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Space–time distribution of interplate moment release including slow earthquakes and the seismo-geodetic coupling in the Sanriku-oki region along the Japan trench

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Abstract

Along the Japan trench where some Mw8 class interplate earthquakes occurred in the past century such as the 1896 Sanriku tsunami earthquake (M6.8, Mt8.6, 12×10^{20} N m) and the 1968 Tokachi-oki earthquake (Mw8.2, 28×10^{20} N m), the Pacific plate is subducting under northeast Japan at a rate of around 8 cm/year. The seismic coupling coefficient in this region has been estimated to be 20–40%. In the past decade, three ultra-slow earthquakes have occurred in the Sanriku-oki region (39°N–42°N): the 1989 Sanriku-oki (Mw7.4), the 1992 Sanriku-oki (Mw6.9), and the 1994 Sanriku-oki (Mw7.7) earthquakes. Integrating their interplate moments released both seismically and aseismically, we have the following conclusions. (1) The sum of the seismic moments of the three ultra-slow earthquakes was $(4.8–6.6) \times 10^{20}$ N m, which was 20–35% of the accumulated moment $(18.6–23.0) \times 10^{20}$ N m, in the region (39°N–40.6°N, 142°E–144°E) for the 21–26 years since the 1968 Mw8.2 Tokachi-oki earthquake. This is consistent with the previous estimates of the seismic coupling coefficient of 20–40%. On the other hand, the sum of the interplate moments including aseismic faulting is $(11–16) \times 10^{20}$ N m, leading to a “seismo-geodetic coupling coefficient” of 50–85%, which is an extension of the seismic coupling coefficient to include slow events. (2) The time constants showed a large range from 1 min ($\sim 10^2$ s) for the 1968 Tokachi-oki earthquake to 10–20 min ($\sim 10^3$ s) for the 1896 Sanriku tsunami earthquake, to one day ($\sim 10^5$ s) for the 1992 Sanriku-oki ultra-slow earthquake, to on the order of one year ($\sim 10^7$ s) for the 1994 Sanriku-oki ultra-slow earthquakes. (3) Based on the space–time distribution, three “gaps of moment release,” (40.6°N–42°N, 142°E–144°E) 39°N–40°N, 142°E–143°E) and (39°N–40°N, 142°E–144°E), are identified, instead of the gaps of seismicity.

Keywords: crustal deformation; seismic coupling; seismo-geodetic coupling; slow earthquake; Japan trench

1. Introduction

In the Japan trench, the Pacific plate is subducting at a rate of around 8 cm/year under northeastern Japan which is part of the Okhotsk plate (e.g. Seno et al., 1996). In 1950s and 1960s, Mw8 class seismic events successively occurred to the north of 40°N latitude along the Japan and the Kuril trenches as the 1952 Tokachi-oki (Mw8.1), the 1958 Kuril (Mw8.3), the 1963 Kuril (Mw8.5), the 1968 Tokachi-oki (Mw8.2) and the 1969 Kuril (Mw8.2) earthquakes (“oki” means “off”). Fig. 1 shows distribution of aftershock

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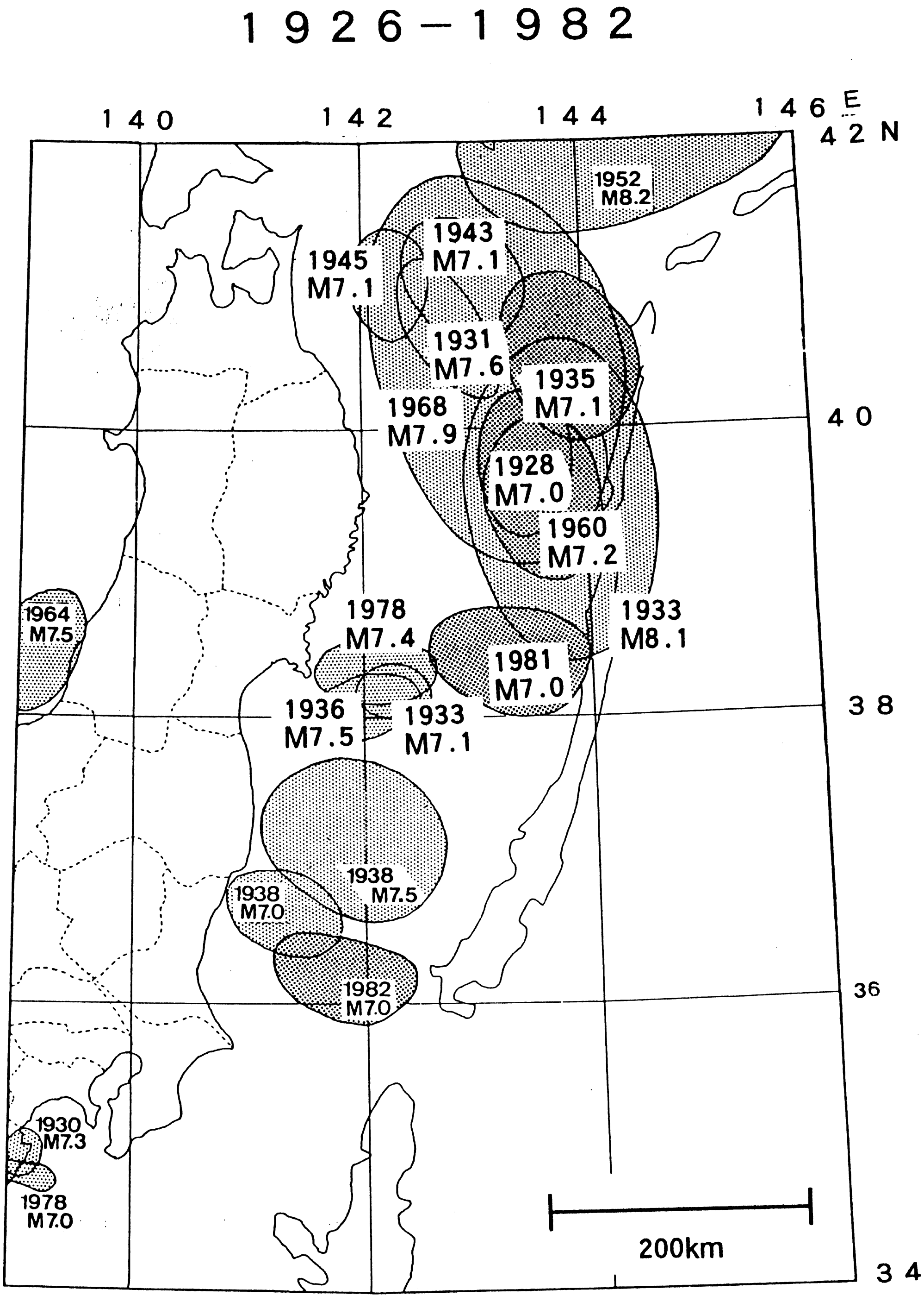

Fig. 1. Aftershock areas of seismic events of magnitude 7 or larger along the Japan trench for a period of 1926–1982. After Tohoku University (1983).

Table 1
Earthquakes in the Sanriku-oki region (Earthquakes of M_{JMA}6.5 or greater are selected from JMA (Japan Meteorological Agency) catalogue for the Sanriku-oki region from 38°N to 42°N and from 142°E to 144°E for the period of 1960 to 1995)

No.	Date			Time[a]			Lat. °N	Long. °E	D[b] (km)	M_{JMA}[c]	Mw[d]
1	1960	03	21	02	07	26.1	39.833	143.433	0	7.2	
2	1960	03	23	09	23	17.8	39.417	143.717	0	6.7	
3	1960	07	30	02	31	39.1	40.300	142.517	50	6.7	
4	1960	10	09	18	00	40.3	40.783	141.517	70	6.9	
5	1962	04	30	11	26	21.0	38.733	141.133	0	6.5	
6	1968	05	16	09	48	53.0	40.733	143.583	0	7.9	
7	1968	05	16	19	39	01.3	41.417	142.850	40	7.5	
8	1968	05	17	08	04	50.6	39.767	143.483	30	6.7	
9	1968	06	12	22	41	42.8	39.417	143.133	0	7.2	
10	1968	09	21	22	05	59.6	41.983	142.800	80	6.9	
11	1971	08	02	16	24	55.1	41.233	143.700	60	7.0	
12	1978	02	20	13	36	57.1	38.750	142.200	50	6.7	6.5
13	1978	06	12	17	14	25.3	38.150	142.167	40	7.4	7.6
14	1979	02	20	15	32	33.3	40.217	143.867	0	6.5	6.3
15	1981	01	19	03	17	23.8	38.600	142.967	0	7.0	7.0
16	1981	01	23	04	34	40.1	38.233	143.050	0	6.6	6.8
17	1983	04	30	23	03	48.3	41.480	144.038	76	6.7	6.3
18	1987	01	09	15	14	46.0	39.833	141.780	72	6.6	6.0
19	1989	10	29	14	25	37.8	39.518	143.743	0	6.5	6.4
20	1989	11	02	03	25	33.5	39.855	143.057	0	7.1	7.4
21	1992	07	18	17	36	56.6	39.380	143.655	0	6.9	6.9
22	1992	07	18	17	39	02.3	39.403	143.437	0	6.9	6.4
23	1994	04	08	10	10	41.1	40.563	143.965	3	6.6	6.4
24	1994	12	28	21	19	20.9	40.427	143.748	0	7.5	7.7
25	1994	12	29	07	37	49.4	40.312	143.815	15	6.5	6.2
26	1995	01	07	07	37	37.1	40.220	142.308	48	7.2	7.0

[a] Time indicates origin time in JST.
[b] D is a source depth.
[c] M_{JMA} is JMA magnitude.
[d] Mw is a moment magnitude from the Harvard CMT Catalogue.

areas of earthquakes of M_{JMA} 7 or greater for a period from 1926 to 1982.

Based on the historical records, the recurrence interval of the Mw8 class seismic events in this region was inferred to be around 110 years (Utsu, 1972). The relative displacement accumulated during the inter-seismic period of 110 years amounted to 9 m. However, seismic dislocations of the Mw8 class seismic events estimated by modern seismological and geodetic methods were around 3 m, leading to an estimate of seismic coupling coefficients of around 30% (e.g. Kanamori, 1977a).

The seismic coupling coefficient is the key for understanding plate boundary dynamics. It has been investigated by Ruff and Kanamori (1980), Peterson and Seno (1984) and Pacheco et al. (1993). They commonly suggested values of 20–40% for the Japan trench. To the south of 40°N, Abe (1977) showed that the seismic coupling coefficient was 5% or smaller at Shioya-oki (36°N–38°N), where the five Shioya-oki earthquakes of ~Mw7.5 occurred in 1938.

Then, a question is addressed: does the aseismic part of the relative plate motion occur as steady-state creep or as episodic aseismic faulting through slow and silent earthquakes? The widely accepted answer to this question has been steady-state creep on the subduction interface. However, it should be noted that we have had no direct observations of this steady-state creep.

In this paper, we summarize evidence that the aseismic slip is occurring in slow and silent earthquakes. There have been many approaches to studying slow

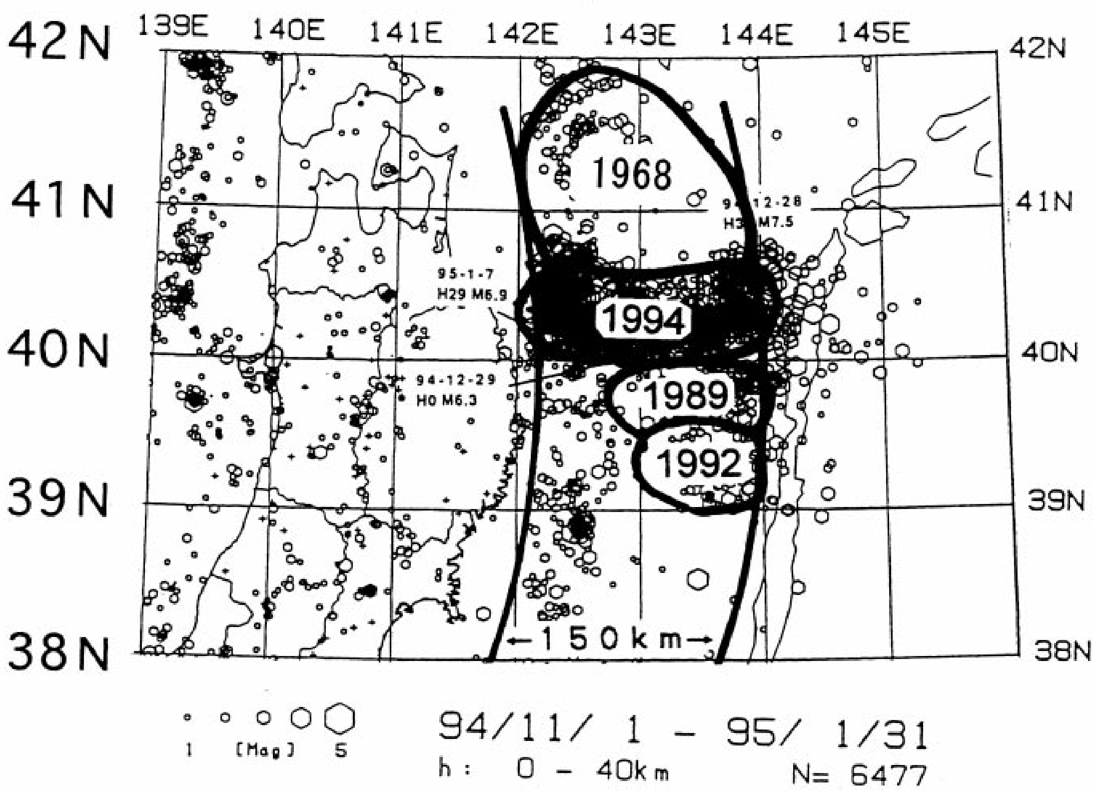

Fig. 2. Seismicity shallower than 40 km in and around the northeast Japan for a period from November, 1994, to January, 1995. Source areas of the 1968 Tokachi-oki earthquake and the 1989, 1992 and 1994 ultra-slow earthquakes are indicated by closed lines. Modified from Tohoku University (1996).

and silent earthquakes: Kanamori and Cipar (1974), Cifuentes and Silver (1989), Pelayo and Wiens (1992) and Kanamori and Kikuchi (1993) from anomalous excitation of long period seismic waves, Beroza and Jordan (1990) and Ihmle et al. (1993) from free oscillations, Sacks et al. (1981, 1982), Linde et al. (1988, 1996), Kawasaki et al. (1995), and Hirose et al. (1998) from continuous recording of crustal strains, Barientos et al. (1992) from tide gauge data and Heki et al. (1995), Johnston (1997), Savage and Svarc (1997) and Hirose et al. (1999) from GPS data.

In the Sanriku-oki region (39°N–40.6°N), three ultra-slow earthquakes have occurred in the past decade. Based on the space–time distribution of the interplate moments, we propose the new concept "seismo-geodetic coupling coefficient", which is the extension of the seismic coupling coefficient to include the slow and silent earthquakes. This new concept will be the key element throughout this paper.

2. Space–time distribution of seismic moments released

The first step of our strategy is to draw a picture of the space–time distributions of the seismic moment release in the interplate earthquakes.

Table 1 lists seismic events of M_{JMA}6.5 or greater in the region (38°N–42°N, 142°E–144°E) from 1960 to 1995. In this period, there were 26 seismic events of M_{JMA}6.5 or greater and 10 events of M_{JMA}7 or greater. Mw is from the Harvard CMT catalogue unless otherwise noted.

Fig. 2 shows seismicity shallower than 40 km for

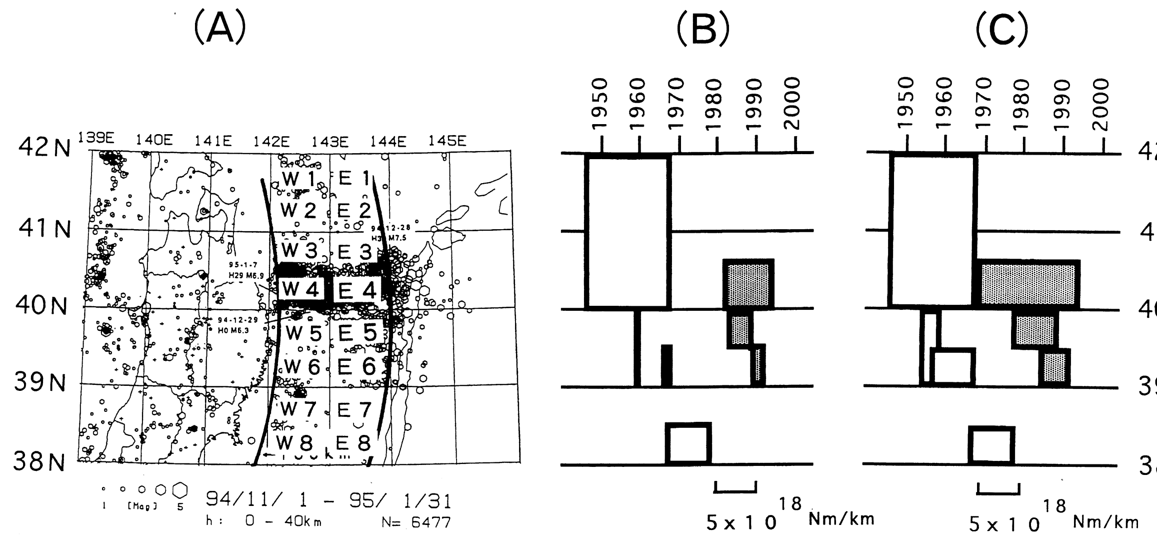

Fig. 3. (A) Regionalization, E1–E8 and W1–W8, of 0.5° spacing of the Sanriku-oki region. (B) Space–time distribution of seismic moments released by major seismic events for the period from 1960 to 1995. (C) Space–time distribution of interplate moments, including the slow faultings associated with the 1989, 1992 and 1994 Sanriku-oki ultra-slow earthquakes (shaded rectangles). Horizontal axis indicates time in year. Vertical axis is latitude. The right side of each rectangle indicates the year of occurrence. Upper and lower sides are northern and southern boundaries of source areas. The width of the rectangle is normalized by 5×10^{17} N m/km/year. Seismic events smaller than Mw7.2 are not plotted.

Table 2
Earthquakes plotted in Fig. 1

No.[a]	Date			M_{JMA}[b]	Mw[c]	Mo[d]	Moa[e]	Reference
1	1960	03	21	7.2		0.8 *	2 **	Watanabe (1985)
6	1968	05	16	7.9	8.2	28		Kanamori (1971)
9	1968	06	12	7.2		0.5		Yoshioka and Abe (1976)
							3.1 **	Aida (1978)
13	1978	06	12	7.4	7.6	3.4		Seno et al. (1979)
20	1989	11	02	7.1	7.4	1.4		Dziewonski et al. (1990)
							0.4	Miura et al. (1993)
							1.4	Present study
21	1992	07	18	6.9	6.9	0.3		Dziewonski et al. (1992)
							1–4	Kawasaki et al. (1995)
24	1994	12	28	7.5	7.7	4.9		Dziewonski et al. (1995)
						1.4+1.7		Tanioka and Satake (1996)
							2.5+1.7	Heki et al. (1997)

[a] The event number in Table 1.
[b] M_{JMA} is JMA magnitude.
[c] Mw is a moment-magnitude.
[d] Mo is a seismic moment. Mo(*) of the 1960 event is obtained by substituting M_{JMA}(7.2) into Mw–Mo relation, log(Mo) = 1.5Mw+9.1, of Kanamori (1977).
[e] Moa is an interplate moment released as the tsunami (**) and ultra-slow faulting.

Table 3
Interplate moments predicted and released by the Sanriku-oki ultra-slow earthquakes

Region[a]	Predicted[b]	Seismic[c]	Seismo-geodetic[d]
E4+W4	8.6	3.1–4.9	7.3–9.1
E4+E5+E6 W4+W5+W6	18.6–23.0	4.8–6.6	11.1–15.9
E4+E5+E6	9.3–11.5	3.0–4.3	7.2–11.2

[a] Region corresponds to regionalization in Fig. 3(A).
[b] Moments in the column of Predicted are those predicted by relative plate motion model, details of which are in the text.
[c] Moments in the column of Seismic are sums of seismic moments released by the 1989, 1992 and 1994 Sanriku-oki earthquakes.
[d] Moments in the column of Seismo-geodetic are sums of both seismic moments and moments released by the ultra-slow faulting associated with the Sanriku-oki earthquakes. Unit of moments is 10^{20} N m.

three months from November 1994 to January 1995. The width of high seismic region was about 150 km across from the Sanriku coast (142°E) to the trench axis (144°E). Thus, the width of coupling is assumed to be 150 km hereafter.

Fig. 3(A) shows the regionalization, E1–E8 and W1–W8, of the Sanriku-oki region. Fig. 3(B) shows space–time distribution of seismic moments released by the major events listed in Table 2. Each rectangle indicates one event. Shaded rectangles indicate the 1989, 1992 and 1994 Sanriku-oki earthquakes. The horizontal axis is time in years. The right side of each rectangle indicates the year of occurrence. The vertical axis is latitude. Upper and lower sides of each rectangle are northern and southern boundaries of the events.

Fig. 3(B) is a rough sketch to help to visualize the mode of interplate moment release on subduction interface. Heterogeneous distribution of seismic dislocation on the earthquake fault is neglected and the seismic moments are roughly allocated to one of segments of 0.5° spacing in the NS direction except the segments E4 and W4 between 40.0°N and 40.6°N.

Assuming a coupling width of 150 km, a subduction rate of 8 cm/year and a rigidity of 4×10^{10} N m/m^2 the accumulated interplate moment per year per length along the trench axis is 5×10^{17} N m/km/year, by which the width of a rectangle is normalized. Thus, if the seismic coupling coefficient is 100%, rectangles should fill all the space in panel (B).

The seismic moment of an Mw7.2 event is 0.8×10^{20} N m, assuming the Mw–Mo relation of Kanamori (1977b) (log(Mo) = 1.5Mw + 9.1). The width of the rectangle for an Mw7.2 event is 0.6 year, assuming the fault length of 55 km (0.5°), and is almost the same as the thickness of solid lines of a rectangle. Thus events of Mw smaller than 7.2 can be neglected in the following discussions and are not plotted in Fig. 3(B).

In the 1960s, three Mw7–8 class seismic events (the 1960 M_{JMA}7.2 Sanriku-oki, the 1968 Mw8.2 Tokachi-oki and the 1968 M_{JMA}7.2 Sanriku-oki earthquakes) occurred between 39°N and 42°N. Thus, the 1960s seem to be the peak period of the interplate moment release.

For the 21.4–26.5 years from the 1968 Tokachi-oki earthquake to the 1989–1994 Sanriku-oki earthquakes, segments E4–E6 and W4–W6 of 180 km (39°N–40.6°N) in the NS direction and 150 km in the EW direction accumulated an interplate moment of $(18.6–23.0) \times 10^{20}$ N m.

The seismic moment of the 1994 Sanriku-oki event in E4 and W4 was estimated as 3.1×10^{20} N m by seismological and tsunami data (Tanioka et al., 1996), while the Harvard CMT moment (Dziewonski et al., 1995) was 4.9×10^{20} N m. Thus, the seismic moment of the 1994 event is represented as $(3.1–4.9) \times 10^{20}$ N m hereafter.

Seismic moments released by the three Sanriku-oki earthquakes were 1.4, 0.3 and $(3.1–4.9) \times 10^{20}$ N m, respectively. Their sum $(4.8–6.6) \times 10^{20}$ N m, is around 1/4 of the accumulated moment $(18.6–23.0) \times 10^{20}$ N m, which leads to a seismic coupling coefficient of 20–35% in the region of 39°N–40.6°N.

The smallest value, 20%, of the estimate 20–35% is obtained by dividing 4.8×10^{20} (the smallest value in the numerator) by 23×10^{20} (the largest value in the dominator) and vice versa. It is impossible at present

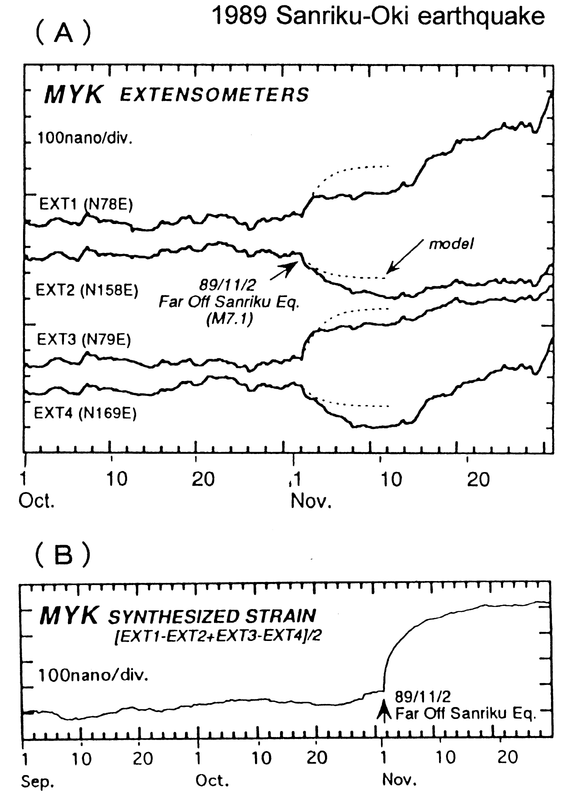

Fig. 4. (A) Crustal strains due to the 1989 Sanriku-oki earthquake by the four component extensometer recording system at Miyako (39.590°N, 141.984°E), Tohoku University. The four extensometers were aligned in directions of N78°E(EXT1), N79°E(EXT3), N158°E(EXT2) and N169°E(EXT4) in a tunnel of abandoned mine pits. (B) Crustal strain synthesized by (EXT1 + EXT3 − EXT2 − EXT4)/2. After Miura et al. (1993).

to obtain an evaluation of the coupling coefficient that includes a heterogeneous distribution of the seismic dislocation. However, the true value should be within the range of 20–35%.

3. The 1989 Sanriku-oki ultra-slow earthquake

The second step of our strategy is to expand the picture of space–time distributions to include slow earthquakes. In this and the following two sections, we briefly summarize the aseismic nature of the 1989, 1992 and 1994 Sanriku-oki ultra-slow earthquakes, the seismic moments of which are tabulated in Table 2.

Fig. 4(A) shows crustal strains due to the 1989 Sanriku-oki earthquake, which ruptured segment E5, recorded at the four component extensometer of the Tohoku University at Miyako (39.59°N, 141.98°E) on the Sanriku coast. The four extensometers were installed in directions of N78°E(EXT1), N79°E(EXT3), N158°E(EXT2) and N169°E(EXT4) in a tunnel of abandoned mine pits. (B) shows crustal strain synthesized by adding EXT1 and EXT3 and subtracting EXT2 and EXT4, to obtain (EXT1 + EXT3 − EXT2 − EXT4)/2, which was a rough approximation to shear strain $\epsilon_{EW} - \epsilon_{NS}$. The shear strain is insensitive to atmospheric pressure disturbance and thus atmospheric pressure disturbances in a period range of an order of days were naturally removed. The strain step in Fig. 4(B) had a time constant of 10 days and an amplitude around two times the coseismic strain step.

A strain step in the record at Esashi (39.15°N, 141.34°E), National Astronomical Observatory, was about two times the coseismic strain step although the strain records were unfortunately disturbed by maintenance operation.

Considering the above ambiguities on the two observations at Miyako and Esashi, we assume that strain step due to the silent fault slip was equal to the coseismic strain step. With the assumption that the fault plane of the afterslip was the same as the seismic event, the aseismic moment can be determined to be 1.4×10^{20} N m, the same as the coseismic moment.

Hereafter, the moment that was released by episodic aseismic faulting and its equivalent magnitude are called “aseismic moment” and “aseismic magnitude”, which are abbreviated as Moa and Mwa, respectively.

4. The 1992 Sanriku-oki ultra-slow earthquake

On July 18, 1992, the second Sanriku-oki earthquake of Mw6.9 occurred in segment E6. Kawasaki et al. (1995) found quasi-static strain steps with a time constant of 1–2 days and amplitudes of 3×10^{-8} in the extensometer records at Esashi and 2×10^{-7} at Miyako of Tohoku University, respectively. The similarity between the strain waveforms at Esashi and Miyako was remarkable except for their amplitudes, and was convincing evidence of ultra-slow faulting of a time constant of 1–2 days.

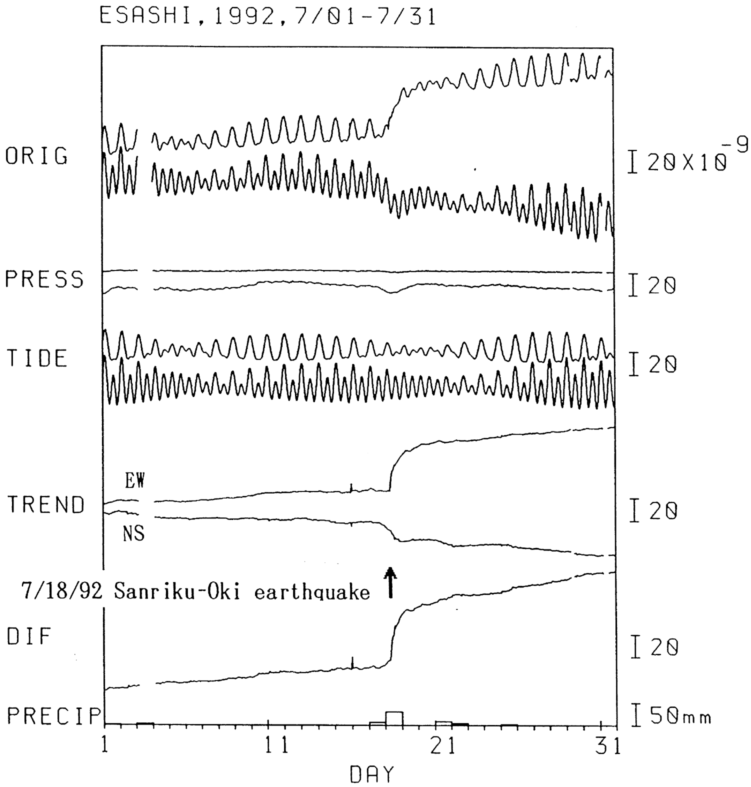

Fig. 5. One month record of the crustal strains at Esashi (39.15°N, 141.34°E), National Astronomical Observatory at Mizusawa due to the 1992 Sanriku-oki earthquake. One horizontal division is one day. ORIG was the original record. By Bayesian tidal analysis method (e.g. Tamura et al. (1991)), ORIG was separated into atmospheric pressure effects (PRESS), tide (TIDE), and trend (TREND). After Kawasaki et al. (1995).

Fig. 5 shows one-month record of the crustal strains at Esashi. One horizontal division is one day. Two traces of ORIG were the original records of EW and NS components. Using Bayesian tidal analysis method (Ishiguro and Tamura, 1985; Tamura et al., 1991), the ORIG was separated into atmospheric pressure effects (PRESS), tide (TIDE), and trend (TREND). Crustal strains due to tectonic events are to be included in the TREND.

Kawasaki et al. (1995) inverted the strain steps of the two stations and of Erimo (43.02°N, 143.16°E) of Hokkaido University to obtain a fault plane solution of a low angle thrusting toward the west, quite consistent with the tectonic setting. The interplate moment of $(1–4) \times 10^{20}$ N m obtained corresponds to those of Mw7.3–7.7 seismic events and was one-order of magnitude larger than the Harvard CMT moment of 0.3×10^{20} N m.

Surface wave magnitude Ms (characteristic period 20 s), tsunami magnitude Mt ($\sim$1000 s) and Moa ($\sim 10^5$ s) were 7.1 (USGS), 7.4 (Abe and Okada, 1992) and 7.3–7.7 present study, respectively. The longer the characteristic period of the magnitude type was, the larger the magnitude value was.

The source area of the 1992 Sanriku-oki ultra-slow earthquake coincided with that of the M_{JMA}7.1 Sanriku-oki earthquake of June 12, 1968, about one month after and 50–100 km away to the south from the 1968 Tokachi-oki earthquake (Mw8.2). The seismic moment determined by Yoshioka and Abe (1976) was 0.5×10^{20} N m, while the moment estimated from tsunami data was 3.1×10^{20} N m (Aida, 1978), one order of magnitude larger than the seismic moment and similar to that of the 1992 Sanriku-oki ultra-slow earthquake. In the sense of the orders of the seismic

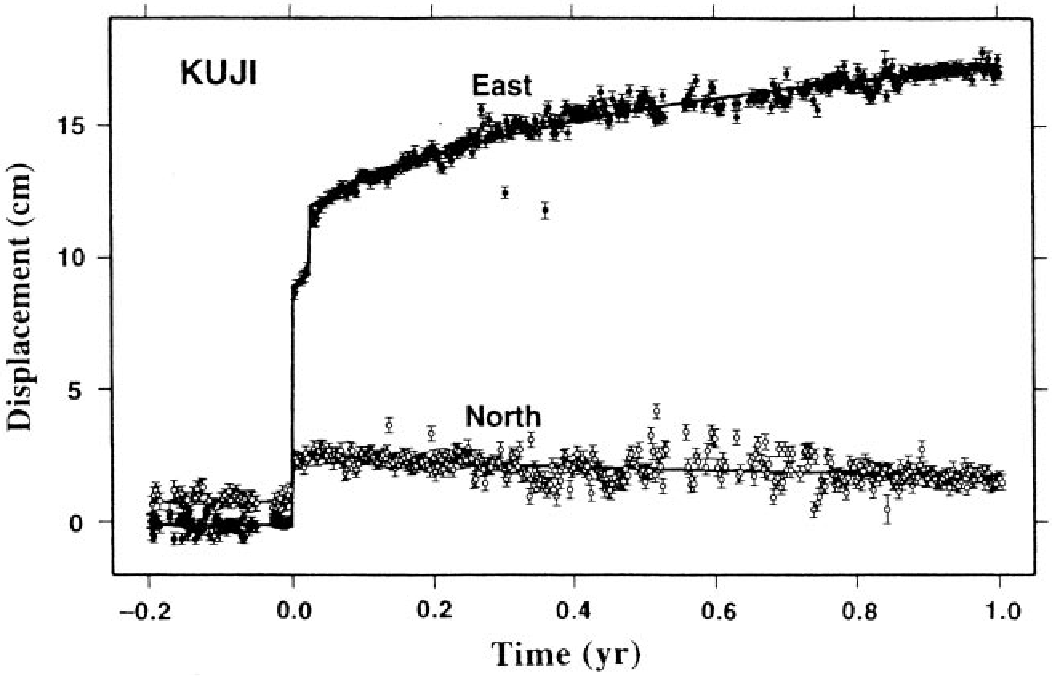

Fig. 6. GPS displacements at Kuji (40.13°N, 141.79°E) of GEONET of Geographical Survey Institute of Japan (Miyazaki et al., 1997) due to the 1994 Sanriku-oki earthquake of Mw7.7. The time constant of the silent fault slip was around a year, during which interplate moment of 4.2×10^{20} N m was released. After Heki et al. (1995).

and aseismic moments, it can be said that the 1968 Sanriku-oki earthquake notably resembles the 1992 Sanriku-oki ultra-slow earthquake.

5. The 1994 Sanriku-oki ultra-slow earthquake

On December 28, 1994, the third Sanriku-oki ultra-slow earthquake of Mw7.7 ruptured segments E4–W4, covering the southern third of the source area (E1–E4 and W1–W4) of the 1968 Tokachi-oki earthquake. Silent fault slip following the seismic event was detected by GEONET, the GPS network of the Geographical Survey Institute of Japan (Miyazaki et al., 1997).

Fig. 6 shows a 1.2 year record of the GPS horizontal displacement at Kuji of the Sanriku coast. Analyzing the GPS data, Heki et al. (1995) showed that the time constant of the silent fault slip was around one year, during which interplate moments of 2.5×10^{20} N m in W4 and 1.7×10^{20} N m in E4 were aseismically released, respectively. Sum of both seismic and aseismic moments amounts to $(7.3–9.1) \times 10^{20}$ N m.

Assuming a source area E4 and W4 of 70 km in the NS direction and 150 km in the EW direction, we have an interplate moment of $\sim 8.6 \times 10^{20}$ N m accumulated in the 26.5 years between the 1968 Tokachi-oki and the 1994 Sanriku-oki earthquakes. Comparing the two estimates of $(7.3–9.1) \times 10^{20}$ N m and $\sim 8.6 \times 10^{20}$ N m, the 1994 Sanriku-oki earthquake released 85–105% of the accumulated moment in E4 and W4. Although this estimate could be too simplified, it can be said that to first order the 1994 Sanriku-oki earthquake released all of accumulated moment in the source area.

The definitions of slow and silent earthquakes are not explicit. Beroza and Jordan (1990) defined the characteristic rupture velocity as the ratio of characteristic fault length to characteristic rupture duration time. They called events whose characteristic rupture velocities were orders of km/s–100 m/s, 100 m/s–10 m/s and 0.1–0.01 m/s, slow earthquake, silent earthquake and

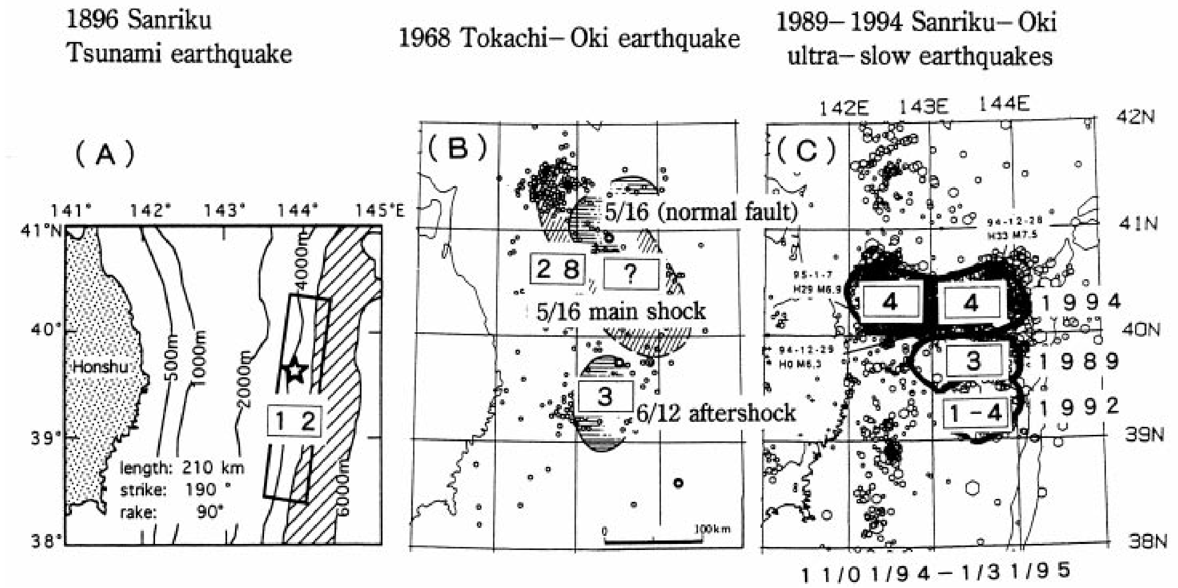

Fig. 7. Source areas of and the interplate moments released by (A) the 1896 Sanriku tsunami earthquake, modified from Tanioka and Satake (1996), (B) the 1968 Tokachi-oki earthquake, modified from Usami (1996), and (C) the 1989–1994 Sanriku ultra-slow earthquakes. Numerals in the squares are the interplate moments in 10^{20} N m released both seismically and aseismically in the respective segements.

creep event, respectively. Following their definition, the 1989–1994 Sanriku-oki earthquakes, with time constants of days to a year, should be called silent _earthquakes and creep event, rather than slow earthquakes. However, they accompanied seismic events of ~Mw7 and thus were not silent in the literal meaning. In view of this, Kawasaki et al. (1995) called them "ultra-slow earthquakes". More precisely, they consisted of two elements, an ordinary earthquake and a silent earthquake or a creep event.

6. Seismo-geodetic coupling

Fig. 3(C) is the space–time distribution of interplate moments including aseismic faultings. Comparing Fig. 3(C) with Fig. 3(B) shows that the episodic aseismic faulting is more important than the seismic faulting in the region between 39°N and 40.7°N.

In Sections 3–5, we have summarized how interplate moments were released in respective segments in the region between 39°N and 40.7°N. Based on this summary, the sum of the seismic moments released by the 1989, 1992 and 1994 Sanriku-oki earthquakes in segments E4–E6 and W4–W6 was $(4.8–6.6) \times 10^{20}$ N m, which was about 20–35% of the accumulated moment $(18.6–23.0) \times 10^{20}$ N m. On the other hand, the sum of both seismic and aseismic moments was $(11.1–15.9) \times 10^{20}$ N m, which was 50–85% of the accumulated moment. The estimate of 50–85% is called the "seismo-geodetic coupling coefficient", a simple and natural extension of the seismic coupling coefficient.

We thus recognize that the 1989, 1992 and 1994 Sanriku-oki earthquakes released a major part, 50–85%, of the relative plate motion in the seismo-geodetic band. In other words, 1989–1994 was the peak period of the interplate moment release, subsequent to the 1960s.

Let us focus on trench-side segments E4–E6. How the Harvard CMT moment of the 1994 Sanriku-oki earthquake were divided into segments E4 and W4 is not known. The dominant part of the seismic moment of the 1968 Tokachi-oki earthquake was released in W1–W4 to the west of 143°E within the aftershock area (e.g. Mori and Shimazaki (1985)) but the tsunami seems to have been evenly excited in

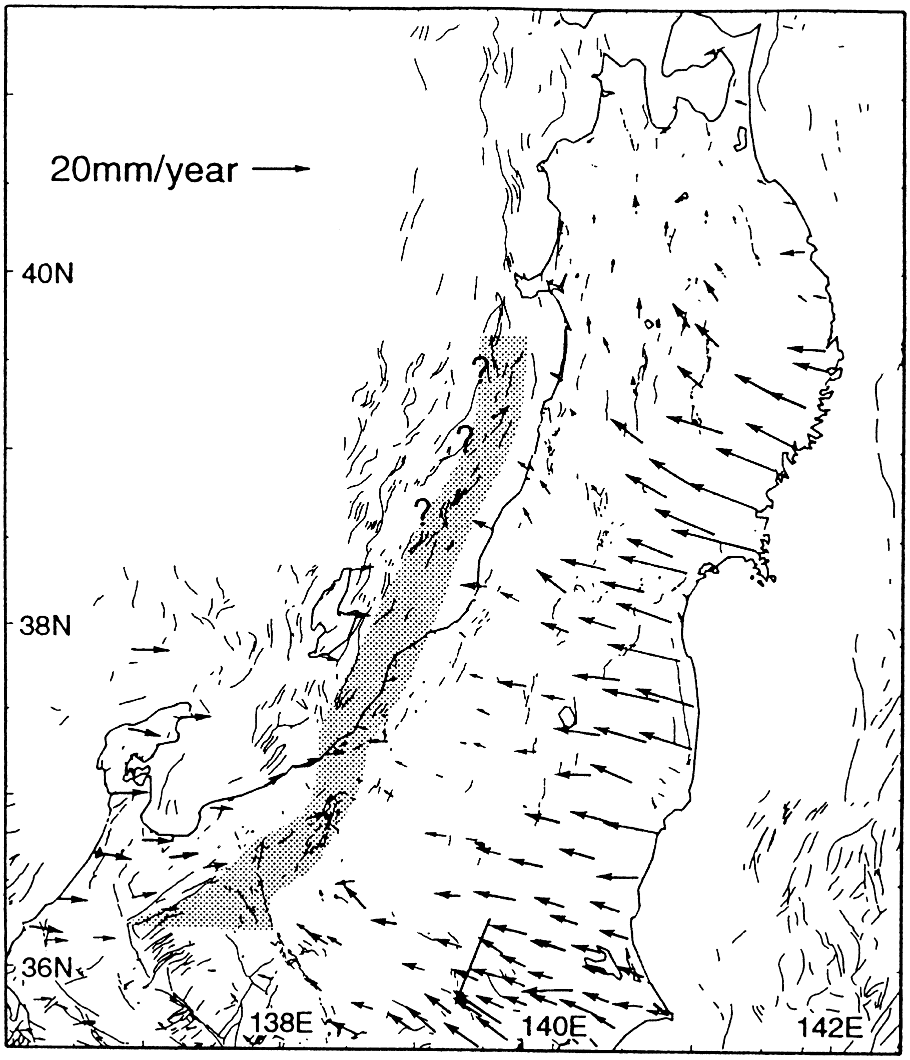

Fig. 8. Surface displacements in the northeast Japan for 1997 observed by GEONET of Geographical Survey Institute of Japan. From Sagiya and Tada (1998).

E1–E4 to the east of 143°E and in W1–W4 to the west of 143°E (Satake, 1989)

Here, we assume that 2.7×10^{20} N m was released in E4 and 2.4×10^{20} N m in W4 by the ratio of 1.7×10^{20} N m in E4 and 1.4×10^{20} N m in W4 of Tanioka et al. (1996), which is consistent with the assumption in previous paragraph. Then, the sum of both seismic and aseismic moments released in E4 and W4 was $(7.2–11.5) \times 10^{20}$ N m, while the interplate moment accumulated since the 1968 Tokachi-oki earthquake was $(9.4–11.5) \times 10^{20}$ N m. Thus, the seismo-geodetic coupling coefficient is 60–120% in the segments E4–E6.

Thus, the three Sanriku-oki ultra-slow earthquakes released most of the moment accumulated in E4–E6 since the 1968 Tokachi-oki earthquake. In other words, the plate interface in E4–E6 seems to first order to have been locked during the interseismic period between the 1968 Tokachi-oki and the 1989–1994 Sanriku-oki ultra-slow earthquakes.

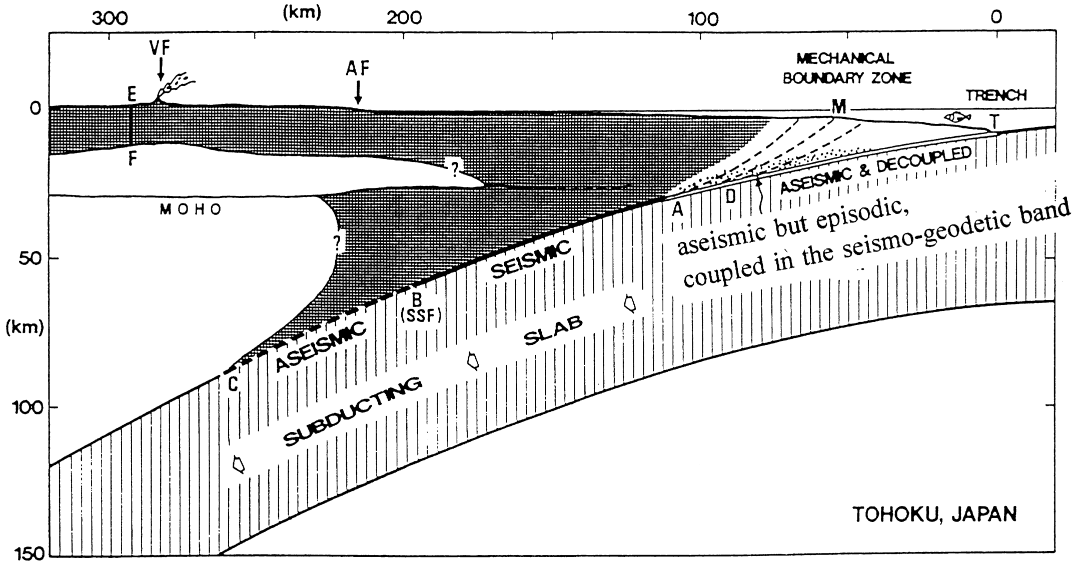

Fig. 9. Schematic diagram of friction on the subduction interface for Sanriku-oki region. Shallower interface indicated by a bold line was labelled as "aseismic, decoupled" in the original figure of Shimamoto (1985) and is relabelled as "aseismic but episodic, coupled in the seismo-geodetic band".

7. Working hypothesis proposed

Fig. 7 is comparison of moments released by (A) the 1896 Sanriku tsunami, (B) the 1968 Tokachi-oki and (C) the 1989–1994 Sanriku ultra-slow earthquakes. Key element here is the interplate moment of $\sim 4 \times 10^{20}$ N m, accumulated in each segment E1–E9 and W1–W9 for 30 years.

As recognized by comparing Fig. 7(A) with (C), the source area of the 1896 giant tsunami earthquake overlaps the segments E4–E7 and its moment was 12×10^{20} N m in the four segments (E4–E7), $\sim 3 \times 10^{20}$ N m/segment. The moment of 12×10^{20} N m was close to $(7.2–11.5) \times 10^{20}$ N m, the sum of both seismic and aseismic moments due to the 1989, 1992 and 1994 Sanriku-oki ultra-slow earthquakes.

The 1968 Tokachi-oki earthquake released a moment of 28×10^{20} N m in eight segments E1–E4 and W1–W4, and thus about 3.5×10^{20} N m in each segment on average. The 1968 Sanriku-oki earthquake released 3×10^{20} N m in one segment E6. The 1989, 1992 and 1994 ultra-slow earthquakes released $(11–16) \times 10^{20}$ N m in E4–E6 and W4 $(1–4) \times 10^{20}$ N m/segment. Thus, all of the events released $(1–4) \times 10^{20}$ N m/segment.

1928 was a high seismicity period of M6 seismic events in E5–E6, similarly to the period of the 1989, 1992 and 1994 ultra-slow earthquakes. There was no other period of high seismicity of M6 seismic events between 1896 and 1968.

Fig. 8 shows the recent result of GEONET. The east coast of northeast Japan was steadily moving to the west at rates of a few centimeters per year for one year of 1997. Ito and Yoshioka (1998) inverted this westward movement to obtain backslip distribution of 10 cm/year or less, leading to a conclusion that the plate interface along the Japan trench was fully coupled, to the first-order approximation, except the Sanriku-oki region where healing of the plate interface had been taking place subsequently to the afterslip of the 1994 Sanriku-oki earthquake (Tada et al., 1997).

The above discussions can be summarized as:

(1) Plate interface along the Japan trench from 36°N to 40°N seems to be fully coupled, to the first order approximation, as revealed by the GPS data for one year of 1997.

(2) The subduction interface seems to be fully

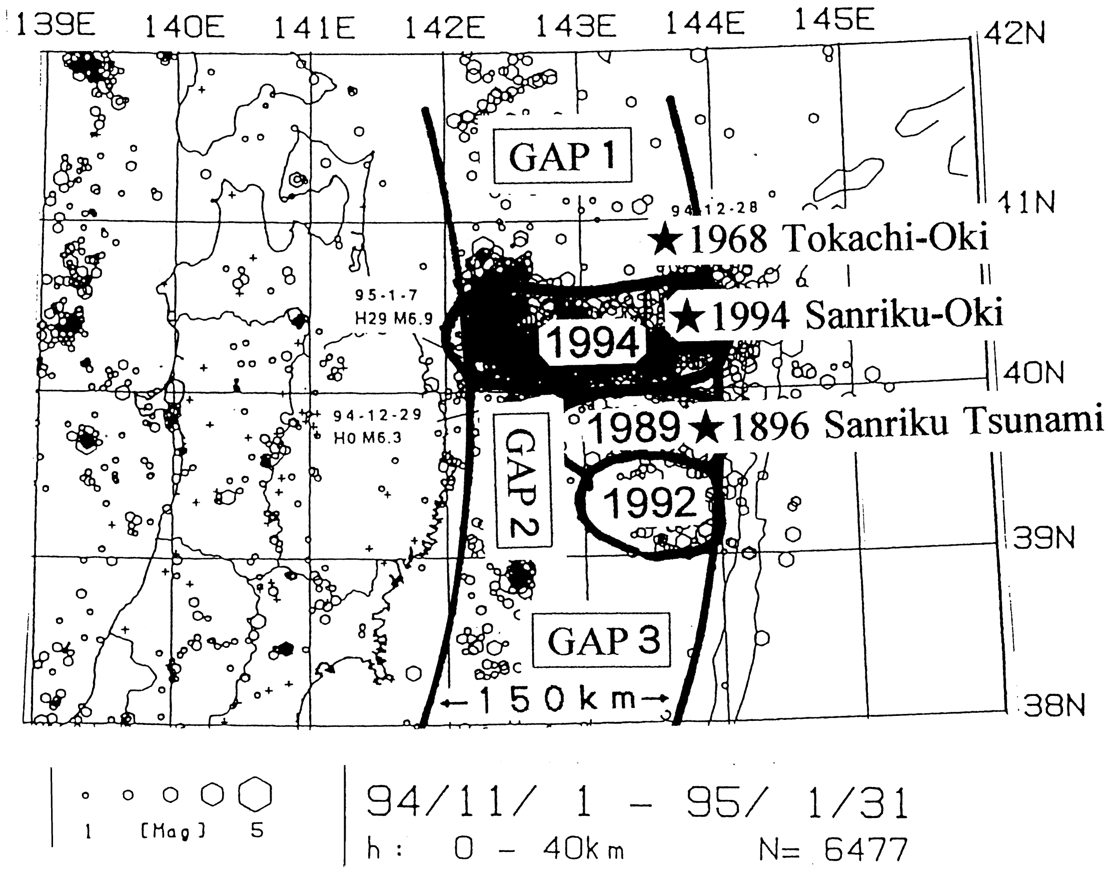

Fig. 10. **GAP**s of the moment release where the interplate moment accumulated since the 1968 Tokachi-oki earthquake has not been released. * indicates rupture initiation points of respective events.

coupled in E4–E6 for the period from 1968 to 1989–1994 as suggested in Section 6.

(3) All of the events of interest released $(1–4) \times 10^{20}$ N m in respective segments.

(4) There was no period of high seismicity, M6 seismic events, in E5–E6 except 1928 between 1896 and 1968.

Integrating these basic facts (1)–(4), we propose a working hypothesis that *there are peak periods for every 30–40 years that release a major part of the relative plate motion in the Sanriku-oki region, such as 1896, 1928, 1960s and 1989–1994, and the plate-interface is locked during the inter-seismic periods, to first order*.

It follows as a consequence that we have failed to notice silent earthquakes which released possibly as large as an aseismic moment of $\sim 4 \times 10^{20}$ N m. Kisslinger and Hasegawa (1991) showed that the aftershock sequence of the Iwaizumi, Mw6.6, earthquake of January 9, 1987 (39.83°N, 141.76°E, depth = 74.6 km) reactivated on May 12, independent of any strong aftershocks. They attributed this to an unknown silent earthquake in the shallower plate interface, which resulted in the transfer of the stress to the aftershock area. This could be a symptom of “missing silent earthquakes”.

Fig. 9 is a schematic diagram of the plate interface friction for Sanriku-oki region modified from Shimamoto (1985). The shallower half was indicated as “aseismic, decoupled” in the original figure and is

Table 4
Diversity of time constants (^{*1}indicates tsunami magnitude. The moment ^{*2} is re-estimated in the present study. The moment ^{*3} is a sum of those by tsunami data and aseismic silent slip. Unit of moments is 10^{20} N m)

Year	Event name	Mw[a]	Mo^{SUMb}	*T*1(d)[c]	*T*2[c]	Ref.
1968	Tokachi-oki	8.2	28	0.001	90 s	Kanamori (1971)
1896	Sanriku Tsunami	8.6^{*1}	12	0.01	10 ∼ 20 min	Tanioka and Satake (1996)
1992	Sanriku-oki	6.9	1 ∼ 4	1	1 day	Kawasaki et al. (1995)
1989	Sanriku-oki	7.4		10	10 days	Miura et al. (1993)
			3^{*2}			Present study
1994	Sanriku-oki	7.7	9^{*3}	300	1 year	Tanioka and Satake (1996)
						Heki et al. (1997)

[a] Mw is moment-magnitude.
[b] Mo^{SUM} is sum of interplate moments released by both seismic and aseismic faulting.
[c] *T*1 and *T*2 are time constants measured in day and a time unit indicated, respectively.

relabeled as "aseismic but episodic, coupled in the seismo-geodetic band", following the above working hypothesis.

8. Gaps of moment release

Here we define "the gaps of moment release" between 38°N to 42°N where the interplate moment accumulated since the 1968 Tokachi-oki earthquake has not been released either as seismic or aseismic events. We recognize three gaps as illustrated in Fig. 10 as

GAP1: E1–E3 and W1–W3, northern two-third of the source area of the 1968 Tokachi-oki earthquake.
GAP2: W5–W6, where is no records of M7 class seismic events for 1400 years (Seno, 1979).
GAP3: E7–E8 and W7, the source area of the 1897 Miyagi-oki earthquake of M7.4, determined by seismic intensity data (Usami, 1996).

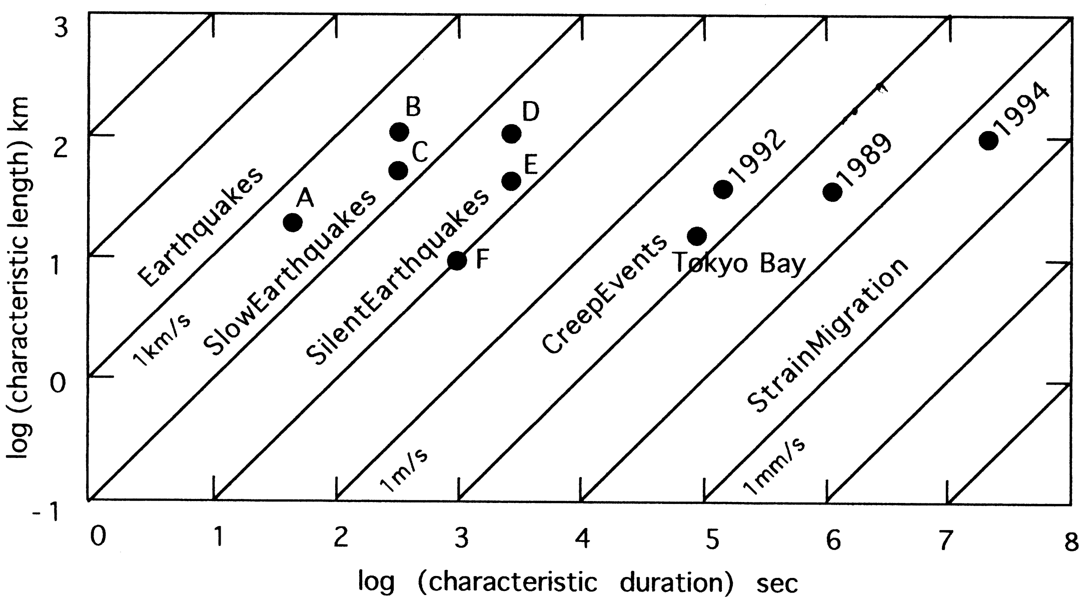

Fig. 11. A plot of the characteristic time versus characteristic fault length. The 1989–1994 Sanriku-oki ultra-slow earthquakes are added to Fig. 1 of Beroza and Jordan (1990).

The core of any mid-term/long-term prediction should be (1) reliable estimate of recurrence interval and (2) reliable estimate of lapse time since the latest event. If the recurrence interval is 110 year in the Japan trench, the next M8 class seismic event should occur in around 2080 in the source area of the 1968 Tokachi-oki earthquake. If the working hypothesis proposed is true and recurrence interval including the aseismic faulting could be 30–40 years, the next event will occur in GAP1 in the near future as either ordinary earthquakes or slow and silent earthquakes of Mwa 7.5.

We are especially interested in **GAP3** because it has had no earthquake for 100 years since the 1897 Miyagi-oki earthquake, a repetition of which would be very dangerous to the densely populated and industrial area of Sendai, Miyagi prefecture, northeast Japan. The 1897 Miyagi-oki earthquake occurred one year after the 1896 Sanriku tsunami earthquake released interplate moment of 12×10^{20} N m in the segments E4–E7. Recently, the 1989–1994 Sanriku-oki ultra-slow earthquakes released $(7.2–11.5) \times 10^{20}$ N m in E4–E6. From the analogy of the sequence of the 1896 Sanriku tsunami and 1897 Miyagi-oki earthquakes, we are interested in how the recent slow earthquakes will have effect on the **GAP3**.

9. Diversity of time constants of faulting

Table 4 lists time constants of the interplate earthquakes. Fig. 11 is a plot of the characteristic time versus characteristic fault length, modified from Fig. 1 of Beroza and Jordan (1990), to which the 1989–1994 Sanriku-oki ultra-slow earthquakes are added. The time constant of ordinary earthquakes is of order of one minute, one example of which was 80 s for the 1968 Tokachi-oki earthquake (Kanamori, 1971). On the contrary, the time constant of the ultra-slow faultings varied in the seismo-geodetic band from 10–20 m ($\sim 10^3$ s) for the 1896 Sanriku tsunami earthquake and ~1 day ($\sim 10^5$ s) for the 1992 Sanriku-oki earthquakes to ~1 year ($\sim 10^7$ s) for the 1994 Sanriku-oki ultra-slow earthquake.

The 1896 Sanriku tsunami earthquake generated a tsunami with a maximum height of 33 m that killed about 22,000 people. Although the 1989 Sanriku-oki ultra-slow earthquake started close to the initial break point (* in Fig. 10) of the 1896 tsunami earthquake (Tanioka and Satake, 1996), it did not accelerate and it was confined to the single segment E5 with final characteristic rupture velocity two or three orders of magnitude smaller than that of the 1896 Sanriku tsunami earthquake. What made the faulting so slow? Why did the faulting of the 1989 Sanriku-oki ultra-slow earthquake not accelerate?

The friction parameter depends on heterogeneity of the physical properties of the plate interface (e.g. Marone et al. (1990) and Dmowska and Lovison (1992)). Recently, Kato and Hirasawa (1999) showed that, depending on slip and slip-velocity dependencies of fault interface friction, events of a wide range of time constants were possible. However, we really do not know the heterogeneity and can not interpret the diversity of the time constant based on the actual plate interface friction parameters at the present stage. One possibility is that the deep sea sediments subducting with the underlying plate are responsible for the slow events as suggested for the slow nature of the 1992 Nicaragua tsunami earthquake by Kanamori and Kikuchi (1993).

10. Summary

The seismic coupling coefficient in the Sanriku-oki region along the Japan trench has been considered to be 20–40%. However, including aseismic faulting, the seismo-geodetic coupling coefficient reaches 50–85% in E4–E6 and W4–W6 between 39.0°N–40.6°N and 142°E–144°E. Focusing on the trench side half (E4–E6) between 143°E and 144°E, the seismo-geodetic coupling amounts up to 60–120%.

Integrating the many observations considered in this paper, we have proposed the working hypothesis that the peak period of the interplate moment release repeats every 30–40 years in the Sanriku-oki region. Within the peak period, the major part of the moment accumulated between the Japan trench and the Sanriku coast was released as both ordinary earthquakes and aseismic faulting. In other words, steady-state creep may not be a dominant factor in releasing interplate moment and the subduction interface is principally locked during the interseismic period. However, it should be noted that the hypothesis is strongly dependent on extrapolating from a short time interval of ~100 years to the long term situation.

Now we wonder if the working hypothesis can be applied to other regions such as off the Boso Peninsula and Izu-Mariana regions where the seismic coupling coefficient is ~0%. There is no clue to this question at the current stage. However, it is certain that an investigation to study episodic aseismic faulting is crucial for a better understanding of subduction zone dynamics.

Three gaps of the moment release, **GAP1**, **GAP2** and **GAP3**, are identified as in Fig. 10. This new concept could play an important role in mid-term/long-term prediction of interplate earthquakes.

Investigations of plate boundary dynamics incorporated with aseismic faulting has just been started. Thus, we have made many simplifications and assumptions. However it could be a good starting point for future development in this direction. Tactics for coming years should be to increase observations of aseismic faulting.

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