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6. *Tsunami Magnitude and Source Area of the Aleutian-Alaska Tsunamis.*

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Abstract

Based on tide-gauge records of the USCGS and Japanese data, the magnitude and source area of the Aleutian-Alaska tsunamis during the past 42 years are investigated. According to the author's method based on the attenuation of wave-height with distance, the tsunami magnitude (Imamura-Iida scale) of the 1946 Aleutian and 1964 Alaska tsunamis are estimated to be $m=3$ and 4 respectively. The magnitudes of the 1957 and 1965 Aleutian tsunamis are $m=3$. According to the empirical formula, the tsunami magnitude is well correlated with seismic moment, but the seismic moment for the 1946 earthquake is considerably small. Its seismic moment may be 1.5×10^{29} dyne-cm judging from the tsunami magnitude.

The source area of the 1946 Aleutian tsunami which inferred from an inverse refraction diagram is especially different from the aftershock area. The source area lies on the steep continental slope extending about 400 km between the Unalaska and Unimak Islands. The source area of the 1957 Aleutian tsunami is the largest. The length of tsunami source is 900 km which agrees with the aftershock area. The western part of the source area overlaps about 200 km of the source area of the 1965 tsunami. In the geographic distribution of the tsunami source in the Aleutian-Alaska region, a remarkable gap of the tsunami source is found between the Unimak and Shumagin Islands. Tnis significant segment of 300-400 km may be considered a region of relatively high tsunami risk having the magnitude $m=2-3$.

1. Introduction

During the past 42 years (1938-1980), five tsunamis of various types accompaning large earthquakes were generated in the Aleutian-Alaska region. The Aleutian tsunami of April 1, 1946 which accompanied an earthquake of $M=7.4$ hit the Hawaii Islands (SHEPARD et al., 1950). KA-

NAMORI (1972) explained a tsunami earthquake by an unusual long process time. The length of the aftershock area of the Aleutian earthquake on March 9, 1957 is about 1,000 km (SYKES, 1971). The Alaska earthquake of March 28, 1964 is one of the greatest earthquake in this century. HATORI (1965a, b) reported the behaviors of the 1964 Alaska and 1965 Aleutian tsunamis observed at tide stations of Japan.

In the present paper, tsunami magnitude and source area are investigated making use of the tidal data (GREEN, 1946; SPAETH and BERKMAN, 1967; COX and PARARAS-CARAYANNIS, 1976) plus Japanese records. Based on the distribution of the tsunami source area obtained from the present analysis, the tsunami (seismic) gap is examined.

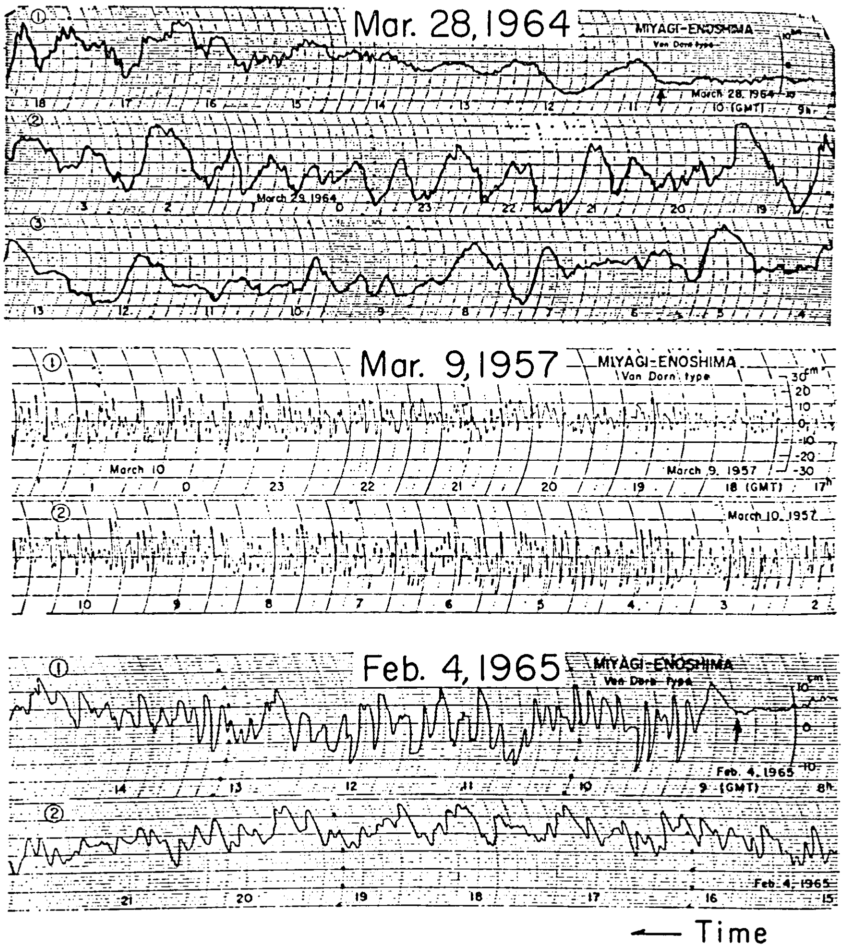

Fig. 1. Records of the Aleutian-Alaska tsunamis obtained by the Van Dorn type long-wave recorder at Miyagi-Enoshima.

2. Tsunami data in Japan

Fig. 1 shows the records of three tsunamis obtained by the Van Dorn long-wave recorder at Miyagi-Enoshima. The period of the 1964 Alaska tsunami is conspicuously longer than that of other tsunamis. Wave-heights of the 1964 Alaska and 1965 Aleutian tsunamis were 20-30 cm on the average along the coast of Japan and run-ups with a maximum of 50-60 cm were recorded in localities in North Japan (HATORI, 1965a, b). The wave-heights of the 1957 Aleutian tsunami were 10-20 cm (Table 1), but those at Hiroo were especially high. At the time, there was low atmospheric pressure to the east of Hokkaido, so that the waves of tsunami

Table 1. Aleutian tsunami on March 9, 1957, as recorded by tide stations of Japan. Wave originated near the earthquake epicenter (51.6°N, 175.4°W) off Adak Is., at 14: 22 (GMT), March 9, 1957.

Tide station	Initial wave			Maximum wave		
	Travel time	Rise	Period	Double ampl.	Height*	τ
Kushiro	4 h 02 m	7 cm	28 min	25 cm	11 cm	10 h 20 m
Hiroo	4 10?	20	10	106	55	8 44
Hakodate	4 52	5	30	26	17	15 10
Onahama	4 46	6	18	23	16	7 24
Aburatsubo	4 50	4	15	42	26	12 42
Kainan	6 08	5	38	15	10	12 24
Kochi	6 32	4	20	14	8	8 18
Hososhima	7 28?	3	20	14	8	3 23

* Crest-height above the ordinary level. τ: Time interval between the arrival of wave front and the maximum wave.

Table 2. Aleutian tsunami on April 1, 1946, as recorded by tide stations of Japan. Wave originated near the earthquake epicenter (53.3°N, 163.2°W) off Unimak Is., at 12: 29 (GMT), April 1, 1946.

Tide station	Initial wave			Maximum Wave		
	Travel time	Rise	Period	Double ampl.	Height*	τ
Hachinohe	5 h 11 m	5 cm	20 min	23 cm	20 cm	10 h 05 m
Miyako	4 55	3	30	28	17	16 42
Ayukawa	5 18	8	15	90	56	9 00
Choshi	?			10	5	8 00?
Ito	5 55	3	15	25	14	8 43
Uchiura	6 21	4	10	20	12	8 20
Hososhima	7 11?			18	10	14 00?

* Crest-height above the ordinary level. τ: Time interval between the arrival of wave front and the maximum wave.

reinforced by a storm surge inundated the southern coast of Hokkaido.

During the 1946 Aleutian tsunami, a small amplitude of 10–20 cm was also observed along the coast of Japan and a relatively high amplitude was recorded at Ayukawa (Table 2). Fig. 2 shows some tide-gauge records of Japan. The tsunami was of short period as were the 1957 and 1965 Aleutian tsunamis.

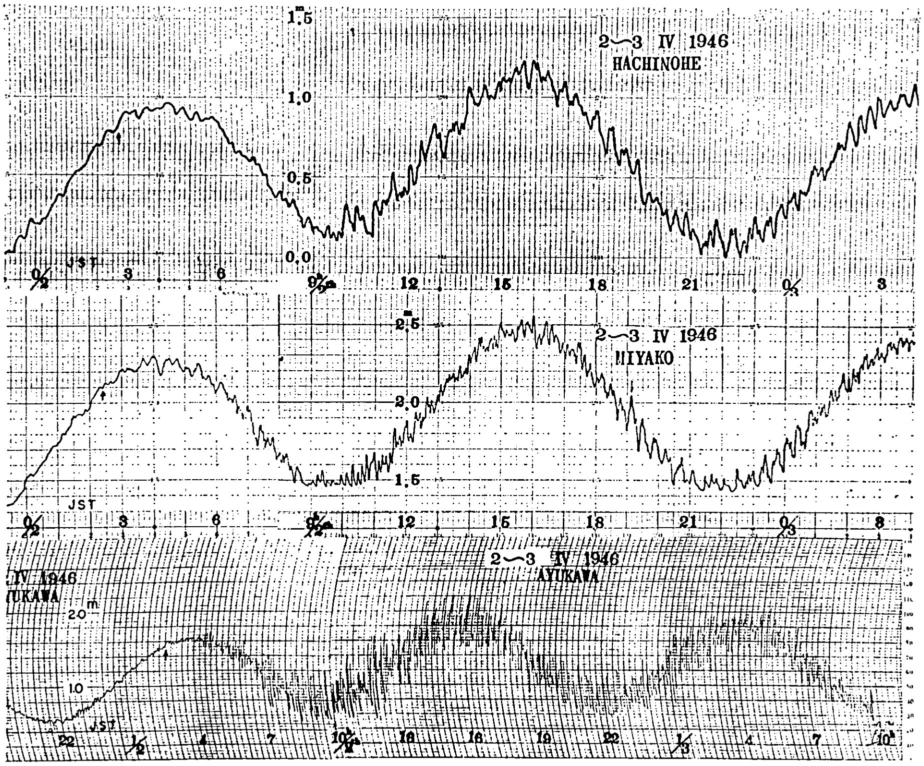

Fig. 2. Tide gauge records of the Aleutian tsunami on Apr. 1, 1946 observed at the tide stations of Japan.

Fig. 3 is arranged in order of the location of the earthquake origin from Western Aleutian to Alaska. The time it took the tsunamis to reach the coast of North Japan was 3.5 to 7 hours. The initial wave front hit at the coast of East Hokkaido first, and then propagated to West Japan an hour or more later. At some tide stations in Japan, the relation between the seiche periods in bays and the maximum amplitude (above ordinary tides) of the Aleutian-Alaska tsunamis is shown in Fig. 4 and the data are given in Table 3. It can be seen that the peak of the maximum wave for the 1964 Alaska tsunami fall in bays whose seiche period is 40 min. In contrast to this, the peak of height distribution for the 1946

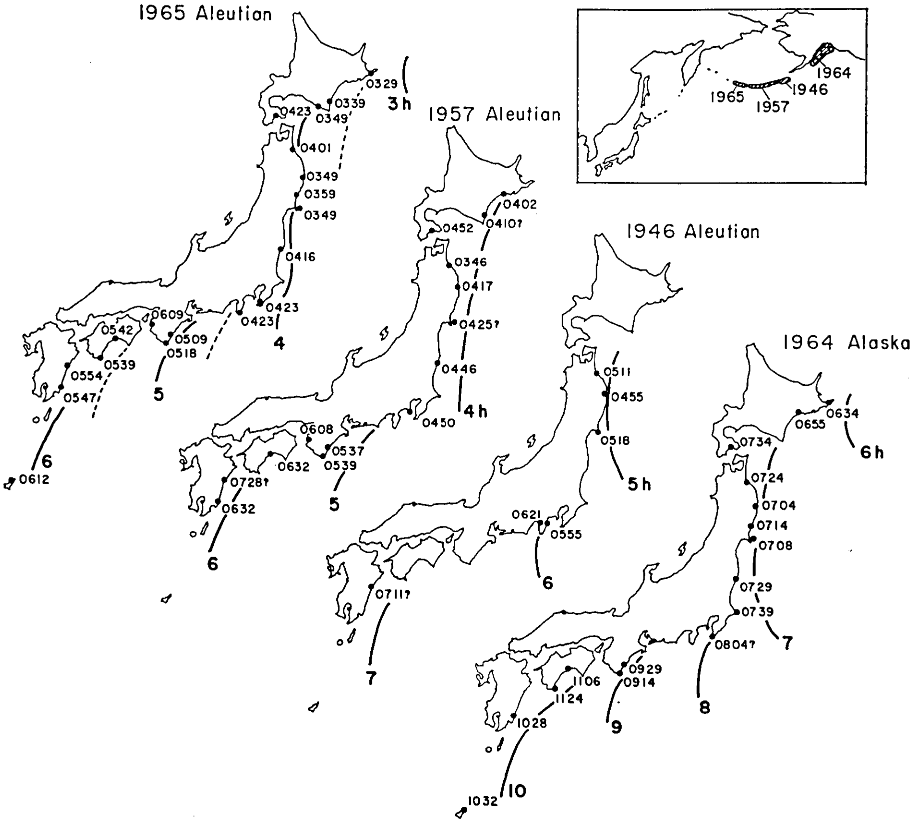

Fig. 3. Refraction diagrams for the Aleutian-Alaska tsunamis, in which arabic numerals indicate the observed travel times (h, m).

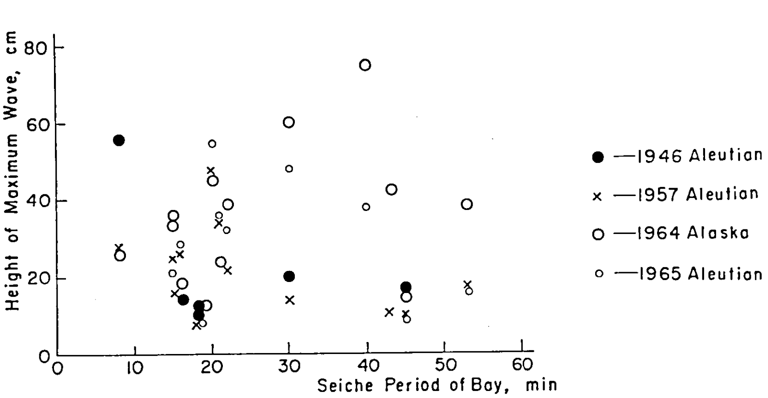

Fig. 4. Relation between the seiche period of bay in Japan and wave-heights of the Aleutian-Alaska tsunamis.

Table 3. Response of the Aleutian-Alaska tsunamis at tide stations of Japan: Seiche period of bay and semi-amplitude of the maximum wave.

Station	Seiche period	1946 Aleutian	1957 Aleutian	1964 Alaska	1965 Aleutian
Hanasaki	15 min	cm	25 cm	36 cm	21 cm
Kushiro	43		11	42	
Hakodate	53		17	38	17
Hachinohe	30	20	14	60	48
Miyako	45	17	10	14	10
Ofunato	40			75	38
Ayukawa	8	56	28	26	
Onahama	15		16	35	20
Choshi	12		25	36	
Aburatsubo	16		26	18	28
Ito	16	14			
Uchiura	18	12		12	
Kushimoto	20		48	45	55
Tosa-Shimizu	21		34	24	36
Hososhima	18	10	8	12	7
Aburatsu	22		22	39	32

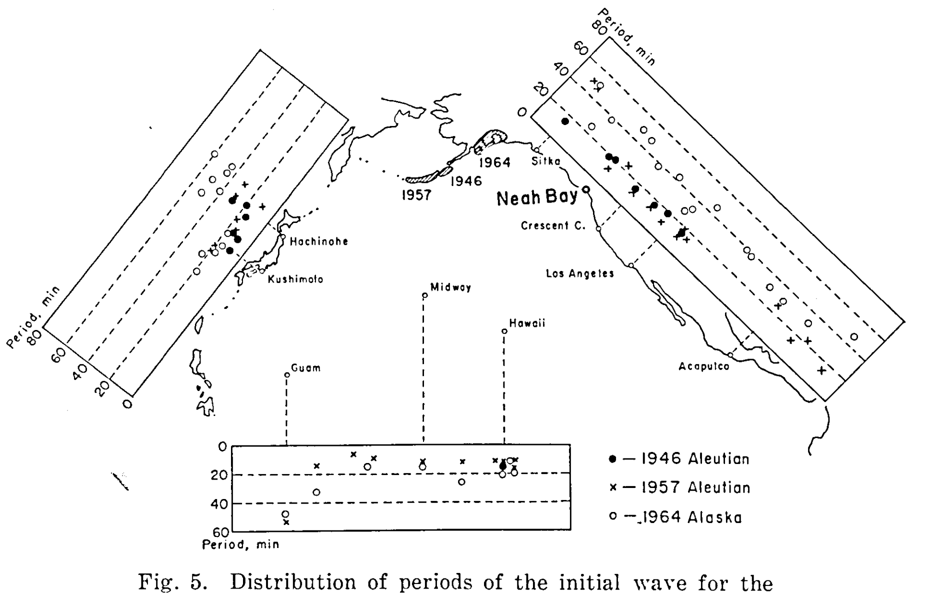

Fig. 5. Distribution of periods of the initial wave for the Aleutian-Alaska tsunamis.

and 1957 Aleutian tsunamis was only 20 min or less. Fig. 5 shows the distributions of the period between the 1st and 2nd crests of waves in the entire Pacific region. Although the periods of three tsunamis at the mid-oceanic islands were 20 min or less, those along the coast of America and Japan are conspicuously different. Along the coast of America, the period of the 1964 Alaska tsunami (SPAETH and BERKMAN, 1967) was 40 min on the average, but these of the other tsunamis were 20 min or less. The feature of periods suggests that the source area of the 1964 Alaska tsunami was located on the continental shelf, but those of the 1946 and 1957 Aleutian tsunamis lay on the continental slope.

3. Tsunami magnitude

For the Aleutian-Alaska tsunamis, the relations between the maximum wave-heights (semi-amplitude) and the distance along the margin of the

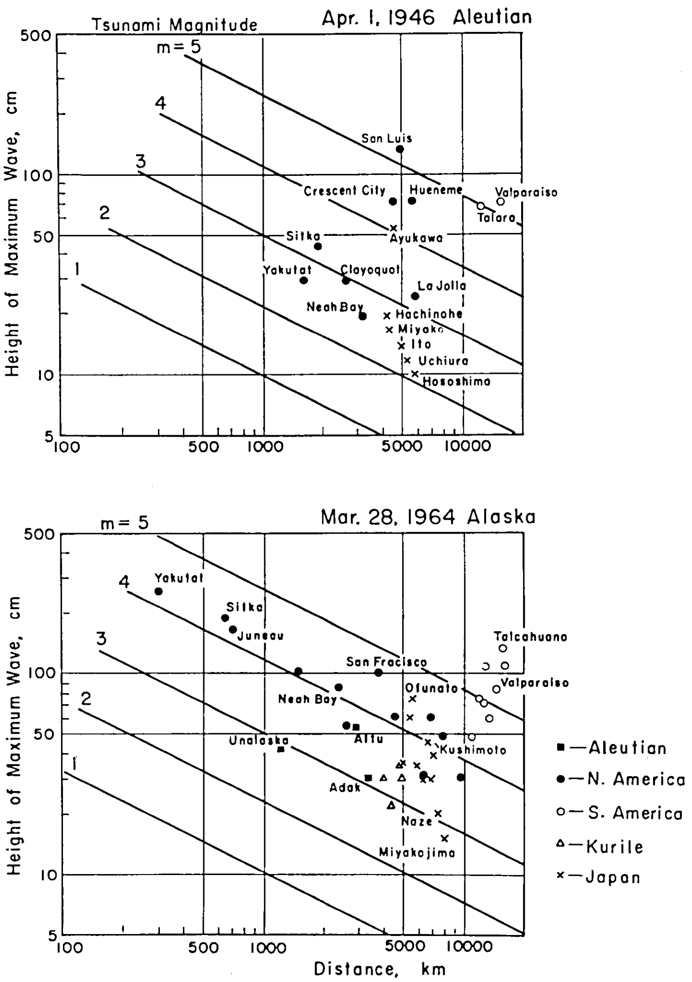

Fig. 6a. Attenuation of the maximum wave height (semi-amplitude) with distance from the epicenter. m: Tsunami magnitude denoted by the Imamura-Iida scale.

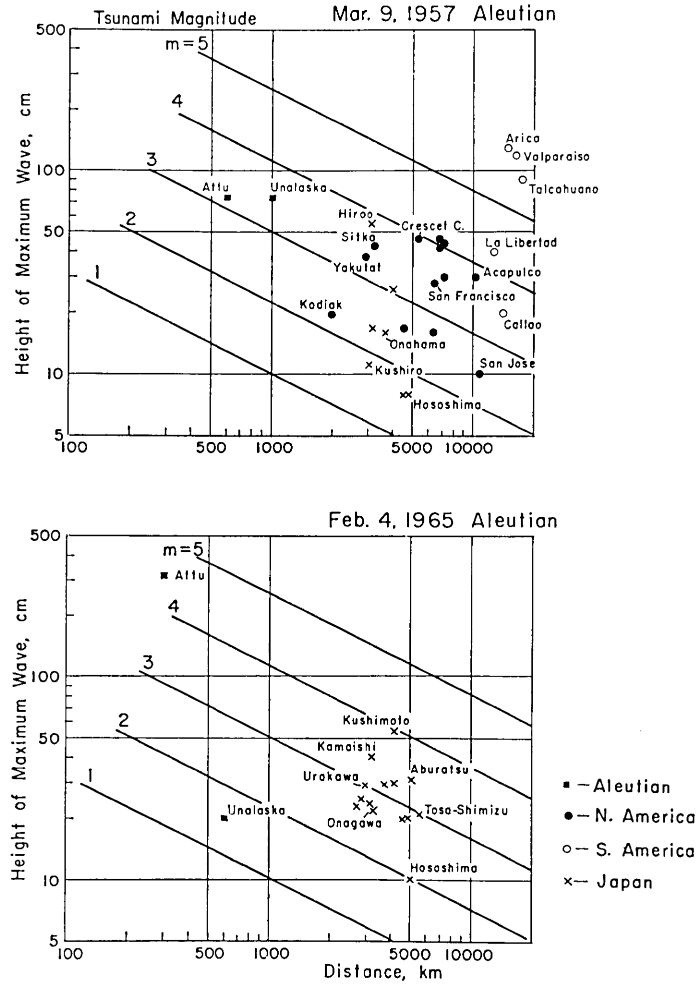

Fig. 6b. Attenuation of the maximum wave height (semi-amplitude) with distance from the epicenter.

continental shelf from the epicenter of the main shock are shown in Figs. 6a and 6b. Here, the tsunami magnitude of the Imamura-Iida scale, *m*, is classified by author's method (HATORI, 1979) as follows: The tsunami magnitude is defined as $m=3$, when the maximum heigh, H, at the distance R=1,000 km is 50 cm on a R-H curve expressed in accordance with $H/\sqrt{R}$. The R-H curves for each magnitude scale are drawn at 2.24 intervals of wave height. Namaly, the tsunami energy is reduced by one-fifth with the decrease of magnitude of unity.

According to Figs. 6a and 6b, the observed values vary greatly because of such topographic effects as the direction of the island arc, shoaling, etc. There is a tendency to have large wave-heights along the coast of South America and small ones in Japan. The data at the mid-oceanic islands are omitted in these figures. On the average, the magnitudes of the 1946 Aleutian and 1964 Alaska tsunamis are determined to be $m=3$ and 4, respectively. The magnitudes of the 1957 and 1965 Aleutian tsunamis may be determined to be $m=3$. Wave-heights of the Aleutian tsunami on Nov. 10, 1938 were 10–30 cm at the Alaska, Aleutian and Hawaii regions (COX and PARARAS-CARAYANNIS, 1976) and those at Tosa-Shimizu, West Japan, were 10 cm. The magnitude of the 1938 tsunami seems to be $m=2$.

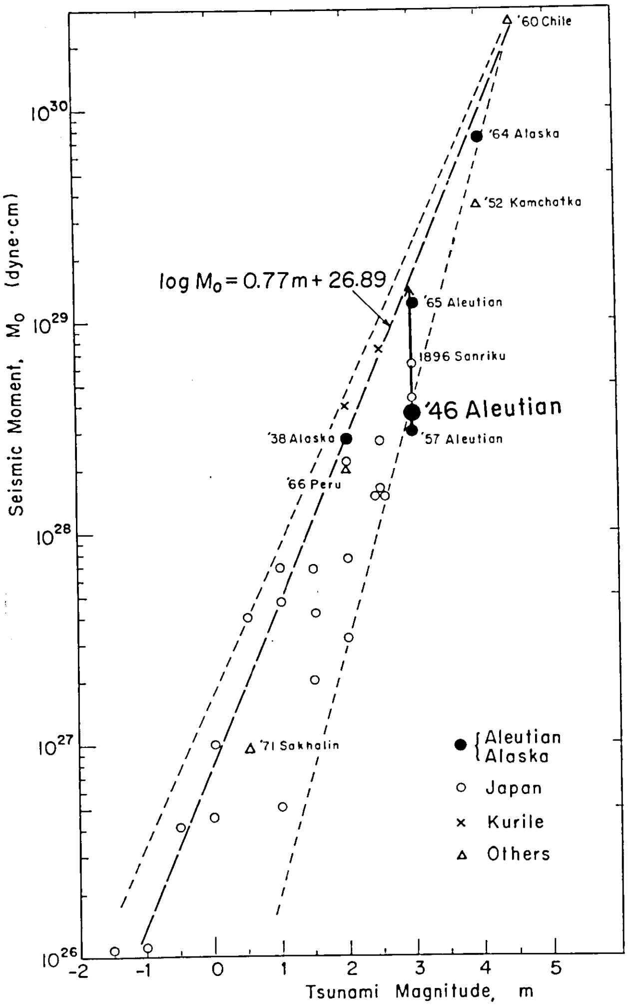

Fig. 7. Relation between tsunami magnitude (Imamura-Iida scale) and seismic moment.

The tsunami magnitude, m, is very closely related to the seismic moment, M_0, calculated from the long period surface waves. This relation is empirically expressed as $\log M_0 = 0.77\, m + 26.89$ (HATORI, 1979). In Fig. 7, the data of the Aleutian-Alaska earthquakes (SYKES, 1971; KANAMORI, 1972) are shown by closed circles. Judging from the tsunami magnitude, the seismic moments of the 1946 and 1957 earthquakes may be estimated as 1.5×10^{29} dyne-cm.

4. Tsunami source area

For the tsunamis generated in the sea adjacent to Japan, the source areas which are estimated by means of an inverse refraction diagram based on the arrival time of tsunami-front nearly agree with the after-shock areas (IIDA, 1958; HATORI, 1969). The tsunami source areas in the Aleutian-Alaska region were investigated by the same method, using tidal data of the USCGS and Japan. Fig. 8 shows the refraction diagrams at Miyako and other tide stations of Japan. It can be seen that the wave ray of the tsunamis does not follow the great circle route from the Aleutian-Alaska origin.

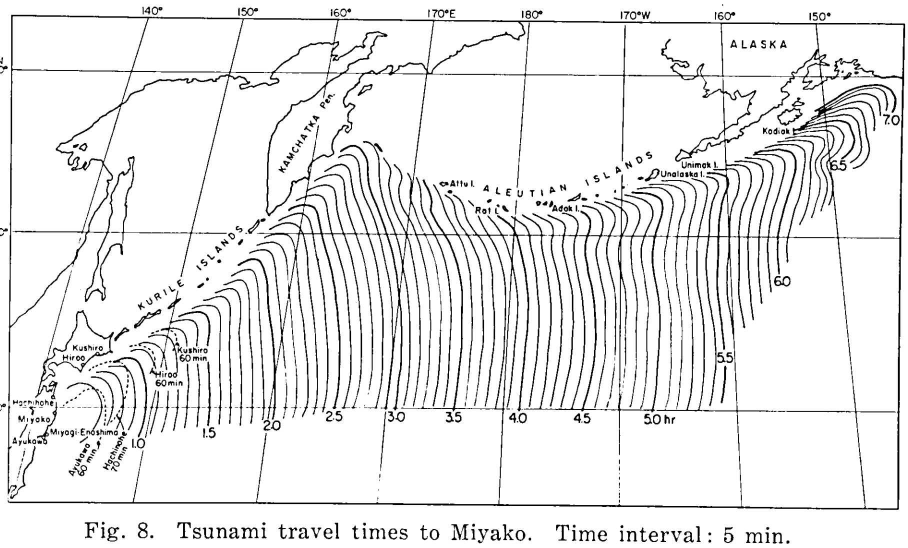

Fig. 8. Tsunami travel times to Miyako. Time interval: 5 min.

Fig. 9 shows the estimated source areas of the 1957 and 1965 Aleutian tsunamis, where the last wave-fronts of the inverse refraction diagram are shown with the names of the tide stations and the tsunami travel times (h, m). The source areas of the 1957 and 1965 tsunamis lie on the continental slope, extending about 900 km and 600 km, respectively, along

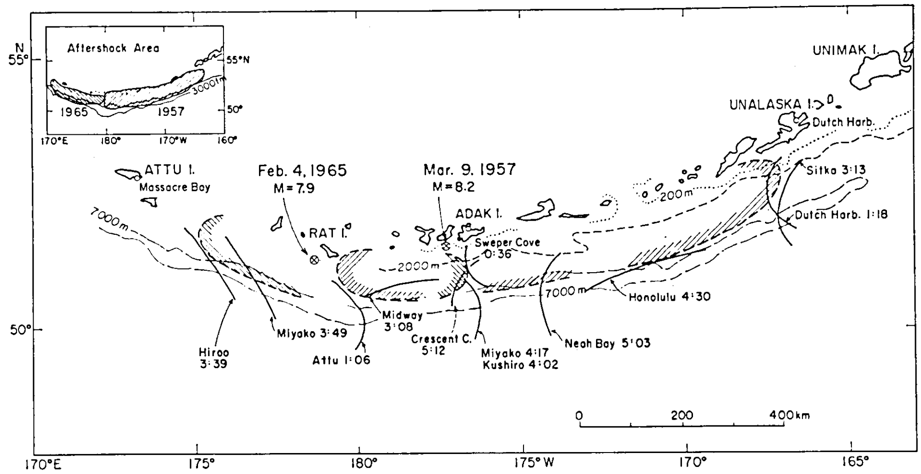

Fig. 9. Estimated source areas of the 1957 and 1965 Aleutian tsunamis. The last wave fronts are shown with the names of the tide stations and travel times (h, m). Left upper figure: Aftershock areas of the 1957 and 1965 earthquakes (Sykes, 1971).

the Aleutian Arc. Both of the tsunami sources generally agree with the aftershock areas, but a segment of about 200 km overlaps each other. As pointed out by MOGI (1968), the dimension of the aftershock areas and the tsunami sources in the Aleutian-Alaska region are considerably longer in comparison with those in the Japan region.

The aftershock area of the 1946 earthquake was located near Unimak Island and its length was 75-125 km denoted by the hatched area in Fig. 10 (SYKES, 1971). However, according to the present method based on tide-gauge records, the tsunami source area is elongated in the west direction along the Aleutian trench. The source length is about 400 km and its area is 48×10^3 km^2. The uncertainty of the refraction diagrams may be within ± 100 km because of the far field data. The 1946 tsunami was observed with the short period waves. It suggests that the tsunami source lies on the steep continental slope near the trench.

The source area of the 1938 tsunami lies on the contiental shelf along the Alaska Peninsula. Both ends of the source area can not be delineated because of a lack of data. The source area of the 1964 Alaska tsunami was estimated by PARARAS-CARAYANNIS (1967). Adding the new data, the source area is re-examined in Fig. 10. The estimated source area agree well with the crustal deformation zone (PLAFKER, 1969). It extends about 700 km on the continental shelf. Therefore, very long-period waves were predominant. The source dimension of these tsunamis is given in Table 4.

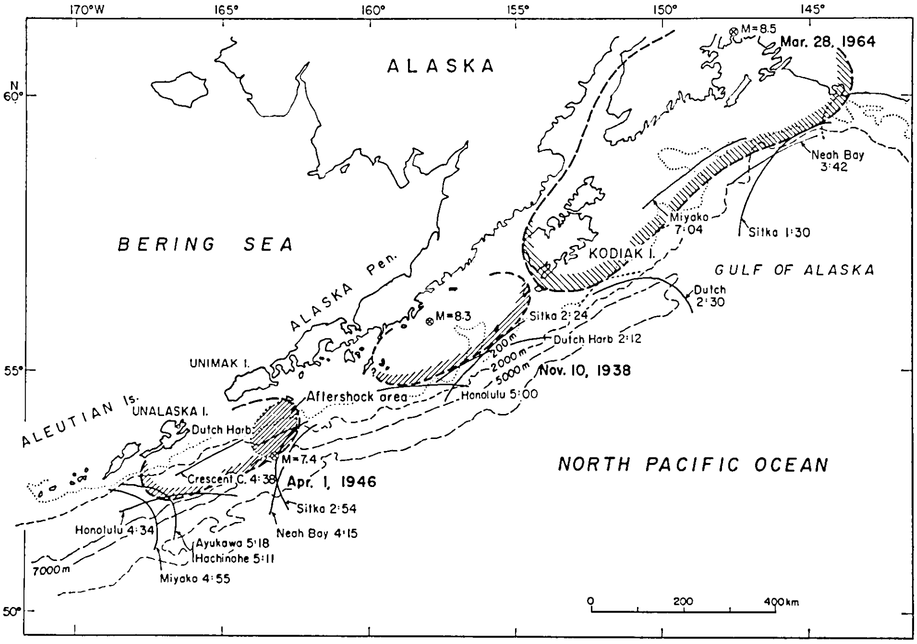

Fig. 10. Estimated source areas of the 1938, 1946 and 1964 Aleutian-Alaska tsunamis.

Table 4. Source dimension of the Aleutian-Alaska tsunamis.

Date	Location	*M*	*m*	L (km)	S ($\times 10^3 km^2$)
Nov. 10, 1938	Alaska Pen.	8.3	2	400?	
Apr. 1, 1946	Aleutian	7.4	3	400	48
Mar. 9, 1957	Aleutian	8.2	3	900	90
Mar. 28, 1964	Alaska	8.5	4	700	110
Feb. 4, 1965	Aleutian	7.9	3	600	60

m: Tsunami magnitude (Imamura-Iida scale). L: Length of tsunami source.
S: Area of tsunami source. *M*: Earthquake magnitude.

5. Conclusion

Adding the tide-gauge records of Japan, the tsunami magnitudes and the source areas of the Aleutian-Alaska tsunamis during the past 42 years are investigated. The features of each tsunami differ greatly. Generally speaking, the estimated source areas of the tsunamis nearly agree with the aftershock areas. However, the source area of the 1946 tsunami is especially different. Its source area lies on the steep continental slope, extending about 400 km between Unimak and Unalaska Islands. The source length of the 1957 tsunami is about 900 km. The source dimension in the

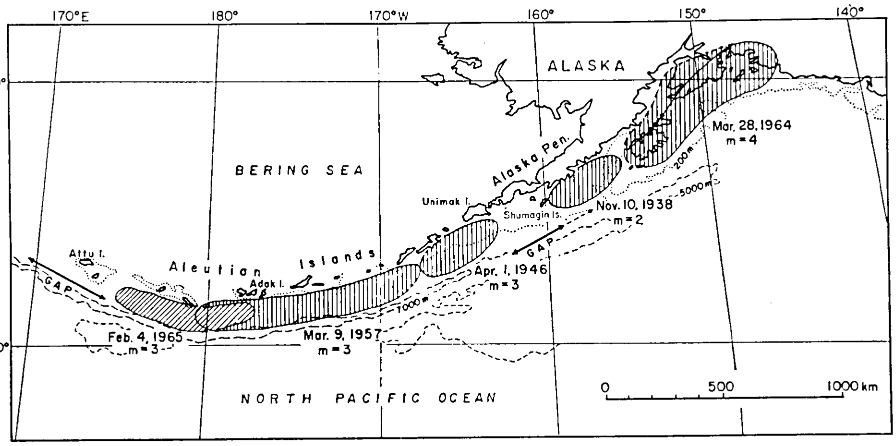

Fig. 11. Geographic distribution of the source areas of the Aleutian-Alaska tsunamis. Dates and tsunami magnitudes (Imamura-Iida scale) are indicated.

Aleutian-Alaska region is 2–3 times larger than that of tsunamis generated near Japan.

The source areas of five events which were estimated by the inverse refraction diagrams are denoted by the hatched areas in Fig. 11. Two tsunami (seismic) gaps can be seen in this region. The West Aleutian region off Attu Island has had low seismic activity since the historic times. However, another gap along the Alaska Peninsula on the Pacific side is a very active seismic region. The seismic gaps were found by the earthquake data (MCCANN et al., 1980), and its existence can be clearly seen from the present analysis using the tsunami data. The tsunami gap of 300–400 km between Unimak and Shumagin Islands should be considered a region of relatively high tsunami risk.

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6. アリューシャン・アラスカ津波の規模と波源域

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最近50年の間に，アリューシャン・アラスカ海域におこった5個の巨大地震に伴った津波について，米国の CGS 記録に日本の観測データも加え，津波の規模と波源域を調べ，この海域の津波特性を検討した．まず，各津波の規模（m：今村・飯田スケール）を，震央から島弧にそった沿岸の波高データをもとに，筆者の方法で判定すれば，ハワイに大被害を与えた1946年津波は $m=3$ と格付けされる．この地震のマグニチュードは $M=7.4$ とみなされているが，津波データによれば地震モーメント M_0 は 1.5×10^{29} ダイン・cm と見積もれる．一方これとは対照的に，地震規模が上回った1938年のアラスカ半島沖地震（$M=8.3$）の津波は，$m=2$ と推定される．そのほか1964年アラスカ津波は $m=4$，1957年・1965年のアリューシャン津波は $m=3$ と見積もれ，それぞれ地震モーメントに見合った津波であった．

各地で観測された津波の伝播時間をもとに，逆伝播図から波源域を推定すると，1964年アラスカ津波の波源域の長さは 700 km で，余震域と大体合致する．しかし，1946年津波の波源域は余震域と著しく異なり，ウナラスカ島からウニマク島に至る長さ 400 km と推定される．

1957年津波の波源域は，余震域とほぼ合致して 900 km にもなり，そのほかの津波も日本近海の津波と比べて，波源域は数倍も長い．1964年アラスカ津波では40分の周期が卓越したのに対し，1946年・1957年・1965年津波の周期は10～20分と短かく，波源域が海溝寄りにあったことを暗示している．解析の結果，この50年の間に，各波源域はアッツ島沖からアラスカに至る海域に，島弧にそって並んで分布しているが，アラスカ半島ぞいのウニマク島からシュマーギン島に至る 400 km の間に津波の空白域が見出せる．これは，近い将来，この区間に $m=2\sim3$ クラスの津波発生の可能性が大きいことを考えさせる．