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Long-Period Volume-Strain Seismogram of the 8 August 1993 Esashi-Oki Earthquake, off Southwest of Hokkaido, Japan and its Source Mechanism

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Abstract

We present an analysis of the volume-strain data for source parameters of the 8 August 1993 Esashi-Oki earthquake ($M_{JMA}=6.3$) which may have been induced by the 12 July 1993 Hokkaido-Nansei-Oki earthquake ($M_{JMA}=7.8$). Several numerical experiments were carried out to test the hypothesis that the data dependency is attributed to the effect of the source mechanism on the volume-strain seismograms. We used the long-period volume-strain seismogram ($DC \leq T \leq 30$ Hz) recorded at the Urakawa Seismological Observatory (KMU) of Hokkaido University, about 230 km south-east of the epicenter of the mainshock. The synthetic volume-strain seismograms were calculated using the normal mode theory. The experiments provided the best fitted source parameters: (strike, dip, rake)=(196°, 57°, 90°) with the seismic moment $M_0=2.8\times10^{18}$ Nm ($M_W=6.2$). This solution is similar to the CMT solution obtained by using the world-wide long-period seismograms, of which mechanism is characterized by steeper-dipping and north-south-directing nodal planes. This result is supported by the distribution of aftershoks. Such a volume-strain seismogram may provide not only an estimation of the seismic moment but also a refinement

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of the earthquake mechanism solution.

1. Introduction

The measurement of strain change in the earth is fundamentally important to the understanding of earthquakes in two ways. The first is to observe the changes in the "DC" strain field, the so-called "strain steps" associated with earthquakes in an active seismic region. These provide clues to the earthquake mechanism and may allow an assessment of seismic efficiency to be made. It is also of great interest to see whether there is any recognizable change in the strain field shortly before an earthquake. The second is to observe the secular changes in the strain field to determine how strain accumulation and earthquake occurrence are related.

Sacks et al. (1968) developed the Sacks-Evertson bore-hole strainmeter (hereafter referred to as SEBS) to observe such strain changes. The SEBS have a large dynamic range and high sensitivity from zero frequency to 30 hertz. Strains smaller than 10^{-11} can be observed. Vibration tests have demonstrated that the instrument behaves linearly even when subjected to high accelerations. They have reported on direct observations of strain changes which occur as slow earthquakes (Sacks et al., 1978, 1981). These slow earthquakes resemble normal earthquakes but have longer time scales; i.e. lower rupture velocities and/or longer rise times. This suggested that such slow earthquakes may provide one mechanism for stress redistribution. The Japan Meteorological Agency (JMA) installed SEBS at numerous observation points centering on the Tokai and Kanto regions of Japan (Suyehiro, 1982). Sacks et al. (1981) have demonstrated that slow rupture followed the Izu-Oshima earthquake of 1978. SEBS were also installed at the three stations (GJM, TAZ and SWU) of the Tohoku University observation network in Tohoku region, Japan. By using the data come from one station GJM of the network, Linde et al. (1988a, 1988b) found the episodic slow events which were observed to occur before the Japan Sea earthquake of magnitude 7.7 on 26 May 1983. They proposed that episodic aseismic slip events were an important mechanism for stress redistribution in seismically active regions.

Furuya and Fukudome (1986) studied the instrumental reponse of SEBS to various disturbances; atmospheric pressure change, seismic waves, tides, secular strain changes, abnormal step-like signals and co-seismic steps. They have drawn the conclusion that SEBS can provid data necessary for determining seismic moment from the magnitude of co-seismic steps.

In November of 1982, we also installed SEBS at the Urakawa Seismological Observatory in Urakawa (hereafter referred to as KMU), Hidaka district of Hokkaido, Japan, as part of a cooperative program between Hokkaido University and the Carnegie Institution of Washington.

On 12 July 1993 at 04:42 JST, the Hokkaido-Nansei-Oki earthquake ($M_{JMA}=7.8$) occurred off southwest Hokkaido, roughly 250 km north of the mainshock of the 1983 Japan Sea earthquake ($M_{JMA}=7.7$). These source regions of the two great earthquakes adjoin each other to the north and south. They also lie along the eastern end of the Japan Sea, which is the boundary between the Eurasian (or Amur) and North Amemican plates proposed by Nakamura (1983) and Kobayashi (1983). The 1993 Hokkaido-Nansei-Oki earthquake is the first significant event recorded by SEBS at KMU, thus providing us the first opportunity to examine the source mechanism of a major earthquake along this plate boundary. However the mainshock was too large for SEBS recording system to record a perfect strain step even though SEBS acted upon the strain change associated with the mainshock. One of the original features of the recording system was dual protection of the sensors against acceleration due to nearby large earthquakes. Therefore, the first protection level setting was not suitable for the recording of the Nansei-Oki earthquake ($M_{JMA}=7.8$) mainshock.

On the contrary, SEBS accurately captured the volume-strain seismogram from the largest aftershock ($M_{JMA}=6.3$), which we called the Esashi-Oki earthquake, which occurred at 04 : 42 JST on 8 August 1993, roughly 100 km southeast of the mainshock of the Hokkaido-Nansei-Oki earthquake. The former Hokkaido-Nansei-Oki earthquake may have induced this event.

In the present paper, we first deal with the dependency of the volume-strain data on the source mechanism of the event using the normal mode theory (Gilbert and Dziewonski, 1975). After such theoretical experiments to test the attribution of the volume-strain to the source mechanism solution, we next try to refine the source mechanism and the moment magnitude for the later event. In advance of this analysis, we will review the 1993 Hokkaido-Nansei-Oki earthquake in the next chapter.

2. The 1993 Hokkaido-Nansei-Oki earthquake

2.1 The variety of focal mechanisms

At 13 : 17 (GMT) on 12 July 1993, the volume-strain meter at KMU recorded an earthquake measuring magnitude 7.8 on the Richter scale which occurred off southwest Hokkaido, Japan. The earthquake was named the Hokkaido-

Nansei-Oki earthquake by JMA. The earthquake and its subsequent tsunamis that struck Hokkaido caused about 200 deaths. This was the biggest of the earthquakes that have occurred along the east side of the Japan sea in recorded history. The seismic moment M_0 of 5.6×10^{20} Nm (corresponds to $M_W = 7.8$) with a (fixed) centroid depth (a point source representive of the overall faulting) of 15 km was estimated by Harvard University scientists (1993). Assuming a fault length of about 150 km and a fault width of 50 km based on aftershock data and a shear modulus of 3×10^{10} N/m^2, this moment and fault geometry suggests an average slip of 2.5 m on the fault plane.

Immediately after the earthquake, several preliminary investigations of the long-period CMT inversions were reported by the Harvard University scientists group (1993), Sipkin (1993), Nakanishi et al. (1993), and Tanioka et al. (1993). These inversions propose similar focal mechanisms, which are characterized by a shallow-dipping east-plunging nodal plane. Several investigators proposed that the source process of the event was very complex, mainly based on inversions of long-period waves using the Centroid-Moment-Tensor (CMT) inversion method and on body-wave inversion by Nakanishi et al. (1993). However, the body-wave inversion presents some dissenting information; it proposed a nodal plane with shallow dip dipping toward the west rather than the east. The discrepancy between the two methods was discussed in some papers (see August 24 issues of EOS). As stated in EOS, the CMT method gives an integrated view of the overall faulting geometry. Therefore if we had analyzed the observed strain seismogram ($T > 70$ sec) from the mainshock, it should have been much more similar to the result obtained by the CMT method rather than to that obtained by the body-wave inversion method. A problem that is pertinent to the fault-dip controversy is, however, raised again by recent analyses by Mendoza and Fukuyama (1994) and Kuge et al. (1996). For the source process of the 12 July 1993 Hokkaido-Nansei-Oki earthquake, Kuge et al. (1996) emphasized that the preferred-rupture model consists of a series of thrust-fault subevents which are characterized by one of two faults geometries with shallow-dipping nodal planes toward the west or east. Such a rupture model may be also consistent with the volume-strain seismogram at KMU. The observation equipment, however, was not suited to record such a huge earthquake. We had not experienced such a huge earthquake before this event. In Chapter 3, the observation by SEBS at KMU will be discussed in detail, showing the volume-strain seismogram for the Hokkaido-Nansei-Oki earthquake.

In the next subsection, we will review the distribution of the aftershocks of the Hokkaido-Nansei-Oki earthquake.

2.2 *Aftershock Distribution*

Numerous aftershocks of the Hokkaido-Nansei-Oki earthquake have been observed by the seismic network of the Research Center for Earthquake Prediction of Hakkaido University (hereafter referred to as RCEP). The distribution of aftershock foci determined by RCEP is shown in Fig. 1 (a)

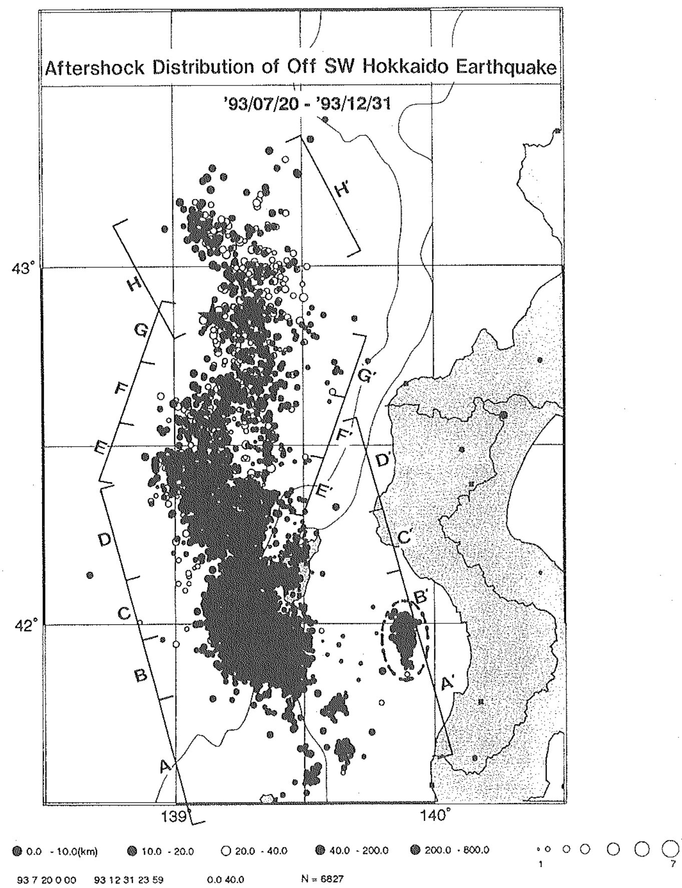

Fig. 1. (a): Aftershock distribution of the 1993 Hokkaido-Nansei-Oki earthquake located by the RCEP of Hokkaido University during the period between 20 July 1993 and 31 December 1993. Star indicates the epicenter of the mainshock. Solid squares indicate the seismograph stations. AA′, BB′, ⋯, HH′, SN indicate the regions in which the foci of hypocenters are projected on the vertical cross-sections (b), ⋯, (d). The source region of the Esashi-Oki earthquake is circled by a dotted line.

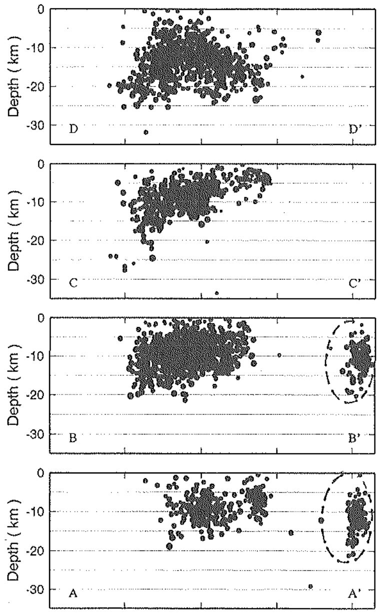

Fig. 1 (b).

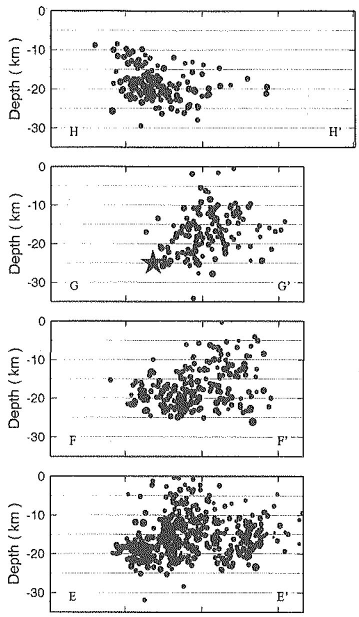

Fig. 1 (c).

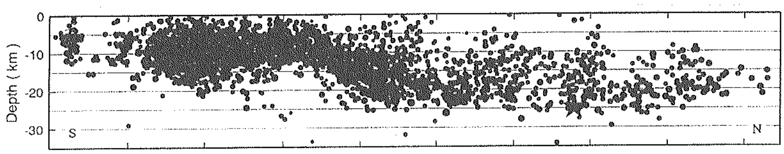

Fig. 1 (d).

together with the main event for the period from 20 July 1993 to 31 December 31 1993 (Kasahara et al., 1994 ; Kodaira et al., 1994). The distributions of the foci projected on vertical cross-sections for eight different areas are shown in Fig. 1 (b)-(d).

Such an aftershock distribution is one of the basic data used to delimit the fault planes of the earthquake process. The size of the aftershock area is roughly consistent with the seismic moment estimated by the Harvard University scientists group (1993). But in the nearly east-west cross-section, we notice a weak indication for a westerly dipping aftershock distribution. It seems to be inconsistent wih the idea of stable subduction of the Eurasian (or Amur) plate beneath the North American plate along the eastern end of the Japan Sea. This result might suggest that the earthquake process of the main event was fairly complex.

In this connection, Hino et al., (1994) deployed 23 OBS (Ocean Bottom Seismographs) over the aftershock area during the period from 21 July 1993 to 16 August 1993. Using the data obtained from the dense OBS network covering the source region, they determined that the distribution of aftershocks was narrower and/or thinner than that deduced by the Hokkaido University seismic network deployed on land. They further argued that several active clustered zones were definitively found in the aftershock area. They asserted that their findings were attributed to proximal the proper OBS deployment over the aftershock area. The configuration of the clustered aftershocks might correspond to the complexity evidenced during stress release in the source region.

Meanwhile, on 8 August 1993, the Esashi-Oki earthquake ($M_{JMA}=6.3$) occurred outside the source region of the Hokkaido-Nansei-Oki earthquake. The epicenter of the event was located at a distance of about 100 km to the southeast of the position of the first break of the main quake. In view of the extent of the rupture, it thus remains a controversial question whether the event is the largest aftershock associated with the Hokkaido-Nansei-Oki earthquake or not. Even though it is isolated from the major aftershock region, we think it occurred as a consequence of the tectonic-stress release induced by the

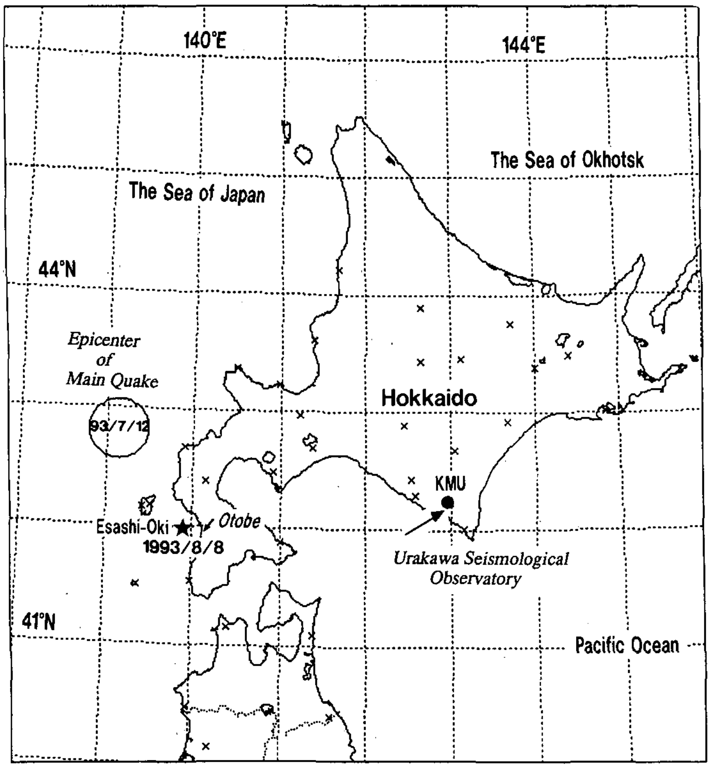

Fig. 2. Geographical map of the locations of the epicenter of the 1993 Hokkaido-Nansei-Oki earthquake (large circle), the 1993 Esashi-Oki earthquake (asterisk) and SEBS of the Urakawa Seismological Observatory (solid circle).

Hokkaido-Nansei-Oki earthquake.

As the epicenter of the Eashi-Oki earthquake is much closer to the coast town of Otobe rather than the principal source region of the main quake (see Fig. 2), the extraordinarily strong acceleration seismogram (maximum acceleration of 1.6 g) was recorded by the temporary observation site in the town (Sasatani et al., 1994). They explained the unusually strong acceleration as result of the larger amplification due to both the thick terrace deposits at the observation site and the radiation pattern at the earthquake source.

The many aftershocks followed the main event within the narrow region with a north-south length of 15 km, an east-west width of 5 km and a depth of 15 km. The distribution of events seems to be clustered around the main event and its area is apparently larger than that inferred from both the size of the seismic moment of 2.8×10^{16} Nm (Harvard University scientists group, 1993) and the common stress drop of 30 bar (by assuming a circula crack model). In general, it is not surprising that the distribution of the hypocenters spreads spatially with the elapse of time from the first break of the main quake. Further, the locations of the hypocenters have their own errors corresponding to the configuration of the observational network. The location errors of the hypocenters may be as great as several km due to the limitations inherent in the present sparse observation network. The activity of the aftershocks is a kind of induced seismicity coupled to the occurrence of the main quake. It is of great interest to better understand the source mechanism of the event, which may be reflected in a wider stress field than the source region of the main quake.

In order to derive the mechanism solution from the independent volume-strain seismogram, we calculated the synthetic strain seismograms (>70 sec) by the normal mode theory. To begin the calculation, we referred to the source parameters reported by several authors (e.g., Harvard University scientists group, 1993 ; Sipkin, 1993 ; Kikuchi, 1993). At the same time, we calibrated the observed strain seismograms by the instrument-specific parameters of SEBS. Then we attempted to determine the best fault mechanism solution fitted to the Esashi-Oki earthquake. In this connection, we can say that the long-period surface-wave inversion calculated by the Harvard University scientists group (1993) provided a quite similar earthquake mechanism to the result calculated by the body-wave inversion method of Kikuchi (1993). It is also supported by Iwata and Irikura (1993) and Fukuyama (1994). The result is very helpful in considering whether our final solution is viable or not.

Fortunately, SEBS have recorded the full-strain signal of the Esashi-Oki earthquake. In the later chapter 4, we will discuss the co-seismic behavior of the earthquake.

3. Observation of volume-strain data at the Urakawa Seismological Observatory (KMU)

As described in the preceding chapter, in late 1982 we installed SEBS at the Urakawa Seismological Observatory (KMU) of Hokkaido University, located in the Hidaka region of Hokkaido, Japan. The signal from SEBS has been continuously recorded on paper charts whose speeed is 0.5 cm/hour. At the same time, the digital record (processed by 16 bit A/D converter) has been continuously sent to the central recording site of Hokkaido University in Sapporo by the real-time telemetry network system. As an example of a typical record, Fig. 3 shows about two days of strain data from July 11, 00 : 00

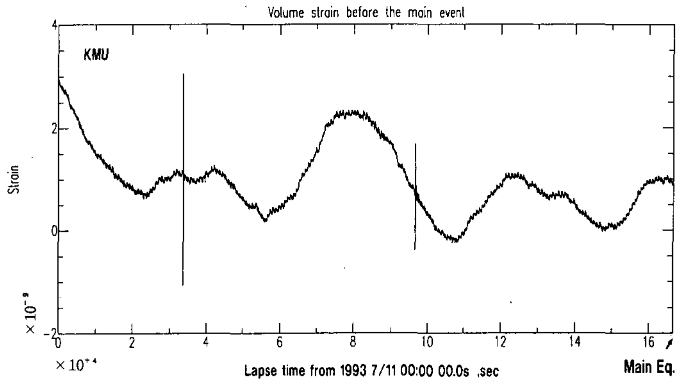

Fig. 3. The raw volume-strain change just before the main event of the 1993 Hokkaido-Nansei-Oki earthquake since *00 : 00* hours, *11* July *1993*. Two vertical lines on the trace indicate the co-seismic responses of the regional earthquakes off Urakawa, M=4.6 and the Kuril islands, M=5.5).

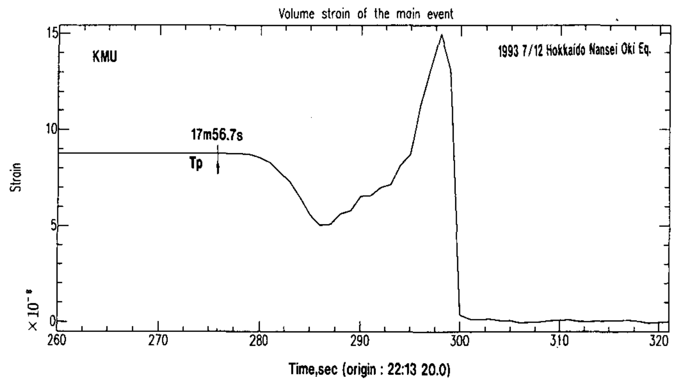

Fig. 4. The volume-strain seismogram for the 1993 Hokkaido-Nansei-Oki earthquake recorded by SEBS at KMU. The starting time of the trace is measured from 22 : 13 hours, 20.0s, 12 July 1993. The vertical line on the trace shows the arrival time of P-wave, read from the short period seismogram at the same station (KMU).

hours just prior to the main event. The main long period (order of half-day) variations shown are primarily in response to earth tides, but they are not important in the present context. Two vertical lines across the trace mean the regional earthquakes off Urakawa (July 11, 09 : 25 hours 15.55s, M=4.6, depth=65 km) and in the Kuril islands (July 12, 02 : 48 hours 09.95s, M=5.3, depth=21 km), respectively. The additional noise may be related to weather conditions, since local fluctuations in atmospheric pressure have been shown to be sources of noise (Sacks et al., 1971 ; Evertson, 1975). The digital record transmitted to the recording site is shown in Fig. 4 for the Hokkaido-Nansei-Oki earthquake. As for the Hokkaido-Nansei-Oki earthquake, the valve was opened automatically by SEBS circuits during the main motion since we had set the safty cut-off threshold to the lower emergent level for advance protection against potentially damaging strains. Consequently, the best possible strain seismogram of the event was not recorded by SEBS. The valve was opened 23 seconds after the P wave arrived and remained open for about 3 minutes. Therefore, we could not estimate the main strain steps while the valve had been opened. However, following Nakanishi and Kikuchi (1993), the total duration-time of the first break in the two prominent fractures of the complex fault movement event took about 20 seconds. Therefore, we thought that the strain change accompanying the first break in the faulting event might be estimated correctly. From the strain change recorded on the paper chart at the KMU, we estimated the strain change (Fig. 5). 1.6×10^{-9} (peak to peak in strain) was estimated from

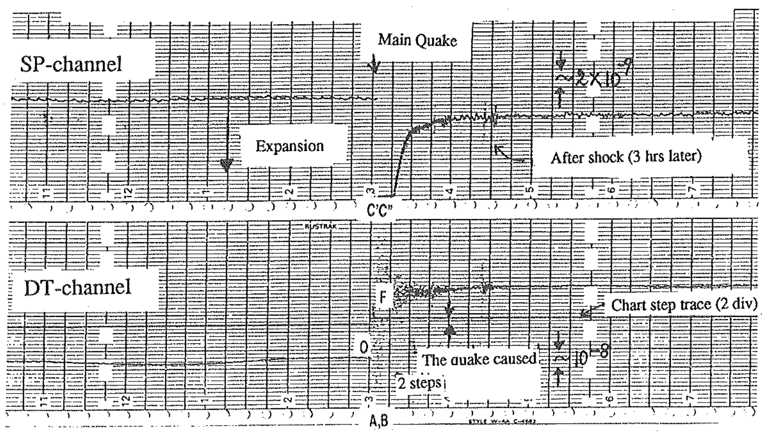

Fig. 5. The paper-chart record for the volume-strain changes produced by the 1993 Hokkaido-Nansei-Oki earthquake, recorded at KMU. The paper speed is: 2 divisions on the time axis = 1 hour. The frequency response of the DT-channel (lower) is flat to zero frequency, but the SP-channel (upper) is high-pass filtered at a period of 25 minutes with one pole. The amplitude ratio of SP-channel to DT-channel is 5×. The deflection through five small divisions as marked, is equivalent to about 1.5×10^{-8}. At point A, the trace shifted to the top of the chart. And the trace moved to bottom of the chart at point C becuse of the earthquake, then shifted to point B. The trace shifted again to the top of chart, then moved to its final position, F. Note: the total step is obtained by $OA+C'B+C''F$ ($A\equiv B\equiv$ & $C''\equiv C'$).

the first swing of maximum amplitude, which is close to the strain value of 1.55×10^{-9} which is inferred from the seismic moment of 2.5×10^{19} Nm estimated by Nakanishi et al. (1993). The best calculated strain step derived from observations is roughly consistent with the other seismic moment estimated from the moment tensor inversion by using the world-wide seismological network data.

On the contrary, the Esashi-Oki-earthquake regarded as the Hokkaido-Nansei-Oki earthquake's largest aftershock, occurred near the coastline of southwest Hokkaido. The epicenter was about 100 km to the southeast of the main event, as shown in Fig. 1. The strain seismogram for the event was completely recorded by SEBS from start to finish.

Motivated by this perfect observation, we have studied the strain seismogram from the point of view of dependency on the source mechanism, using the theoretical strain seismograms calculated by the normal mode theory.

In the next chapter, we will describe the experiments using the strain seismogram of the Esashi-Oki earthquake.

4. Experiments of the dependency of volume-strain seismogram on the source mechanism

4.1 Estimation of the parameters of the source mechanism

In order to explore the dependency of the volume-strain seismogram observed for the Hokkaido-Nansei-Oki earthquake, several numerical experiments have been carried out assuming that the strain data is attributed to the effects of the source mechanism on the strain data, and that the geomery of the focal mechanism of the earthquake is mainly characterized by the directions of strike and dip angles of the two fault planes. Changing these fault parameters, we calculated the theoretical volume-strain seismograms based on the normal mode theory (Gilbert and Dziewonski, 1975). Then we used a data set of eigen periods ($T>45$ sec) and associated eigen functions calculated by Buland and Gilbert (1976) for earth model 1066A after Gilbert and Dziewonski (1975).

Generally speaking, the normal modes of oscillation of the non-rotating, sherically symmetric Earth are of two kinds, the poloidal (spheroidal) and the toroidal (torsional) oscillationss. Gilbert and Dziewonski (1975) showed that it is convenient to factor the displacement response $\boldsymbol{u}$ into three terms: the source, represented by the moment rate tensor $\boldsymbol{M}$, the multiplet spectrum $\boldsymbol{C}_k(\omega)$, and the state function or transfer function $\boldsymbol{A}_k$,

$$\boldsymbol{u}(\boldsymbol{r},\omega)=\sum_k \boldsymbol{A}_k(\boldsymbol{r})\cdot\boldsymbol{M}(\omega)\boldsymbol{C}_k(\omega)$$

Before representing the expressions for $\boldsymbol{A}_k(\boldsymbol{r})$, we write the elements of the moment rate tensor in terms of its principal values. In the conventional coordinate system, adopted here, for the source mechanisms, the pole is the epicenter, r-axis inreases radially, the θ-axis southerly, and the ϕ-axis easterly. In terms of the principal values of the moment tensor, τ_i: $i=1, 2, 3$, their azimuths ζ_i, measured with respect to North, and plunges η_i, the elements of the moment rate tensor $\boldsymbol{M}(\boldsymbol{t})$ for the spherical coordinates (r, θ, ϕ), with the source coordinates adopted, the epicentral coordinates of a receiver at azimuth η from the source are co-latitude (epicentral distance) θ and epicentral longitude $\phi=\pi-\zeta$, are

$$M_{rr}=\tau_i \sin^2 \eta_i,$$
$$M_{\theta\theta}=\tau_i \cos^2 \eta_i \cos^2 \zeta_i,$$
$$M_{\phi\phi}=\tau_i \cos^2 \eta_i \sin^2 \zeta_i,$$
$$M_{r\theta}=\frac{1}{2}\tau_i \sin^2 \eta_i \cos\ \zeta_i,$$
$$M_{r\phi}=-\frac{1}{2}\tau_i \sin^2 \eta_i \sin\ \zeta_i,$$
$$M_{\theta\phi}=-\frac{1}{2}\tau_i \cos^2 \eta_i \sin^2 \eta_i,$$

where summation over $i=1, 2, 3$ is implied. A spheroidal motion is one for which the radial component of $\nabla\times \boldsymbol{u}$ and $\nabla\cdot\boldsymbol{u}=\boldsymbol{0}$ (Aki and Richard, 1980). We can obtain the strain components for the spherical coordinate by the following operation:

$$e_{rr}=\frac{\partial u_r}{\partial r},$$
$$e_{\theta\theta}=\frac{1}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{u_r}{r},$$
$$e_{\phi\phi}=\frac{1}{r\sin\theta}\frac{\partial u_\phi}{\partial\phi}+\frac{u_\theta}{r}\cos\theta+\frac{u_r}{r},$$
$$\Delta=e_{rr}+e_{\theta\theta}+e_{\phi\phi},$$

where u_r, u_θ, and u_ϕ are the r, θ, ϕ components of displacement. Δ is the cubical dilatation neglecting higher-order terms. The volume strain Δ for spheroidal modes at $r=R_E$ is

$$\Delta^\ell=\frac{(1-2\sigma)}{(1-\sigma)}(e_{\theta\theta^\ell}+e_{\phi\phi^\ell}),$$

where σ, R_E, ℓ are the Poisson's ratio, Earth radius, and the normal modes $\ell=(n, l, m)$, respectively. The volume-strain change for spheroidal modes is

$$\frac{\Delta V}{V}=\frac{2-\sigma}{1-\sigma}\Delta.$$

Consequently, we can obtain the volume-strain change from only the $e_{\theta\theta}$ and $e_{\phi\phi}$ for the spheroidal modes.

Based on the above theory, we can synthesize the volume-strain seismogram from the principal values of the moment tensor for the Hokkaido-Nansei-Oki earthquake. There are various mechanism solutions obtained by different authors (e.g. Harvard University scientists group, 1993 ; Nakanishi et al. 1993 ; Nakanishi and Kobayashi, 993 ; Sipkin, 1993 ; Kikuchi, 1993 ; Kuge et al., 1994 ; Fukuyama, 1994). But their solutions are quite different from each other. As

(a)

(b)

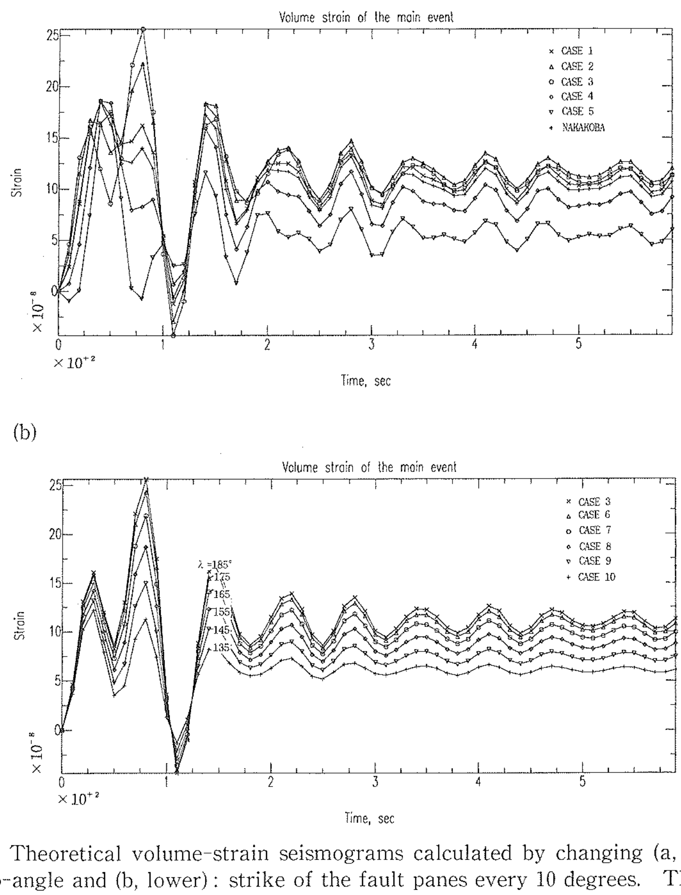

Fig. 6. Theoretical volume-strain seismograms calculated by changing (a, upper) : dip-angle and (b, lower) : strike of the fault panes every 10 degrees. The parameters used in the calculationare shown in Table 1.

Table 1. Parameters of mechanism solutions used for synthetic seismograms.

	strike (°)	dip (°)	slip (°)	M_{rr}	$M_{\theta\theta}$	$M_{\phi\phi}$	$M_{r\theta}$	$M_{r\phi}$	$M_{\theta\phi}$	References
NAKAKOBA	85.3	64.4	96.1	41.02	−9.10	−31.92	−6.25	−28.79	1.76	1)
case 1	185.3	64.4	90.0	36.47	−0.31	−36.16	−2.71	−29.20	−3.35	
case 2	185.3	54.4	90.0	44.30	−0.38	−42.93	−1.39	−15.02	−4.07	
case 3	185.3	44.4	90.0	46.79	−0.40	−46.39	0.09	0.980	−4.30	
case 4	185.3	74.4	90.0	24.24	−0.21	−24.04	−3.70	−39.86	−2.23	
case 5	185.3	84.4	90.0	9.09	−0.08	−9.01	−4.24	−45.71	−0.84	
case 6	175.3	44.4	90.0	46.79	−0.31	−46.48	−0.08	0.98	3.82	
case 7	165.3	44.4	90.0	46.79	−3.01	−43.78	−0.25	−0.95	11.48	
case 8	155.3	44.4	90.0	46.79	−8.17	−38.62	−0.41	0.89	7.76	
case 9	145.3	44.4	90.0	46.79	−15.16	−31.62	−0.56	0.81	21.90	
case 10	135.3	44.4	90.0	46.79	−23.15	−23.64	−0.69	0.70	23.39	
SIPKIN	200.0	39.0	108.7	0.26	0.01	−0.26	−0.05	0.07	−0.04	2)
case 11	200.0	40.0	90.0	0.28	−0.03	−0.24	0.02	0.05	−0.08	
case 12	200.0	50.0	90.0	0.28	−0.03	−0.24	−0.02	0.05	−0.09	
case 13	200.0	60.0	90.0	0.24	−0.03	−0.21	−0.05	−0.13	−0.08	
case 14	200.0	70.0	90.0	0.18	−0.02	−0.16	−0.07	−0.20	−0.06	
case 15	200.0	80.0	90.0	0.10	−0.01	−0.08	−0.09	−0.25	−0.03	
case 21	196.0	37.0	121.08	0.23	0.03	−0.26	−0.09	0.10	0.01	
case 22	196.0	47.0	116.85	0.25	0.03	−0.28	−0.09	0.01	0.01	3)
case 23	196.0	57.0	112.23	0.24	0.03	−0.27	−0.08	−0.09	0.01	4)
case 24	196.0	67.0	107.07	0.19	0.03	−0.22	−0.08	−0.17	0.01	
case 25	196.0	77.0	101.42	0.12	0.02	−0.14	−0.08	−0.23	0.01	
case 26	196.0	87.0	95.44	0.03	0.01	−0.04	−0.08	−0.26	0.01	
case 27	196.0	27.0	125.44	0.18	0.02	−0.20	−0.10	0.16	0.01	

1) After Nakanishi and Kobayashi (1993), 2) After Shipkin (1993), 3) After Harvard University scientists group (1993), 4) Best solution for the Esashi-Oki earthquake obtained in the present study.

for the reasons, Kuge et al. (1996) for instance, claimed the data dependency from the results of surface-wave source inversion. This earthquake revealed complex rupture processes and variation in fault orientations. For the sake of simplification, we considered only the overall relationship between the volume-strain seismogram and the geometry of the focal plane. Event if such source complexity should exist during the rupture process, we decided that it is how more important to grasp the overall appearance and earlist indication of a big earthquake in order to receive and broadcast the earliest possible warning.

To investigate the relationship mentioned above, we have used the focal mechanism calculated by Nakanishi and Kobayashi (1993) as an initial model. It has the source parameters: (strike, dip, slip) = (185.3°, 64.4°, 96.1°) and seismic moment $= 4.68 \times 10^{20}$ Nm ($M_W = 7.7$). The solution was based on the CMT inversion of long-period waves (>70 sec). SEBS has frequency characteristics that provide a response that remains almost the same for the range from DC to about 30 Hz. A theoretical strain seismogram (>70 sec) can be compared with the long-period strain data observed by SEBS. We have used both the theoretical and the observed seismograms (sampling rate of 10 sec) applied the lowpass filter of Butterworse with a cutoff frequency of 0.0142 Hz (70.0 sec). At the same time, the observed strain seismogram was calibrated by the constant coefficient previously obtained. On the contrary, the various theoretical volume srain seismograms are calculated by changing the strike and dip angles of the focal mechanism every 10 degrees (Fig. 6). Table 1 shows the parameters of focal mechanisms assigning the model codes. The model coded NAKAKOBA, after Nakanishi and Kobayashi (1993), was used as the initial model. In the calculation of synthetic strain seismograms, we have assumed a slip angle of 90° for all models to make clear the difference in waveforms based mainly on the change of the strike and dip angles. Incidentally, Nakanishi and Kobayashi (1993) obtained slip angles of 96.1° and 77.4°.

In Figure 6(a), we show that the amplitude of the strain seismogram is very sensitive to the dip angles of the nodal planes. On the other hand, it is not so sensitive to their strikes. Afer testing the dependency of the parameters of the source mechanisms on amplitude, we will discuss the solution fitted to the observed strain seismogram of the Esashi-Oki earthquake in the next subsection.

4.2 Analysis of long-period volume-strain seismogram of the Esashi-Oki earthquake

The Esashi-Oki earthquake ($M_{JMA} = 6.3$), the largest aftershock of the 1993

Hokkaido-Nansei-Oki earthquake, occurred off the town of Otobe in the southwest Hokkaido at 04 : 42 JST, on 8 August 1993, 100 km southeast of the Hokkaido-Nansei-Oki earthquake, which occurred 26 days earlier. The raw digital volume-strain seismogram is shown in Fig. 7. In ordr to compare the observed strain seismogram with the theoretical ones, we synthesized the strain

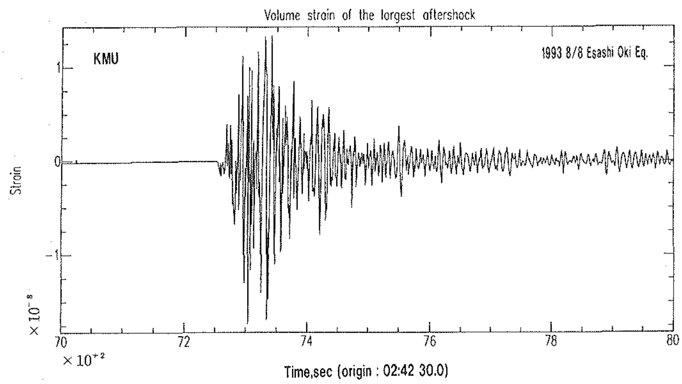

Fig. 7. The raw volume-strain seismogram for the 1993 Esashi-Oki earthquake recorded by SEBS at KMU. The origin of abscissa is 02 : 42 hours, 30.0s, 8 August 1993. The starting time of the seimogram shown is measured from the origin.

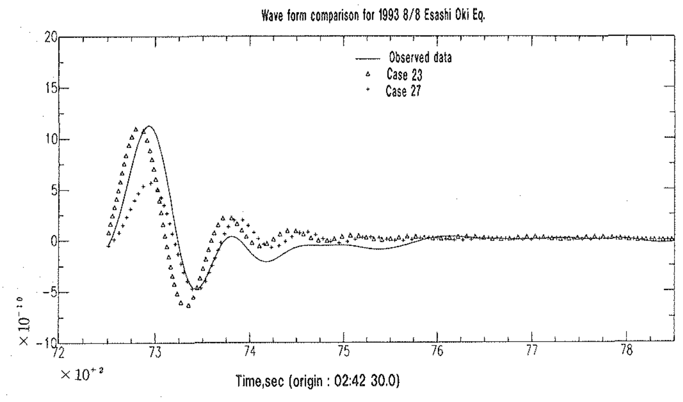

Fig. 8. Comparison of the volume-strain seismograms. Solid line : observed volume-strain seismogram recorded on CD-channel. Synthetic volume-strain seismograms for case 23 and case 27 are shown by lines marked with triangles and crosses, respectively. Their cases are modified from the solution by the Harvard University scientist group (1993). The origin of the abscissa is measured from the time 02 : 42 hours, 30.0s, 8 August 1993. Note : Case 23 was chosen as a final best fitted solution from the many cases.

seismograms by using the normal mode theory. Before doing so, we calibrated the digital strain data using an equivalent seismogram recorded on a Rastrak paper-chart at KMU. Then we multiplied the digital raw strain seismogram by the calibration factor. The observed and synthetic strain seismograms were applied through the six-pole two-pass Butterworth low-pass filter with cut-off period of 70 sec. As a starting model, we used the solution reported by Sipkin (1993). The null axis of 6° is quite similar to the direction of the apse of the aftershock area of the Esashi-Oki earthquake, as shown in Fig. 1. Namely, it shows the approximate direction being from south to north. The whole distribution of the foci suggested that the source area formed a narrow rectangular solid with north-south length of 20 km, east-west width of 10 km and depth of 15 km. Assuming that the direction of the null axis is zero degrees, we tried to find the synthetic strain seismogram best fitted to the observed one, changing only the dip directions of the fault planes. Through the experiments, we found the dip angles of the fault planes to be 57° and 33°, respectively. The solutions by Sipkin (1993) and Harvard University scientists group (1993) showed the fault plane dip angles having 40°～50°. Their solutions were based on applications of the moment tensor inversion method to the world-wide long-period seismograms. The body-wave inversion method obtained by Kikuchi (1993) also showed almost the same dip angles as those determined by these researchers. On the contrary, the present results were drawn from a quite different set of data i.e. the volume-strain seismogram recorded at a single station. Nevertheless the source parameters fitted to the strain data were fairly similar to those determined by Sipkin (1993) and the Harvard University scientists group (1993). The final best fitted synthetic strain seismogram (case 23) is shown in Fig. 8.

5. Discussion and Concluding remarks

In order to calculate the long-period volume-strain seismograms, we used the normal mode theory (Gilbert and Dziewonski, 1975) and a data set of eigen periods ($T > 45$ sec) and associated eigen functions calculated by Buland and Gilbert (1976) for earth model 1066A, after Gilbert and Dziewonski (1975). The calculation of the volume-strain is straightforward in terms of spheroidal modes. We used the observed digital strain seismogram passed through a low-pass filter with a cut-off frequency of 0.01428 Hz (period of 70 sec). With regard to the filtering, previous studies (Nakanishi et al., 1991; Nakanishi, 1993) suggested that if we used a seismogram with a cut-off frequency of around 0.01428 Hz, the effects of structural heterogeneities in and around the Japanese Islands may be considered to be small for most earthquakes. This assumption has been confirmed by comparing the results with the synthetic volume-strain seismograms calculated by the normal mode theory.

By applying the normal mode theory to the observed volume strain seismogram of the Esashi-Oki earthquake, we found that its source mechanism is consistent with those obtained from the world-wide seismograms by using the seismic-moment tensor inversions. Namely, the long-period digital strain seismogram ($T>70$ sec) of the aftershock indicates that the refined source parameters are: (strike, dip, rake)=196°, 57°, 90°), with the seismic moment $M_0=2.8\times10^{18}$ Nm ($M_W=6.2$). They are fairly similar to those in the CMT solution obtained by using the world-wide long-period seismograms. It is further supported by the distribution of the clustered events concentrated around the Esashi-Oki earthquake.

Significantly, the co-seismic volume strain change was utilized to determine the source mechanism as well as the seismic moment. Futhermore, we can say that such a volume-strain seismogram provides a refinement of the source mechanism model. In May 1996, adding the present KMU, we have installed the newly SEBS at two stations in the eastern part of Hokkaido (Takanami et al., 1998). A set of SEBS data at three stations can provide more accurate and detailed infomation about the crustal movement related to a big earthquake in and around Hokkaido.

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References

Aki, K. and P.G. Richards, 1980. Quantitative Seismology, Theory and Methods, Vol. 1. Freeman and Company, San Francisco, 557 pp.

Buland, R. and F. Gilbert, 1976. The theoretical basis for the rapid and accurate computation of normal mode eigenfrequencies and eigenfunctions. Unpublished Research News. Univ. of Calif., San Diego.

Fukuyama, E., 1994. Source processes of the 1993 Hokkaido-Nansei-Oki earthquake and the largest aftershock, Hokkaido-Nansei-Oki earthquake and its tsunami. Kaiyo, **7**, 29-34 (in Japanese).

Furuya, I. and A. Fukudome, 1986. Characteristics of borehole volume strainmeter and its application to seismology. J. Phys. Earth, **34**, 257-296.

Gilbert, F. and A.M. Dziewonski, 1975. An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra. Phil. Trans. Roy. Astr. Soc. London, Ser. A, **278**, 187-269.

Harvard University Scientists group, 1993. Quick report on the Centroid Moment Tensor solution, Harvard University.

Hino, R., T. Kanazawa, K. Suyehiro, T. Sato and H. Shimamura, 1994. Aftershock distribution of the 1993 Hokkaido-Nansei-Oki earthquake located by an array of ocean bottom seismometers, Hokkaido-Nansei-Oki earthquake and its tsunami. Kaiyo, **7**, 35-42 (in Japanese).

Iwata, T. and K. Irikura, 1994. Source Process of the M 6.5 event at 8 Aug., 1993 of the largest aftershock of the 1993 SW-Off Hokkaido Earthquake. Abstracts of 1994 Japan Earth and Planetary Science Joint Meeting, 294, F12-04 (in Japanese).

Kasahara, M., S. Kodaira, Y. Motoya, T. Takanami, I. Maeda, M. Okayama, H. Ishikawa, M. Ichiyanagi, A. Yamamoto, S. Matsumoto, N. Tsumura, T. Okada, Y. Yabe, T. Iidaka and N. Hirata, 1994. The aftershock activity of the 1993 Hokkaido-Nansei-Oki earthquake and the distribution of aftershocks. Grant-in-Aid for Scientific Research, No. B-5-2, No. 05306012, 13-19 (in Japanese).

Kikuchi, M., 1993. Source process of the Hokkaido-Oki earthquake of July 12, 1993 inferred from teleseismic body wave inversion. Programme and Abstracts, The Seismological Society of Japan, No. 2, 28 (in Japanese).

Kobayashi, Y., 1983. On the initiation of subduction of plates. Earth Monthly, **5**, 510 (in Japanese).

Kodaira, S., T. Takanami, Y. Motoya and M. Kasahara, 1994. Aftershock distributions of two great earthquakes (M=7.8) around Hokkaido, Japan, in 1993. International Association of Seismology and Physics of the Earth's Interior, 27th General Assembly, Wellington, New Zealand, 1994 January 10-21, S8. 13.

Kuge, K., J. Zhang and M. Kikuchi, 1996. The 12 July 1993 Hokkaido-Nansei-Oki, Japan, Earthquake: Effects of Source Complexity on Surface-Wave Radiation. Bull. Seism. Soc. Am., **86**, 505-518.

Linde, A.T., K. Suyehiro, S. Miura, I.S. Sacks and A. Takagi, 1988a. Episodic aseismic strain signals; Precursors to the Japan Sea Earthquake of 1983. Tohoku Geophys. Jour. (Sci. Rep. Tohoku Univ., Ser. 5), **31**, No. 2, 29-41.

Linde, A.T., K. Suyehiro, S. Miura, I.S. Sacks, and A. Takagi, 1988b. Episodic aseismic earthquake precursors. Nature, **334**, No. 6182, 513-515.

Mendoza, C. and E. Fukuyama, 1994. Finite-fault source analysis of the 1993 Hokkaido Nansei-Oki, Japan, earthquake. EOS, Trans. Am. Geophys. Union, **75**, 427.

Nakamura, K., 1983. Possible nascent trench along the eastern Japan Sea the convergent boundary between Eurasian and North American plates. Bull. Earthq. Res. Inst., University of Tokyo, **58**, 711 (in Japanese with English abstract).

Nakanishi, I., Y. Hanakago, T. Moriya and M. Kasahara, 1991. Performance test on long-period moment tensor determination for near earthquakes by a sparse local network. Geophys. Res. Lett., **18**, 223-226.

Nakanishi, I., 1993. Long-period moment tensor determination for regional earthquakes by a local very-broad-band seismograph array in Hokkaido, Japan. Proc. Int. Symp. Earthq. Disas. Prev., Mexico, **1**, 70-80.

Nakanishi, I. and M. Kikuchi, 1993. The special report of the 1993 Hokkaido-Nansei-Oki

earthquake. Jishin Kougaku Shinkoukai NEWS, No. 133, 1-5 (in Japanese).
Nakanishi, I. and R. Kobayashi, 1993. The source mechanism of the 1993 Hokkaido-Nansei-Oki earthquake. Programme and Abstracts, The Seismological Society of Japan, No. 2. **29** (in Japanese).
Nakanishi, I., S. Kodaira, R. Kobayashi, M. Kikuchi and M. Kasahara, 1993. The 1993 Japan Sea earthquake. EOS, Trans. Am. Geophys. Union, **74**, 377-379.
Sacks, I.S. and D.W. Evertson, 1968. A sensitive borehole strain-rate meter. Carnegie Institution Yearbook, **68**, 448-455.
Sacks, I.S., S. Suyehiro, A.T. Linde and J.A. Snoke, 1978. Slow earthquakes and stress redistribution. Nature, **275**, 599-602.
Sacks, I.S., A.T. Linde, J.A. Snoke and S. Suyehiro, 1981. A slow earthquake sequence following the Izu-Oshima Earthquake of 1978. Earthquake Prediction, Maurice Ewing Series *4*, 617-628.
Sasatani, T., S. Saito, H. Nagumo, M. Furumura, H. Okada, K. Kudo, M. Sakagami, M. Takahashi, K. Irikura, K. Matsunami, T. Iwata, T. Shibuya and K. Kamae, 1994. The observation of strong ground motions during the 1993 Hokkaido-Nansei-Oki earthquake sequence. Grant-in-Aid for Scientific Research (B), No. B-5-2, No. 05306012, 27-34 (in Japanese).
Sipkin, S., 1993. Quick report on the moment tensor solutions, USGS.
Suyehiro, S., 1982. Continuous observation of crustal movement. Earthquake Prediction Techniques, the University of Tokyo Press, 133-174.
Takanami, T., M. Kasahara, M. Takada, Y. Asai, I.S. Sacks, A.T. Linde, M. Acierno and B. Pandit, 1998. The new volume-strain observation systems in Teshikaga, Hokkaido. Geophys. Bull. Hokkaido Univ., **61**, 1-13 (in Japanese with English abstract).
Tanioka, Y., L. Ruff and K. Satake, 1993. The 1993 Japan Sea earthquake: Unusual rupture process of the Japan Sea earthquake. EOS, Trans. Am. Geophys. Union, **74**, 377.