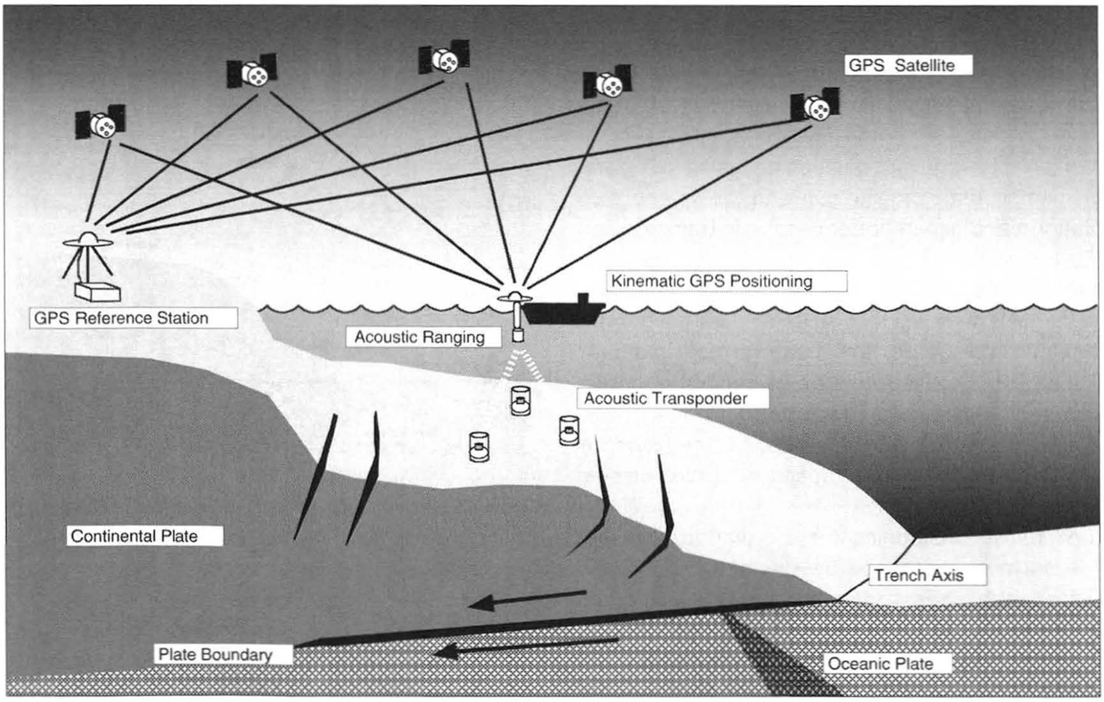

Figure 4: *Schematic Image of observation of sea bottom crustal deformation with the GPS/Acoustic positioning method at the vicinity of convergence plate boundary*

3). The spreading rate at SEPR is estimated to be about 16 cm/year in the plate motion model. Distance between the units was 870 m. In September 1998 all the instruments were recovered and complete acoustic ranging data from 25 July 1997 to 23 September 1998 were acquired. The duration of the observation was 426 days. The maximum difference of temperatures through all the duration observed was only 0.05 degrees Celsius, not only at the positions of the twin units but also at the mid point between them. Due to this stable condition, scattering of distances calculated from acoustic measurements and temperatures was so small that even the semi-diurnal variation with an amplitude of several millimeters was recognisable in calculated distances. This variation was caused by pressure variation due to ocean tide. After the correction using the global ocean tide model, the repeatability of the measurements proved to be 0.38cm in standard deviation.

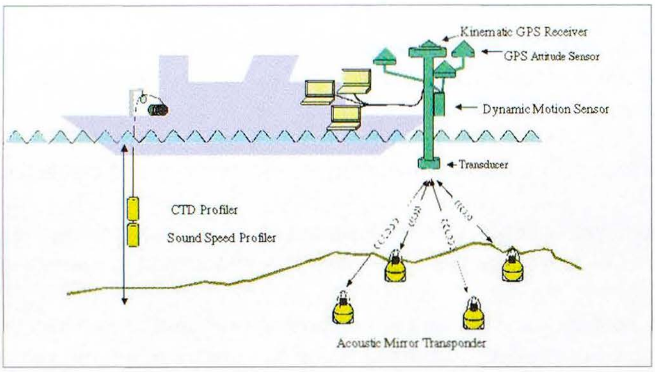

Figure 5: *On board system for the data collection with the GPS/Acoustic positioning method*

This is an important result to demonstrate the application of acoustic technique to the precise geodesy. Repeated measurements with short time interval clarified the dynamics of plate motion at fast spreading plate boundary. However there are disadvantages in the DPAR method. Because of the nature of sound ray path that is convex downward in the waters deeper than, typically, 1000 m, the measurement of a long-range baseline is difficult. This is serious for the subduction plate boundary, where the deformation area expands the zone of 100 km width or more, while in the fast spreading boundary, the deformation area is concentrated in a narrow zone of about a few km.

GPS/Acoustic Positioning

Another approach for sea bottom geodesy is promoted at several institutes (Spiess and Hildebrand, 1995; Spiess et al., 1998; Obana, 1998; Asada and Yabuki, 1999). This is analogous to GPS geodesy on land, while the linkage is necessary of sea surface precise positioning using GPS and precise acoustic ranging between the sea surface platform and ocean bottom acoustic transponders (Figure 4). In this paper, the authors call this method GPS/Acoustic Positioning (GAP) method. In the GAP method, four kinds of data have to be obtained on board the sea surface platform (Figure 5); (1) GPS signal measurement data, (2) acoustic ranging data of sea bottom transponder, (3) records of the dynamic motion of sea surface platform, and (4) sound speed structure of sea water.

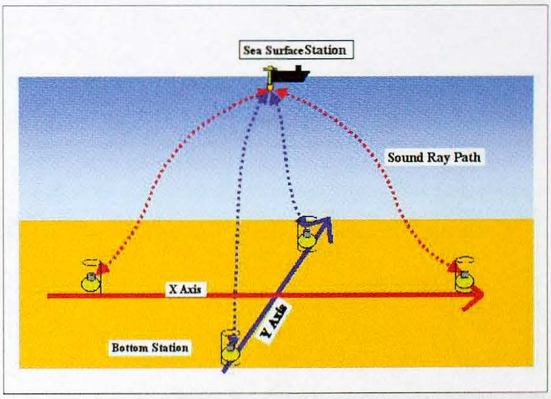

Figure 6: *Simultaneous multi-directional acoustic ranging with rhombus formation of four bottom transponders. If the sound speed structure is stratified, the curves of ray paths are symmetrical and the position of sea surface transducer is able to determine precisely if given the assumed positions of sea bottom transponders. By comparing the position of sea surface platform obtained kinemathic GPS, we can estimate the deviation of true postion of sea bottom transponders from assumed positions*

The precise positioning for the platform on the sea surface is realised by kinematic GPS technique which uses carrier wave phase measurements as well as code based pseudo ranges (e.g. Colombo, 1999; Han, 1997). For the realisation of precise acoustic range measurement from the sea surface to sea bottom, it was necessary to develop a precise acoustic transducer (Spiess et al., 1980).

The complexity of the sound speed structure is a further environmental problem to measure the range between sea surface and sea bottom transducers. As is well known, the sound speed structure depends strongly on the water depth. It is possible to obtain, with some accuracy, the dependence of sound speed on vertical co-ordinate by using the CTD (Conductivity Temperature and Depth) sensor and/or sound speed meter. However, it is necessary to take into account that the structure must contain horizontal non homogeneity as well as its dependence on time. It may be difficult to reveal the temporal and spatial complexity of structure accurately by the observations from the sea surface platform.

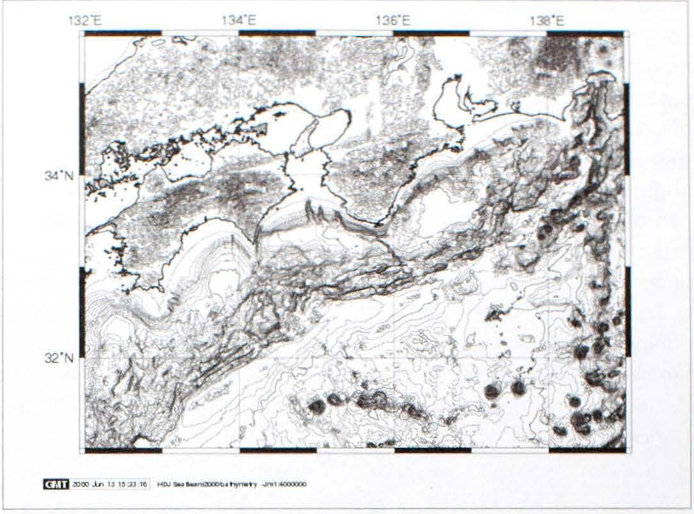

Figure 7: *Positions of Sea bottom Geodetic Mark established with three transponders in Feburary 2000 (Solid Triangle). Contour chart is prepared from Digital Map 50 m grid (Elevation) of Geographical Survey Institute and JEGG-500 bathymetry grids (Asada, 2000)*

One way to overcome this problem is simultaneous multi-directional range measurement with three or more stations on the sea floor (Figure 6). With this method, it is intended to decrease the errors caused by the temporal changes of vertical sound speed profile, although the errors caused by horizontal variations may remain.

The advantages of GAP for the observation at deep sea bottom around subduction zones are the following. (1)The sea bottom precise acoustic transponder is rather simple in design because of its simple function to send the signal that has the same wave form as the received form (Spiess et al., 1980). (2) Neither underwater cable connection nor acoustic data transmission technique is necessary; which may be very expensive or rather unreliable. (3) It is easy to establish a network of geodetic stations on the sea floor. On the other hand, a disadvantage is the difficulty or high cost performance to continue observations for a long term because it needs some platform on the sea surface to collect the data. Furthermore, as mentioned above, the acoustic ranging path travels in the surface layer that is rather unstable and complex. Also the pitch, roll and heave of sea surface platform are sources that may reduce the precision.

Figure 8: *Photo of a precise transponder of JHD to use GPS/Acoustic positioning just before the placement on the sea floor*

Spiess et al. (1998) have already succeeded in the detection of ocean plate motion at the Juan de Fuca ridge. The location of the sea floor station is in the Northeast Pacific ocean, about 150 km off the coast of North America. Two GPS reference stations are located in Vancouver Island, Canada. The result of three survey cruises conducted from 1994 to 1996 shows the linear change of the sea floor station relative to the GPS reference station with a rate of about 4 cm/year, the trend of which is consistent with the plate motion model. This is the first report of the successful plate motion detection.

The JHD has also pursued the GAP method as an acoustic geodetic technique since 1996 (Asada and Yabuki, 1999). After many trials and errors, succeeding in designing of implementing instruments of sea bottom precise transponder, work was started in February 2000, to collect the field data for GAP. An ocean bottom geodetic station has been deployed, in an area of about 2,010 m depth, on the land side of the Nankai Trough subduction plate boundary, about 70 km south off of the Kii peninsula, central Japan (Figure 7 and 8). That station consists of a set of three precise acoustic transponders placed at three corners of a square on the flat sea floor, with side spacing of about 1400 m. The first trial to collect the measurement data was conducted just after the deployment. The GPS reference stations are located at two points on land 70-100 km away from the sea bottom station. During the collection of the acoustic data, the ship drifted to avoid the propeller noise.

Experiencing the success of first trial measurements this February, JHD plans to repeat the cruise a few times per year to collect GPS/acoustic positioning data in order to investigate the long term repeatability. Furthermore, in addition to the accumulation of field data of acoustic ranging and kinematic GPS positioning, the data processing program had to be improved, focusing especially to clarify the influence of the horizontal heterogeneity of the sound speed structure. In addition to this first station at the vicinity of Nankai trough, the JHD has established in July 2000, another stations at the landward side of the Japan Trench.

Concluding Remarks

The JHD has been promoting the development and field survey with both the DPAR and the GAP methods. Both have already demonstrated the applicability for the detection of sea bottom crustal movements through the successful field experiments.

Now, the JHD implements operational surveys to collect field data with the GAP system at the Japan Trench subduction boundary by using two stations established in July 2000. As mentioned above, the GAP method is more capable of revealing the deformations at wider zones than the DPAR method. By establishing a network of sea bottom stations along, for example, the Japan Trench, it is expected to understand the nature of ocean bottom dynamics and mechanism of major interplate thrust-type earthquakes. However, both methods have their own advantages. With the DPAR method like the SeaFAR system, it is possible to collect the ranging data more frequently than with the GAP method, it will also be possible to clarify the dynamics of crustal deformations caused by steady plate motions. Therefore, it is considered that it is necessary to promote the observations with the DPAR method by selecting appropriate sites, for the investigation of the sea bottom crustal deformations around Japan.

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References

Ando, M., Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan, Tectonophysics, 27, 119-140, 1975

Asada A., 500m Mesh Bathymetry Data around Japan and Vsiual Edit Program, Jour. Japan Soc. Mar. Surv. Tech. 12, 21-33, 200.

Asada, A. and T. Yabuki, Acoustic ranging system for ocean bottom geodesy and synthetic aperture technique of a multi-beam echo sounder, International Workshop on recurrence of great interplate earthquakes and its mechanism, proc. 65-75, 1999.

Colombo, O. L., Long-Distance Kinemaic GPS, in "GPS for Geodesy 2nd Edition", edited by. P. J. E. Teunissen and A. Kleusberg, Springer, 537-568, 1998

Chadwell, C.D., J.A.Hildebrand, F.N. Spiess, J.L.Morton, W.R. Normark, C.A.Reiss, No Spreading across the Southern Juan de Fuca ridge axial cleft during 1994-1996, Geophys. Res. Lett., 26(16), 2525-2528, 1999

Fujimoto H., Long-term ocean bottom pressure measurement and acoustic ranging across the spreading axis of the southern East Pacific Rise, JAMSTEC J. Deep Sea Res., 14, 35-42, 1999 (in Japanese)

Han, S., Carrier phase-based long range GPS kinematic positioning, Report from School of Geomatic Engineering, University of New South Wales, Sydney, NSW 2052, Australia, 1997

Earthquake Research Committee, Seismic Activity in Japan, -Regional perspectives on the characteristics of destructive earthquakes- (Excerpt), compiled by the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion, 1998 {http://www.jisin.go.jp}

Heki, K., S. Miyazaki, H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench, Nature, 386, 595-598, 1997

Hino, R., T. Kanazawa and A. Hasegawa, Interplate seismic activity near the northern Japan Trench deduced from ocean bottom and land-based seismic observations, Phys. Earth Planet. Inter., 93, 37-52, 1996

Ito T., S. Yoshioka and S. Miyazaki, Interplate coupling in southwest Japan deduced from inversion analysis of GPS data, Phys. Earth Planet. Inter., 115, 17-34, 1999

Ito T., S. Yoshioka and S. Miyazaki, Interplate coupling in northwest Japan deduced from inversion analysis of GPS data, Earth and Planetary Science Letters, 176, 117-130, 2000

Kawasaki, I., Y. Asai, Y. Tamura, T. Sagiya, N. Mikami, Y. Okada, M. Sakata and M. Kasahara, The 1992 Sanriku-Oki Japan, ultra-slow earthquake, J. Phys. Earth, 43, 105-116, 1995

Massonnet, D., M. Rossi, C. Carmona, A. Adragna, G. Peltzer, K. Feigl and T. Rbaute, The displacement field of the Landers earthquake mapped by radar interferometry, Nature, 364, 138-142, 1993

Miyazaki, S. and Y. Hatanaka, Crustal deformation observed by GSI's new GPS array, EOS Trans, AGU, 78, S104, 1997

Nagaya. Y., T. Urabe and T. Yabuki, Crustal Deformation Observation at the Crest of EPR 18.5S with the Seafloor Acoustic Ranging Method, EOS Trans, AGU, 1999 Fall Meeting, 80, No.46, 1999

Nishimura, T., S. Miura, K. Tachibana, K. Hashimoto, T. Sato, S. Hori, E. Murakami, T. Kono, K. Nida, M. Mishima, T. Hirasawa and S. Miyazaki, Distribution of seismic coupling on the subducting plate boundary in the northeastern Japan inferred from GPS observations, Tectonophysics, 323, 217 238, 2000

Obana K., Development of Seafloor Positioning System with GPS-acoustic Link for Crustal Dynamics Observation, D. Thesis, Kyoto University, Japan, 99p, 1998

Sato T. and M. Matsu'ura, Cyclic crustal movement, steady uplift of marine terraces, and evolution of the island arc-trench system in southwest Japan, Geophys. J. Int., 111, 617-629 1992.

Spiess, F. N., C. D. Chadwell, J. A. Hildebrand, L. E. Young, G. H. Percell Jr. and H. Dragert, Precise GPS/Acoustic positioning of seafloor reference points for tectonic studies, Phys. Earth Planet. Inter., 108, 101-112, 1998

Spiess, F. N. and J. A. Hildebrand, Employing Geodesy to Study Temporal Variability at a Mid-Ocean Ridge, EOS Trans., AGU, 76, No.45, p451, p455, 1995

Spiess, F. N., D. E. Boegeman, F. V. Pavlicek and C. D. Lowenstein, 1980, Precision transponder and method of communicating therewith, U.S. Patent 4,214,314, 1980

Thatcher, W., The earthquake deformation cycle at the Nankai trough, southwest Japan, J. Geophys. Res., 89, 3087-3101, 1984

Biography

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