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51. *A Study of the Wave Source of Tsunami generated off West Hokkaido on Aug. 2, 1940.*

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Abstract

The wave source of the tsunami generated off West Hokkaido (Shakotan Peninsula), in the Japan Sea, on Aug. 2, 1940 is estimated by means of an inverse refraction diagram, making use of a new bathymetric chart. The source area extends 170 km in the NNW-SSE direction, which is smaller than that obtained by Miyabe (1941). However, the dimension estimated by the present analysis is still large for the earthquake magnitude of $M=7.0$. From a comparison of the geographic distribution of the earthquake intensity with those of the other tsunamigenic earthquakes that occurred in the Japan Sea, the magnitude of this earthquake is investigated. Effective tsunami height observed on the surrounding coasts of the Japan Sea can be explained by the direction of the present source. Magnitude of the tsunami of 1940 seems to be equal to that of the Niigata tsunami of 1964 and is represented as $m=2$. Besides, the wave source of the tsunami generated off Rumoi, West Hokkaido, on Nov. 4, 1947 is discussed, taking the aftershock area into consideration.

1. Introduction

Off shore of the west coast of Hokkaido belongs to a region with deep earthquakes of focal depth 200 km or more, a few earthquakes there having sometimes been accompanied by tsunami. The tsunami generated off the Shakotan Peninsula at 00 h 08 m (JST) on Aug. 2, 1940 (the Shakotan-oki tsunami) caused moderate damage on the west coast of Hokkaido, Sakhalin, Sikhote-Alin (USSR), North Korea and the Oki Islands. 10 lives were lost at the mouth of the Teshio River. This tsunami was also observed by tide gauges on the surrounding coasts of the Japan Sea. According to the seismological bulletin published by the Japan Meteorological Agency (JMA, 1958), the magnitude of the earthquake has been estimated as M=7.0.

Soon after the occurrence of the earthquake field investigations were carried out by the Sapporo Meteorological Observatory (Saito, 1941;

Takanobu, 1941). Principal behaviors of the tsunami were reported by the Kisho-yoran (JMA, 1940)*. The source area of tsunami was estimated by means of an inverse refraction diagram by Miyabe (1941) as 200 km in diameter. However, taking account of the statistical formula between the source dimension and the earthquake manitude M(Iida, 1958; Hatori, 1969),** the dimension of the estimated source area is abnormally large for the magnitude $M=7.0$. On the other hand, according to the U.S. Coast and Geodetic Survey (CGS), the magnitude of this earthquake M_G was determined as 7.7, so that the estimated value is quite different from that of JMA. In the present paper, employing a new bathymetric chart, the location and dimension of the tsunami source are newly estimated by the same method. Comparing the geographic distributions of the intensity of tsunamigenic earthquakes that occurred in the Japan Sea, the magnitude of the Shakotan-oki earthquake is discussed. The effect of the source direction is investigated with the aid of the refraction diagram and compared with the Niigata tsunami of 1964.

Another tsunami was generated off Rumoi, West Hokkaido, at 09 h 09 m (JST) on Nov. 4, 1947 (the Rumoi-oki tsunami) caused by an earthquake having the magnitude $M=7.0$. The source area of this tsunami is also examined.

2. Source area of tsunami

Wave-fronts of an inverse refraction diagram are drawn at two minutes interval on the bathymetric charts as follows: "Bathymetric chart of the adjacent seas of Nippon" (1/3,000,000, No. 6301, 1968) and others (1/300,000 and 1/500,000) published by the Japan Hydrographic Office are used at deep sea regions and that from the coast to the continental shelf, respectively.

(a) *The Shakotan-oki tsunami of 1940*

According to the tsunami records obtained at Nevelsk (Honto), Otaru, Osyoro, Iwanai, Sakata, Niigata, Wajima and Najin (Rashin), the initial motion of all records clearly began with a rising level. Arrival times of the tsunami at various stations given by Miyabe (1941), are adopted in the present drawing. Data of the initial arrival times observed by eye-witnesses at the coasts of Haboro and Tetyukhe (Sikhote-Aline) are also used. It has been reported that the tsunami front reached in 40–45 min after the occurrence of the earthquake at Tetyukhe (Svyatlovski,

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* Monthly Geophysical Review (in Japanese).

** In case of a shallow earthquake ($0<d<20$ km), the dimension of a tsunami source is 60–100 km for $M=7.0$ and 150–250 km for $M=7.7$.

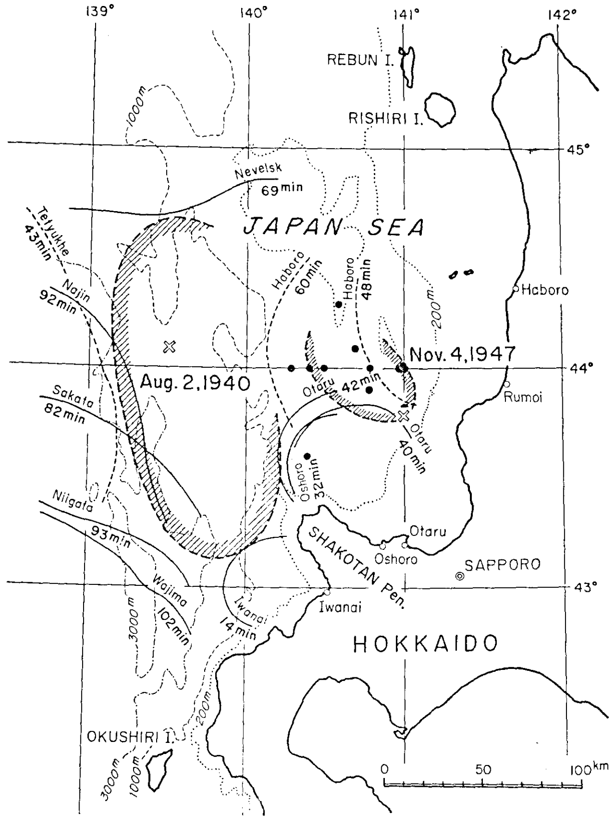

Fig. 1. Estimated source area of the tsunamis generated off West Hokkaido in 1940 and 1947, and the distribution of aftershocks caused by the earthquake of 1947 (closed circle). The last wave fronts correspond to travel times observed by tide gauges (solid line) and visual sense (broken line).

1957; Soloviev and Ferchev, 1961). The final wave-fronts corresponding to the travel times, starting from every station are shown in Fig. 1. The estimated tsunami source is 170 km long, 70 km wide and its area is 9.4×10^3 km^2. If an error of ±2 min is associated with the determination of travel time and drawing, the dimension of the area changes about ±20 km. The major axis of the source runs in the NNW-SSE direction, and the west side of the source is roughly parallel to the east margin of the Japan Basin along the bottom contour of 3000 m. The south side of the source extends up to some 15 km off the cape of Shakotan Peninsula. Within the source area, there are some ridges, the topography of the sea bottom being complex.

Judging from the initial motion of the records, the upheaval of the bottom seems to have occurred in the source area of tsunami. According to the inhabitants at the region around the Shakotan Peninsula (Yoichi, Irika and Iwanai), the initial wave-front of tsunami began with a downward motion 3 min after the occurrence of the earthquake, suggesting the upheaval at the Shakotan Peninsula. Many aftershocks were observed by the seismograph station at Sapporo belonging to the JMA. The frequency distribution of the $P-S$ intervals for these shocks lie in the range of 10 sec to 33 sec, and the predominant peak falls at the position of 20 sec. The linear dimension of the aftershocks region of about 190 km was estimated by Utsu (1961).

The tsunami sources estimated by Miyabe and the present analysis are shown with dotted and solid lines, respectively in Fig. 2. As seen in Fig. 2, the newly estimated area moves to the east from Miyabe's result and becomes strongly elliptical. The dimension has decreased to about two-thirds of Miyabe's. Fig. 2 also shows the distribution of the tsunami height in meters. Compared with the tsunami height at the coast of Shakotan Peninsula near the tsunami source, that at the northwest side of Hokkaido is large. On the southwest side of Rishiri Island, the height of 2.9 m was reported. It is remarked that the maximum height of 3.5 m was observed at Tetyukhe.

Fig. 3 shows a refraction diagram of wave-fronts for 10 min intervals, in which wave-fronts were drawn starting from the margin of the source

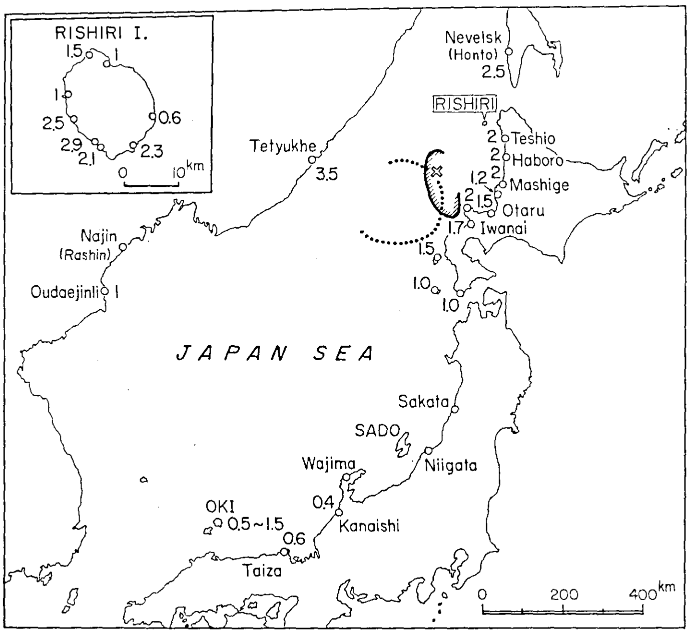

Fig. 2. Distribution of the tsunami height, in meters, for the tsunami of 1940. The tsunami sources inferred from the present and Miyabe's analyses are indicated by solid and dotted lines, respectively.

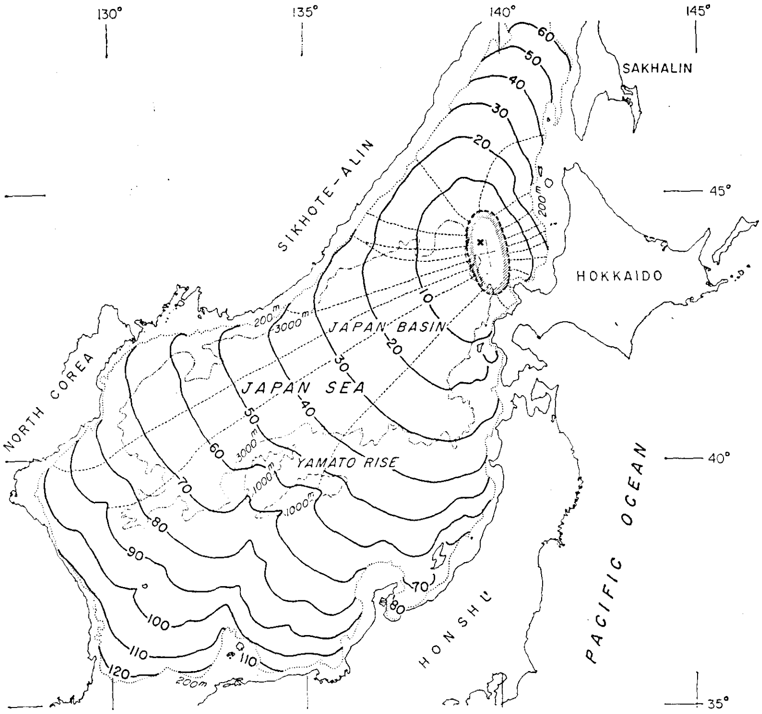

Fig. 3. Refraction diagram and wave fronts at every 10 min intervals from the source. Broken lines represent wave rays, which are emitted from the origin subdivided into equal angles of 20 degrees.

obtained from the present analysis, at every 2 min intervals. In this figure, the trajectories are also drawn by broken lines, the azimuth at the origin being divided into equal angles of 20 degrees. About half of the total tsunami energy is emitted into the northwest coast of Hokkaido. A part of the energy concentrates at the coast of Sikhote-Aline (neighborhood of Tetyukhe) and diverges along the coast of Honshu, the main-land of Japan. Wave rays are expected to concentrate at the Oki Islands because wave-fronts are deformed by the Yamato Rise lying in a center part of the Japan Sea. At the coast of North Korea, wave rays which started from the minor axis of the tsunami source are directly run on to the Japan Basin. According to the refraction diagram in the case of the Niigata tsunami of 1964 (Hatori, 1965 a) the coast of North Korea seemed to be the location of the concentration of the tsunami energy caused by the Yamato Rise.

(b) *The Rumoi-oki tsunami of 1947*

The behavior of the Rumoi-oki tsunami has been reported by the Kisho-yoran (1947) as follows: Forty min after the occurrence of the earthquake, a small tsunami was observed at Otaru by tide gauge. The tsunami front began with a downward motion 48 min after the earthquake at the coast of Haboro and the tsunami height of 70 cm was reported with visual observation. According to the tsunami catalogue compiled by Watanabe (1968), the maximum height of 2 m was observed at Kutsugata, Rishiri I. In Fig. 1, the final wave-fronts starting from Otaru and Haboro and the distribution of aftershocks are shown. Taking account of the area of aftershock activity, the source area of tsunami is roughly inferred as shown in Fig. 1. If the length of the major axis of the source is 60 km, the source dimension may be considered as the standard size for the earthquake magnitude of the range of 6.8–7.0.

3. Magnitude of the earthquake

The magnitude of the Shakotan-oki earthquake is examined by comparison with those tsunamigenic earthquakes that occurred in the Japan Sea as listed in Table 1. The method is to compare the distribution of earthquake intensity. The magnitudes of these earthquakes determined by JMA and CGS are nearly equal except the Shakotan-oki earthquake. In the cases of the 1939 Oga (Kishinouye and Iida, 1939) and the 1964 West Aomori earthquakes (Hatori 1965 b), double wave amplitudes of 50 cm or less were observed by tide gauges along the coasts from Akita prefecture to SW Hokkaido.

Table 1. List of tsunamigenic earthquakes that occurred in the Japan Sea.

Date (JST)	Epicenter Lat. N	Epicenter Long. E	Location	Depth (km)	Earthquake magnitude M
1939 May 1	40.0°	139.8°	Oga	0	7.0
1940 Aug. 2	44.1	139.5	W. Hokkaido (off Shakotan)	0-20	7.0
1947 Nov. 4	43.8	141.0	W. Hokkaido (off Rumoi)	0-30	7.0
1964 May 7	40.3	139.0	W. Aomori	0	6.9
1964 June 16	38.4	139.2	Niigata	40	7.5

From the observation of JMA, the relation between the earthquake intensity and the distance from the epicenter are shown in Fig. 4 where the open circles are the Shakotan-oki earthquake, solid circles the others. The left side from the broken line in Fig. 4 corresponds to the region of open sea for the Shakotan-oki earthquake, so that the intensity should be compared with the right side. It is seen that the Shakotan-oki earthquake is clearly larger than the Rumoi-oki earthquake, nearly of

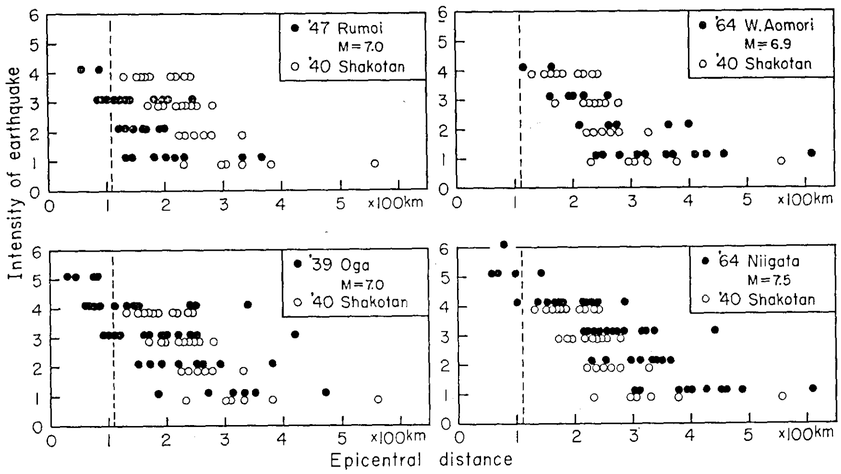

Fig. 4. Relations between intensity of the earthquakes that occurred in the Japan Sea and distance from the epicenter.

the same order as the West Aomori and Oga earthquakes, and smaller than the Niigata earthquake. On the other hand, Yoshiyama (1964) pointed out that the magnitude $M=7.5$ for the Niigata earthquake, might be overestimated on the basis of a comparison with land earthquakes of like intensity by the same method. As seen in Fig. 4, the intensity diagrams are widely scattered according to various conditions of earthquakes such as the locality and focal depth. However, the magnitude $M=7.0$ of the Shakotan-oki earthquake seems to be reasonable. It is considered that the Rumoi-oki earthquake has a magnitude of the order of 6.6–6.8.

4. Comparison with the Niigata tsunami of 1964

For the Niigata tsunami, Iida (1967) indicated the relation between the tsunami height H and the distance r along the trajectory from the margin of the tsunami source, as shown by closed circles in Fig. 5 and expressed the relationship as $H \propto r^{-0.5}$. Soloviev and Militeev (1967) also discussed the decay of tsunami height, adding new data observed in the USSR.

The data obtained from the Shakotan-oki tsunami are plotted with open circles in Fig. 5. The scattered points in the range from 110 km to 300 km correspond to the regions of NW Hokkaido and Sikhote-Alin and these were, as above mentioned, caused by the effective directivity of the tsunami. Magnitude of the Shakotan-oki tsunami is of the same order to that of the Niigata tsunami and is represented as $m=2$. However, the source area of the Shakotan-oki tsunami has three times as large a dimension as that of the Niigata tsunami.

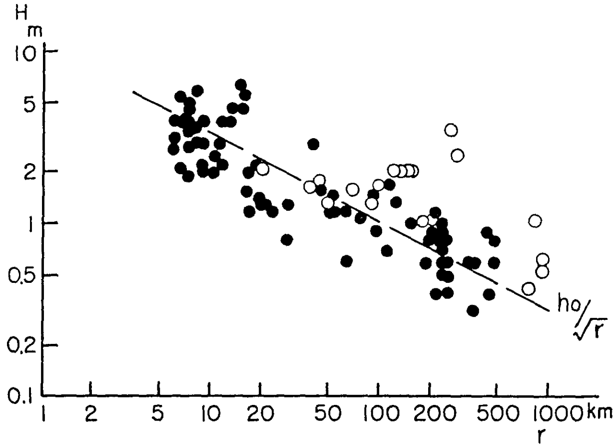

Fig. 5. Attenuation of tsunami height with distance from the tsunami source. Closed circle: the Niigata tsunami of 1964 (after K. Iida), open circle: the Shakotan-oki tsunami of 1940.

5. Conclusion

The estimated source of the tsunami generated off the Shakotan Peninsula, West Hokkaido, on Aug. 2, 1940 has an area of 9.4×10^3 km^2 and a length of 170 km directed NNW-SSE. Compared with Miyabe's analysis, the present source moves to the east side. Its shape is more elongated but the dimension becomes smaller. The south edge of the tsunami source approaches the Shakotan Peninsula and the west side runs almost parallel to the eastern margin of the Japan Basin. Behavior of the tsunami heights on the surrounding coast of the Japan Sea can be explained with the aid of the refraction diagram drawn from the source. Earthquake magnitude seems to be $M=7.0$ judging from the comparison with the intensity distribution of other earthquakes. However, according to the statistical formula, the present dimension of the tsunami source is remarkably large even taking the accuracy of the drawing into account. Tsunami magnitude of the present tsunami may be equal to that of the Niigata earthquake and is ranked as $m=2$.

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51. 1940年8月北海道積丹沖津波の波源とその考察

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1940年8月2日，北海道積丹沖に起きた津波は日本海全域に伝播し，北海道西岸をはじめソ連の沿海州と北朝鮮，隠岐にも家屋，船舶などに被害を与えた．地震の規模 M は，気象庁の地震カタログ (1958) によると M=7.0, USCGS によると M_G=7.7 と示されており，両者の決定値には著しい違いがある．一方，余震は札幌において多数観測され，P-S 頻度分布は 10 sec から 33 sec の範囲にあつて，余震域の長さは約 190 km と推定されている (宇津，1961)．

この津波の波源域は地震直後，宮部 (1940) により検潮記録をもとにして推定された．しかしこの推定値は M=7.0 と取扱つたとき，波源の大きさと地震規模との統計的な関係図 (飯田，1958; 羽鳥，1969) から見積ると異状に大きい．この点を明らかにするために今回，最新の海底地形図 (水路部，1968) を用い，改めて津波の逆伝播図を作図した．なお，各地の津波の到達時間は，記録の明瞭度から宮部の読取値を，そのまま採用する．一方，数個の日本海で起きた地震につき，震度分布を比較して地震の規模を検討した．

解析の結果，宮部の推定に較べて波源域は小さく，その形も扁平な楕円となつた．波源の長径は NNW-SSE 方向に 170 km となり，波源の南側は積丹半島に近接している．西側は日本海盆の東縁に沿い，波源域内の海底地形はかなり複雑である．検潮記録によると，津波の第1波は総べて明瞭な

押し波で始まり，海底の隆起を暗示している．推定波源からの津波伝播図を見ると，津波の全エネルギーの半数は北海道西岸に伝播し，沿海州の一部と北朝鮮に波線が集中している．また大和堆によつて波面の形が不規則になり，局部的に波線が隠岐へ集まることが予想できる．以上，改訂後の波源の向きから，日本海周辺の波高分布は理解される．

震度分布の比較図によると，1940 年積丹沖地震は 1947 年留萠沖地震 ($M=7.0$) より明らかに大きく，1939 年男鹿地震 ($M=7.0$)，1964 年青森西方沖地震 ($M=6.9$) と同程度と見なされるが，1964 年新潟地震 ($M=7.5$) よりは小さい．従つてこの判定方法からは，積丹沖地震の規模は気象庁の決定した $M=7.0$ が適正値となる．

次に波源からの距離と波高との関係を調べると，積丹沖津波は方向性による効果もみられたが，津波の規模は新潟津波と同程度と言える．しかし，波源の面積は 9.4×10^3 km^2 と推定され，新潟津波の約 3 倍にも及ぶ．一方，留萠沖地震では，その余震域を考慮して波源を推測すると，長径は約 60 km となり，これは統計的に標準の大きさである．これに対し，積丹沖津波の波源域は改訂後，作図の誤差を考慮に入れても，なお目立つて大きい．また余震も同様に広い領域に分布しており，地震波による本震の規模の再評価が期待される．