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25. *Recent Horizontal Deformation of the Earth's Crust and Tectonic Activity in Japan (1).*

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1. Introduction

The horizontal deformation of the earth's crust in a region may be mainly explained by the general gradual tectonic movement and the sudden movement due to the occurrences of great earthquakes. From this standpoint, the recent horizontal deformation of the earth's crust in Japan is discussed in this paper.

Recently Harada and Isawa (1969) presented a figure showing reliable displacement vectors of triangulation points in Japan during the recent about sixty years period. During the period, several great earthquakes occurred in Japan and related crustal movements have been intensely studied. It is obvious that the pattern of the recent horizontal deformation of the earth's crust in Japan is markedly affected by the occurrence of these great earthquakes, but this pattern is apparently too complex to give directly a simple explanation.

In this paper, however, it is shown by a suitable analysis that the deformation pattern given by Harada and Isawa can be approximately explained as a typical tectonic movement in island arcs.

2. Horizontal displacements of triangulation points in Japan

The first order triangulation in Japan except for Hokkaido has been carried out twice, for 1882–1908 and 1948–1967 (Fig. 1). Harada (1967) published a figure of displacement vectors obtained by analysis of triangulation data in the whole of Japan as a single net. In this case, errors systematically accumulated for remote stations. Consequently essential relative movements were marred by serious errors. Therefore, tectonic movements in wide areas could not be discussed based on the figure of displacement vectors. Discussions have been made only for angles observed in triangulation and calculated strains (Harada, 1967; Kasahara and Sugimura, 1964).

In order to avoid the above-mentioned difficulties in displacement vectors, Harada and Isawa (1969) analyzed the same triangulation data under the assumption that five stations chosen in quiet regions are immovable. The result is reproduced in Fig. 2. The five fixed stations are indicated by closed double circles in this figure. Although no information on the general deformation of Japanese Islands is obtainable because of the above-mentioned procedure of analysis, regional deformations discussed in the present paper seem to be suitably shown in this figure.

According to recent available information on tectonics in island

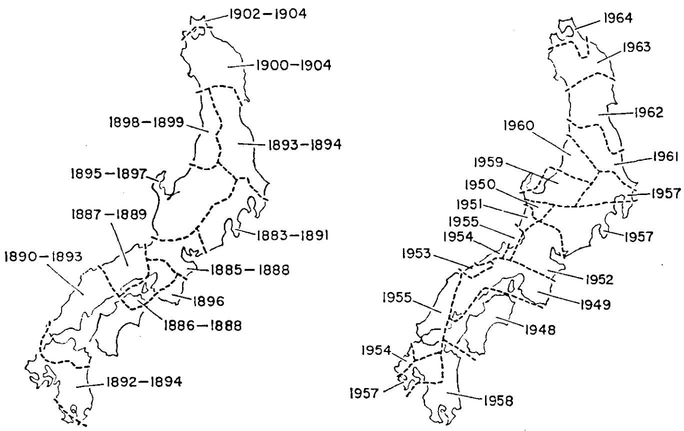

Fig. 1. Periods of the first order triangulation survey in Japan.
left: old survey; right: new survey.

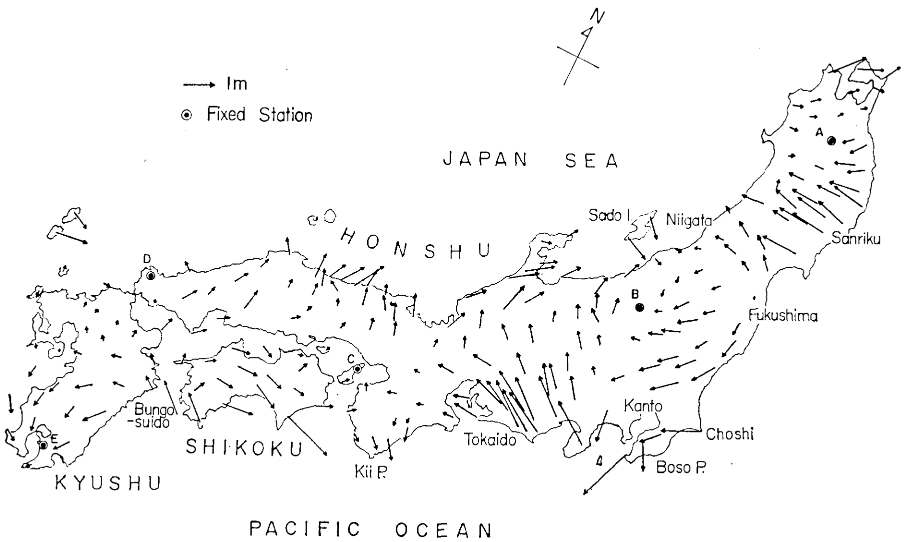

Fig. 2. Horizontal displacements of triangulation points during the period from the old survey (1883–1904) to the new survey (1948–1964). Double circle: fixed stations. (after Harada and Isawa, 1969)

arcs, the stress seems to be predominant in the direction normal to the island arc. In the analysis by Harada and Isawa, most of the fixed stations in Honshu are located in the coastal regions of the Japan Sea, which are quieter regions than those on the Pacific side, and along a curve nearly parallel to the island arc. Therefore, locations of the fixed stations are suitable for study of regional tectonic movements in Japan. In more detail, however, it would seem to be better to correct the location of the fixed station in the Kinki district, and so this correction is made in a later discussion. In this paper, the displacement vectors obtained by Harada and Isawa are directly analyzed.

3. Procedure of investigation

Very remarkable features in island arcs, such as deep-sea trenches, seismic zones of deep earthquakes, etc., suggested a possible mechanism that tectonic movements in island arcs are generated by the down-going movement of the earth's surface layer of the Pacific Ocean beneath the islands. This mechanism is strongly supported by the hypothesis of sea-floor spreading or plate tectonics (cf. Isacks *et al*, 1968).

On the other hand, previous studies pointed out that great earthquakes occurred in a close relation to the island arc system. That is:

(1) Most of the great shallow earthquakes with magnitude 8 or so in the circum-Pacific region occurred on the ocean-facing slope along deep-sea trenches, which was almost continuously covered by source areas of these great earthquakes without any appreciable overlap of source areas (Mogi, 1968; 1969b).

(2) A large part of the seismic energy released in island arc regions was released by these great earthquakes. In Japan, recent seismic activities seem to be attributed to several great earthquakes along the Pacific coast and their fore- and after-shocks in a broad sense (Mogi, 1969a).

(3) According to recent studies of earthquake mechanism, most of these great shallow earthquakes seem to occur by thrust faulting with the direction of the compressive axis normal to the trend of deep-sea trenches (Stauder, 1968; Plafker, 1965; Kanamori, 1970).

These results suggest that the occurrence of great shallow earthquakes in the circum-Pacific belt also are one of tectonic events caused by the above-mentioned down-going movement of the ocean floor.

According to this model, the horizontal compressive stress field predominates in the direction normal to the deep sea trench. In this case, the following tectonic movements are expected (Fig. 3). At a stationary state, stations along the Pacific coast move in the direction from the ocean to the island with some downward component (Fig. 3b). With the increase of shear stress by down-going movement of the ocean floor, a thrust faulting, namely a great earthquake, occurs under the ocean-facing slope of the deep-sea trench and the Pacific coast of the island suddenly moves in the direction from the island to the ocean with some upward component (Fig. 3c). (This mechanism of the crustal movement related to a great shallow earthquake has been discussed by Plafker (1965) and Takeuchi and Kanamori (1968)). Fig. 4 shows the expected horizontal displacement relative to the coast of the Japan Sea in the stationary state (upper), and the displacement before and after the occurrence of a great earthquake along the Pacific coast

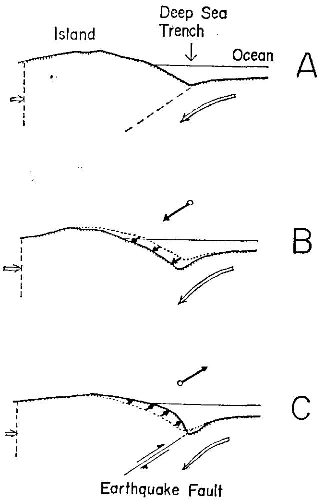

Fig. 3. Assumed tectonic movements in island arcs (vertical section normal to the arc trend). **B**: before a large earthquake; **C**: at the time of a large earthquake.

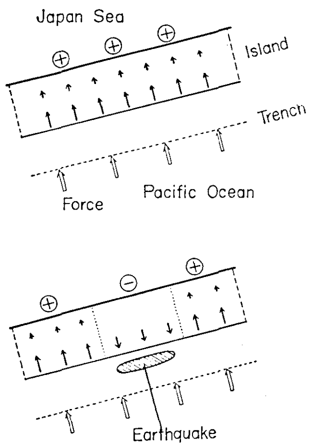

Fig. 4. Horizontal deformation in the island arc expected from the typical tectonic movement in island arc regions. upper: pattern in the stationary state; lower: pattern before and after a large earthquake.

(lower). That is, if no great shallow earthquake occurs during the considered period, the island is compressed in the direction normal to the arc trend. With an occurrence of a great shallow earthquake, a tensile area appears in the corresponding region of the island.

From the standpoint that the above-mentioned process of crustal movements is a typical one in island arc regions, recent horizontal movements of the earth's surface are analyzed in this paper. Since the predominant compressive stress is normal to the trend of the deep-sea trench, horizontal displacement vectors in Fig. 2 are resolved into the component *Hn* normal to the trend of deep-sea trench and the component *Ht* parallel to it, and spatial distributions of *Hn* values are discussed. In this case, the displacement in the direction from the Pacific Ocean to the island is taken as positive.

4. Horizontal deformation of south-western Japan

The Nankai Trough is nearly parallel to the south-western branch of the Honshu arc and forms the north-western boundary of the floor of the Philippine Sea. Although the Nankai Trough is not a typical deep-sea trench, the direction of the compressive stress field in this area was assumed to be normal to the trend of the Nankai Trough (N65°E), and also *Hn* is taken as a component normal to the trend.

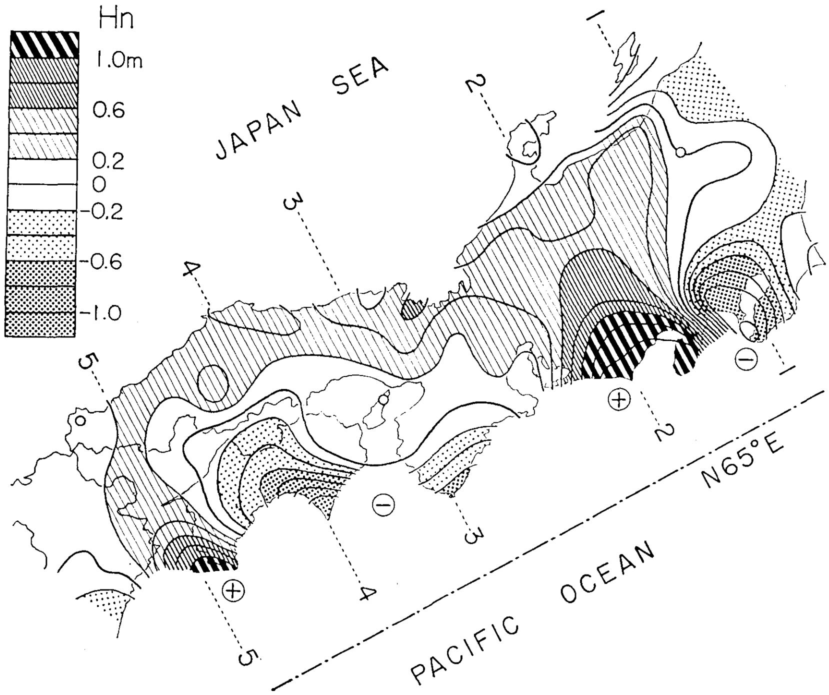

Fig. 5. Spatial distribution of the component *Hn* of the horizontal displacement of triangulation points in south-western Japan. A chain line shows the trend of the Nankai Trough.

Fig. 5 shows the spatial distribution of the component *Hn* of the horizontal displacement of triangulation points obtained from Fig. 2. The *Hn* value along the Japan Sea coast is generally small. In the Pacific side, however, the *Hn* value markedly varies from region to region and some large blocks with high positive and negative values locate alternately. A negative block including the Kii Peninsula and east-central Shikoku is clearly related to the Tonankai earthquake of

1944 ($M=8.0$) and the Nankaido earthquake of 1946 ($M=8.1$), another negative region in the Kanto district being related to the Kanto earthquake of 1923 ($M=8.0$). During the period, no other earthquake with magnitude 8 or so occurred in the regions considered (the Nobi earthquake of 1891 ($M=8$) in the inland area of Honshu occurred almost at the time of the first survey of triangulation). The remaining regions, the Tokaido (the Pacific coast of central Honshu) and the Bungo-suido

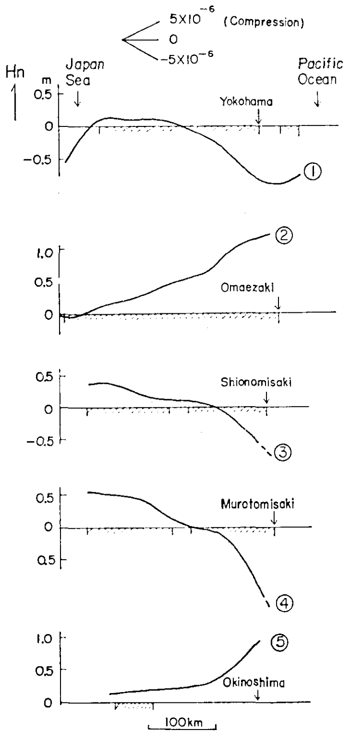

Fig. 6. Distribution of the component Hn of the horizontal displacement of triangulation points in Sections 1 to 5 shown in Fig. 5.

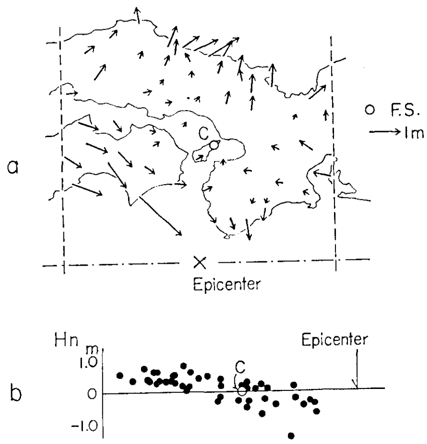

Fig. 7. Horizontal displacement of triangulation points in and around the source area of the Nankaido earthquake of 1946 (above) and the distribution of Hn values in the section normal to the trend of the Nankai Trough shown by a chain line (below). Open circle: fixed station C.

(the channel between Kyushu and Shikoku), are noticeably positive, namely in a compressive state. Thus, the Hn distribution in southwestern Japan is similar to the typical deformation pattern expected from the above-mentioned hypothesis. In Fig. 6 are shown the distribution of Hn values in the five sections 1 to 5 normal to the trend of the Nankai Trough. According to this figure, the above-mentioned blocks are strained $10^{-5} \sim 10^{-6}$ in compression or tension during the considered period.

In the above-mentioned discussion, it was assumed that the Kamaguchiyama Station C did not move, as other fixed stations did. However, it seems to be better to correct this assumption because this station is located close to the boundary of the aftershock area of the Nankaido earthquake of 1946. Fig. 7b shows the distribution of *Hn* values in the section normal to the trend of the Nankai Trough and it suggests that Station C probably locates within the area disturbed by the great earthquake. If the *Hn* value at the coast of the Japan Sea is assumed to be nearly zero, the *Hn* value at Station C is estimated at about -0.5 m. In Fig. 8 is shown the *Hn* distribution obtained

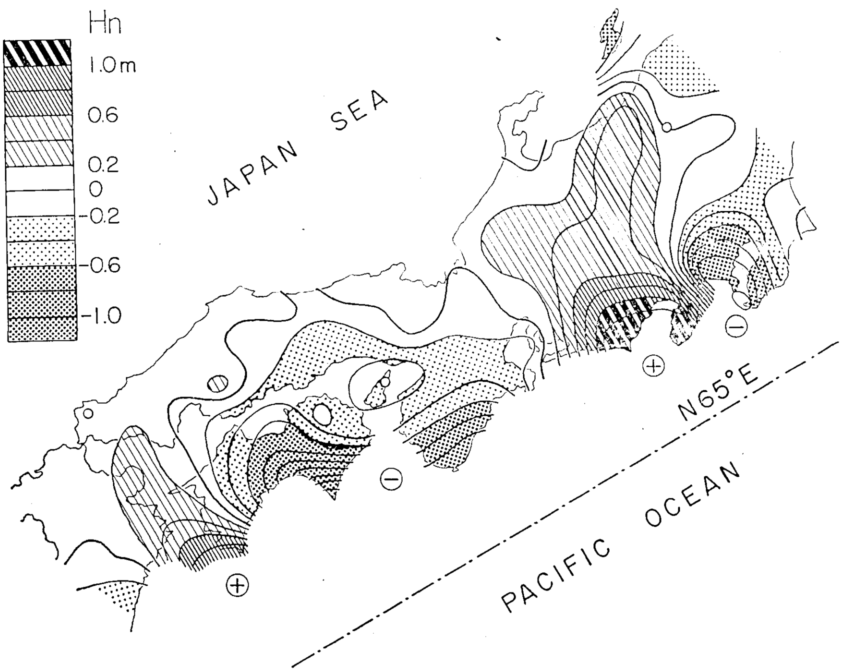

Fig. 8. Spatial distribution of *Hn* values, with a correction for the fixed station C.

under the assumption, that the *Hn* value at Station C is -0.5 m and the effect to other stations due to this correction decreases linearly along the trend of the Nankai Trough and becomes zero at Stations B and D. The distribution is approximately similar to that in Fig. 5, but the negative region related to the Tonankai and the Nankaido earthquakes covers a wider area. It is very interesting that the area affected by these great earthquakes, which was suggested from fore- and after-shocks in a broad sense (Mogi, 1969a), is in agreement with the above-mentioned negative area where the accumulated strain was released during the considered period.

The above-mentioned locations of compressive and tensile blocks are also consistent with the spatial distribution of directions of the maximum compression of strain calculated by Kasahara and Sugimura (1964) (Fig. 9).

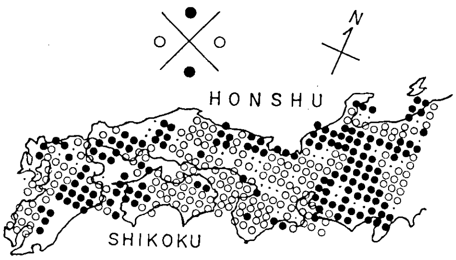

Fig. 9. Spatial distribution of directions of the compressive axes calculated from strain (the original figure by Kasahara and Sugimura (1964) is modified). Solid circles show nearly the direction normal to the trend of the Nankai Trough $\left[N\left(65° \pm \frac{\pi}{4}\right)E\right]$.

5. Horizontal deformation of north-eastern Honshu

North-eastern Japan is a typical branch of the circum-Pacific island arcs. The axis of the Japan Deep-sea Trench is nearly parallel to the island, but it is not linear and the mean trend is about N15°E. The direction normal to this mean trend (N15°E) is taken as that of the vector *Hn*. Fig. 10 shows the spatial distribution of *Hn* in north-eastern Honshu and Fig. 11 shows its distribution in the four sections which are normal to the trend of Japan Trench. Some blocks with

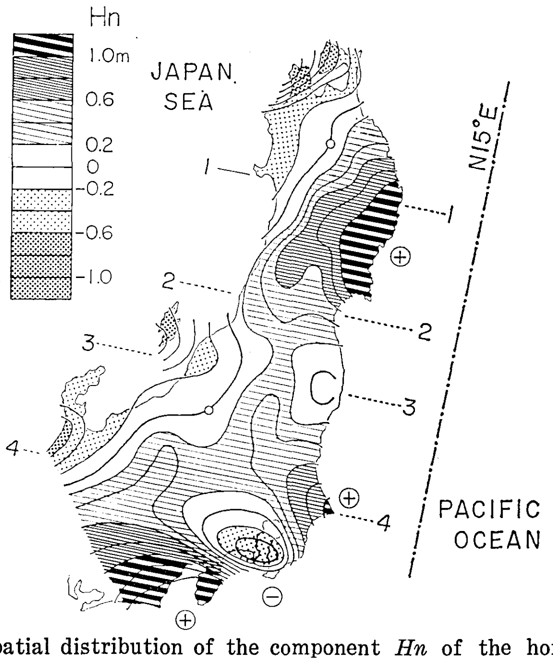

Fig. 10. Spatial distribution of the component *Hn* of the horizontal displacement of triangulation points in north-eastern Honshu. A chain line shows the mean trend of the Japan Deep-sea Trench.

positive or negative values of *Hn* also distribute alternately in the Pacific coast, but the positive movement predominates over the negative ones. This may suggest that the compressive deformation is larger in north-eastern Japan than in the south-western Japan, and this is consistent with various features showing a higher tectonic activity in north-eastern Japan, such as the remarkable deep-sea trench and a higher seismic activity.

A large positive block in and around the Sanriku district, the northern part of Honshu, is very noticeable as that in the Tokaido in south-western Japan. This compressive block extends to the Japan Sea coast including Sado Island. A negative region in the southern Kanto district can be also attributed to the Kanto earthquake of 1923, as pointed out in the preceding section. A local negative area in the Pacific coast of the Fukushima Prefecture may have a relation with the Fukushima-oki earthquake of 1938 which occurred near the Pacific coast. A high positive *Hn* value at Choshi in the eastern Kanto district is also noticeable. The pattern in the Japan Sea side is somewhat complicated. The negative region near Niigata shows a marked compressive state in the considered period.

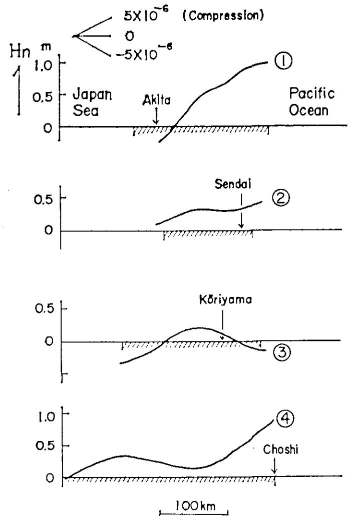

Fig. 11. Distribution of the component *Hn* of the horizontal displacement of triangulation points in Sections 1 to 4 shown in Fig. 10.

6. Horizontal deformation of Japanese Islands

In the above-mentioned discussion, it was assumed that the compressive stress field is normal to the mean trend of the deep-sea trench in each region, and analyses were made separately for south-western and north-eastern Japan because their trends are appreciably different. On the other hand, there is some evidence to suggest an almost uniform stress field in the whole of Japan, as mentioned below. In this section, the displacement vectors in Fig. 2 are again analyzed from the assumption of the uniform stress field. The direction of the uniform stress is assumed to be normal to the trend of the southern part of the Japan Trench (N30°E) shown by the line (A) in Fig. 12 for reasons mentioned below. The southern part of the Japan Trench is the deepest linear part of the Trench parallel to the Honshu arc and the trend is nearly parallel to the eastern margin of the area including contours of 1000 m

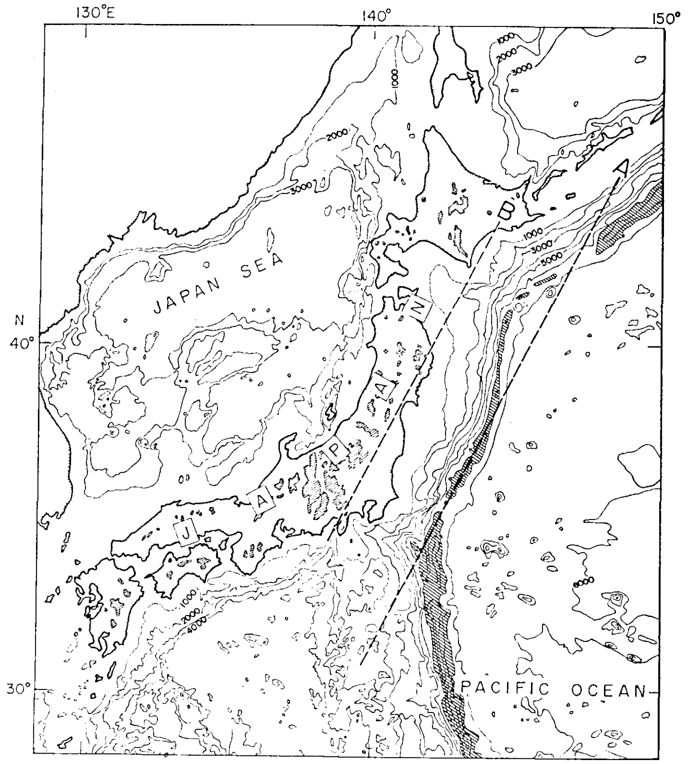

Fig. 12. Topographic map in and around Japan. A: front of the assumed compressive stress field.

height above sea level (B). Furthermore, it should be noted that this direction is roughly the mean direction of the island arc system in the Japanese area. This almost uniform stress field in Japan is suggested by the following data:

(1) *Directions of the maximum compressive stress deduced from the earthquake mechanism*

Fig. 13 represents the directions of the maximum compressive stresses deduced from the mechanism of very shallow and shallow earthquakes in Japan obtained by Ichikawa (1966). Although the directions of the compressive axis vary within a certain range, they are approximately uniform except for the Kyushu district and the Bungo-suido, their directions being nearly in agreement with the above-mentioned direction. (The directions for deeper earthquakes are not uniform and change systematically in connection with each trend of the seismic zones in deeper regions.)

(2) *Directions of active strike-slip faults*

Fig. 14 shows active strike-slip faults and directions of the maxi-

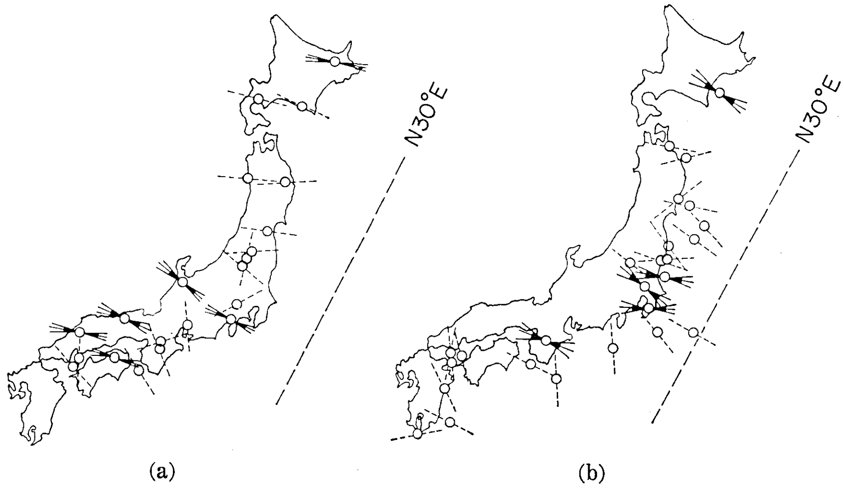

Fig. 13. Directions of the maximum compressive stress deduced from the earthquake mechanism. (a): very shallow earthquakes (1927-1962); (b): shallow earthquakes (1950-1962). (after Ichikawa, 1966)

mum compressive stress which should produce these fault systems (Matsuda, 1967; Research Group for Q.T.M., 1968). Although these directions may not always show those of the present stress fields, it is very suggestive that these directions approximately agree with that of the assumed uniform compressive stress.

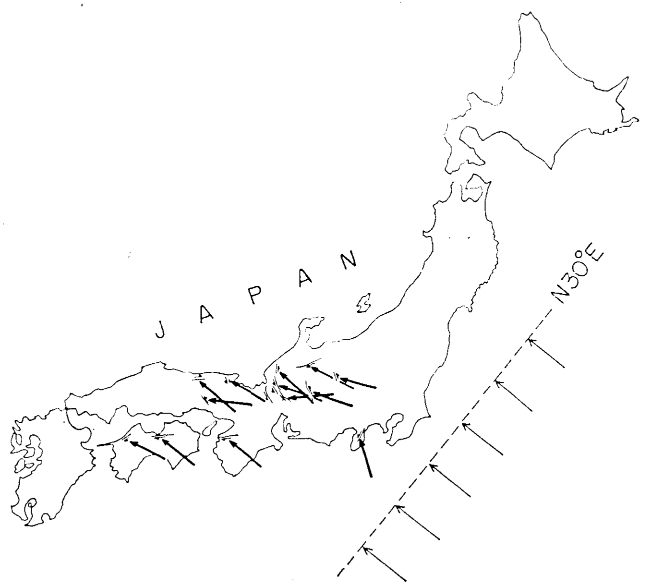

Fig. 14. Active strike-slip faults and directions of the maximum compressive stresses which should produce the faults (Matsuda, 1967; Research Group for Q.T.M., 1968).

(3) *Zonal distribution of shallow earthquakes in the outer seismic belt in north-eastern Japan*

In Fig. 15 is shown the zonal distribution of shallow earthquakes ($M \geq 6$) of focal depths less than 30 km, which occurred in north-eastern Japan during the period (1926–1967) (Mogi, 1969a). The trend of these linear zones seems to suggest a general tectonic pattern with the trend mentioned above.

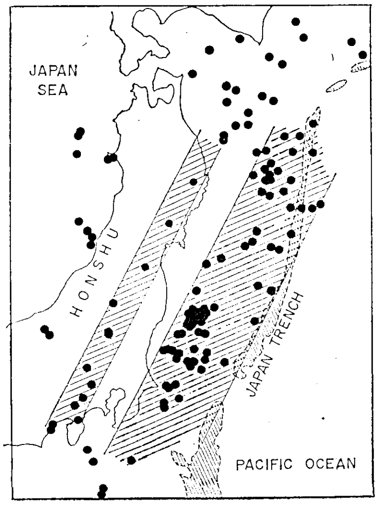

Fig. 15. Zonal distribution of shallow earthquakes ($M \geq 6$) of focal depth less than 30 km in north-eastern Japan for the period (1926–1967).

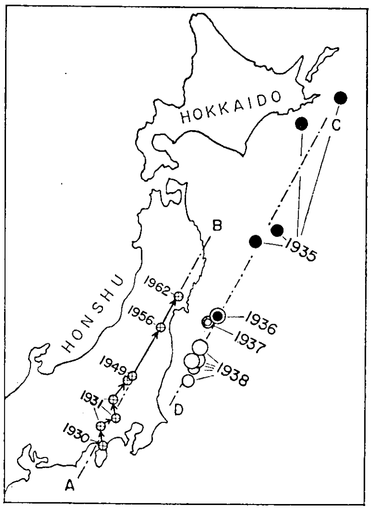

Fig. 16. Two branches of migration of shallow earthquakes in north-eastern Japan. $\overline{AB}$: $M \geq 6$ and focal depth < 30 km; $\overline{CD}$: $M \geq 7$.

(4) *Direction of migration of shallow earthquakes in north-eastern Japan*

In the previous paper (Mogi, 1969a), systematic migration of shallow earthquakes with magnitude 6 and over from the Kita-izu earthquake of 1930 to the Miyagiken-hokubu earthquake of 1962 was pointed out. With this migration branch, another one, in which epicenters of earthquakes with magnitude 7 and over migrated during the period from 1935 to 1938 is shown in Fig. 16. The trends of both migration branches also agree with the above-mentioned direction (N30°E).

(5) *Directions of displacement vectors of triangulation points*

The directions of displacement vectors in Fig. 2 vary widely, but most of the large vectors are nearly parallel to the assumed uniform compressive stress.

Thus, the present assumption that the whole of Japan is covered by a simple compressive stress field with the direction (N60°W) seems to be acceptable as a first approximation. Under this assumption, the *Hn* distribution in the whole of Japan, except for Hokkaido, was obtained as shown in Fig. 17. The result is almost similar to that in the above-mentioned two distributions obtained individually for south-western and north-eastern Japan. The positive and negative blocks locate alternately along the Pacific coast. Consequently it may be said that the pattern of *Hn* distribution is not so markedly affected by some change in the direction of stress field assumed in analysis, and so the present conclusion may be held for various probable stress fields.

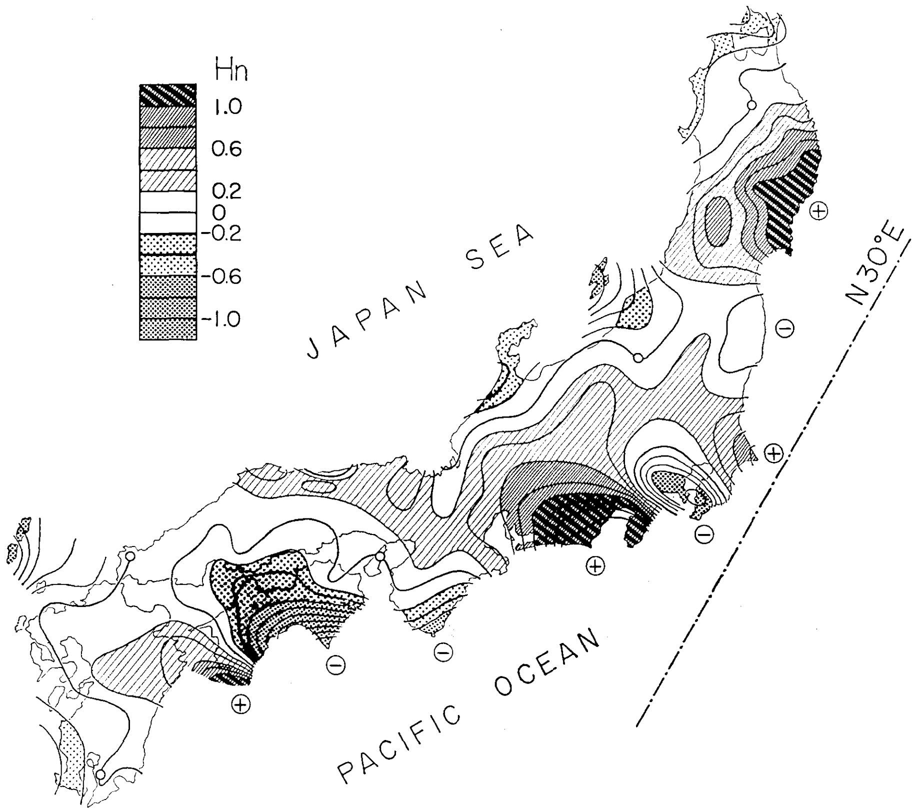

Fig. 17. Spatial distribution of the component *Hn* of the horizontal displacement of triangulation points in Japan. The direction of *Hn* is taken normal to the chain line (N30°E).

7. Crustal movement and seismic activity

The above-mentioned crustal movement in Japan is compared with the seismic activity during the considered period in Fig. 18. Fig. 18b shows the location of source areas of earthquakes with magnitude 6 and over during the period from 1920 to the new survey of triangulation. Although earthquakes which occurred during the period from the old survey to 1920 should also be considered, they are not located in this figure because of low reliability of seismic data in this period. However, the present discussion seems to be not so strongly affected by the insufficiency of seismic data in the earlier period, because great earthquakes did not occur frequently in the earlier period.

As pointed out in the preceding sections, three negative blocks along the Pacific coast locate in a close relation with the following great earthquakes which occurred in and near the Pacific coast: The Fukushima-oki earthquake of 1938, the Kanto earthquake of 1923, and the Tonankai (1944)-Nankaido (1946) earthquakes. The magnitude of the main shock of the Fukushima-oki earthquake sequence of 1938 was only 7.7, but the total energy of this sequence was nearly equal to that of a great earthquake of magnitude 8. Remaining regions are all positive, namely in compressive states. The Japan Sea coast is covered generally by zero or negative regions, so that the area is quiet or compressed. These results lead to the following conclusion:

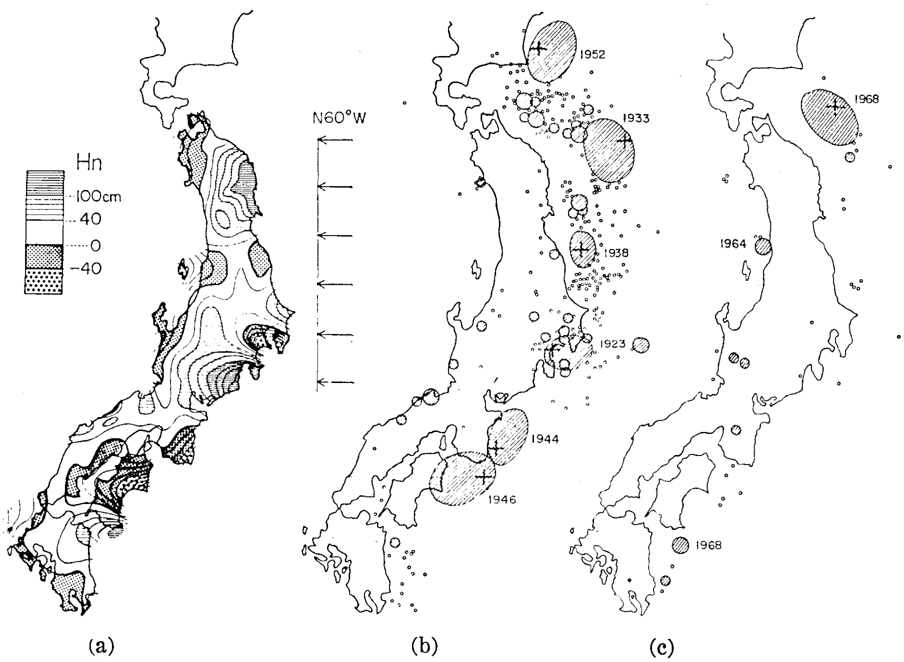

Fig. 18. (a) Spatial distribution of *Hn* with the direction (N60°W); (b) locations of source areas of earthquakes with magnitude 6 and over for the period from 1920 to the time of the new survey; (c) the earthquakes after the new survey.

(1) The Japanese Islands in a stationary state (without any great earthquake) is generally compressed in the direction N60°W or so. This result is strong evidence indicating the existence of the compressive stress field nearly normal to the arc trend, and it is consistent with the hypothesis of plate tectonics.

(2) A large compressive strain is released only by the occurrence of great earthquakes near the Pacific coast.

Although the great Sanriku-oki earthquake of 1933 occurred along the Japan Deep-sea Trench, one of the most remarkable positive areas was still found in the Sanriku district. This seems to be contradictory to item (2). The apparent contradiction may be explained as follows[1]:

(a) The epicenter of the main shock of this earthquake was far distant from the Pacific coast and the source region suggested by its after-shocks was also located some distance from the coast, so the occurrence of earthquake did not result in a marked strain release in the island.

(b) The outer seismic zone of north-eastern Honshu is extremely active, so the accumulation rate of the compressive strain in this area is probably very high and the compressive strain field recovers rapidly after the great earthquake. This possibility is supported by the occurrence of the following great earthquake of 1968 at the region adjacent to the source area of the 1933 earthquake, as will be mentioned below.

The above-mentioned *Hn* distribution shows the deformation of the earth's crust in the direction of the assumed compressive stress field during the considered period, so it suggests approximately the stress state at the time of the new survey of triangulation. From this point of view, the *Hn* distribution is compared with locations of earthquakes which occurred after the new survey of triangulation. The locations of these earthquakes are shown in Fig. 18c. Although only three large earthquakes with magnitude 7.5 and over occurred after the new survey, it is very interesting that these large earthquakes occurred at the compressive areas in the figure. That is, the Hyuganada earthquake of 1968 ($M=7.5$) occurred near the compressed region in the channel between Shikoku and Kyushu (Bungo-suido). The Tokachi-oki earthquake of 1968 ($M=7.9$) occurred adjacent to the compressive block in north-eastern Honshu (Sanriku district), as mentioned above. The Niigata earthquake of 1964 ($M=7.5$) occurred in a marked compressive region in the Japan Sea coast which continues to the above-mentioned compressive block in the Sanriku district. This supports the previous conclusion (Mogi, 1969a) that the Niigata earthquake occurred as a fore-shock of the Tokachi-oki earthquake of 1968 in a broad sense.

From the above-mentioned discussion, the compressed area at Tokaido, where no large earthquakes have yet occurred after the new survey, is looked upon as a region where large earthquakes may occur in future. However, this problem will be again discussed in the following paper

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*) Added in proof. A recent study by Kanamori (1970) showed that the great Sanriku earthquake occurred by normal faulting with a slip plane nearly parallel to the trend of the deep-sea trench. The anomalous mechanism of this earthquake may be a cause of the high positive *Hn* value in the Sanriku district.

(Mogi, 1970).

8. Stress field in Japan

As mentioned above, the observed horizontal deformation in Japan is explained principally by the gradual compression normal to the trend of the Japan trench and the sudden release of the strain caused by great shallow earthquakes. The recent mode of the vertical movement in the Pacific coast (Fujita, 1969) also seems to be consistent with the present model, although further systematic analysis from this standpoint is needed.

Thus, the main stress field in Japan may be deduced as follows (Fig. 19). The general compressive stress field covers a large part of the whole of Japan. The external force causing the main stress field is applied to the island along the deep-sea trench. The direction of this stress field is taken as that of the southern part of the Japan Trench and it nearly agrees with the mean direction of the island arc systems in the Japanese area. The uniform stress field is probably limited to the very shallow layer, the stress field in the deeper part showing some different pattern related to deep seismic zones. The crustal movement, the seismicity, the earthquake mechanism and active fault systems can be reasonably attributed to deformation and fracture of the surface layer under this stress field.

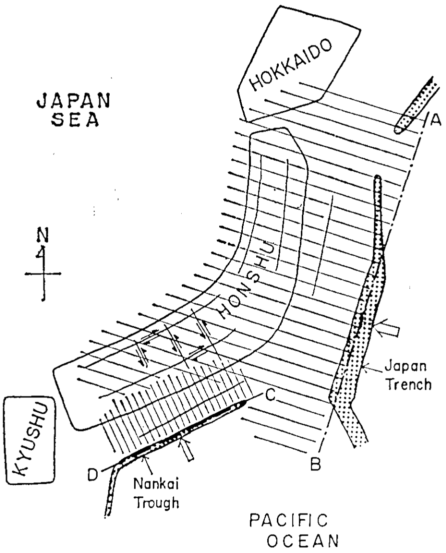

Fig. 19. Simplified stress field in the surface layer in and around Japan. Parallel lines show the directions of an about uniform compressive stress field.

However, the stress field in the Pacific coast of south-western Japan seems to be somewhat complicated, and the compressive stress field normal to the Nankai Trough is probably superposed to the uniform stress field (Fig. 19). This is supported by the following evidence: (1) Great earthquakes had occurred repeatedly along the ocean-facing slope of the Nankai Trough and the pattern of the seismic energy release in the last sixty years shows a marked zonal distribution along the Nankai Trough. The crustal movements at the time of great earthquakes suggest the thrust faulting along the trough. Thus, the Nankai Trough is seismically an active one. (2) The earthquake mechanism in this region changed before and after the Nankaido earthquake of 1946 (Ichikawa, 1966). The directions of the compressive axis of stress deduced from the earthquake mechanism was nearly N-S before the Nankaido earthquake, but they changed to E-W (almost the direction of the uniform stress field) just after the great earthquake. This change in direction of the maximum compressive axis of stress may be attributed to the release of the predominant compressive stress with N-S direction by the occurrence of the Nankaido earthquake. Similar interpretation about the stress system in south-western Japan was given independently by Miyamura (1969).

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25. 日本の最近の地殻の水平変動と地震活動との関係 (1)

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最近，原田・井沢 (1969) は，約 60 年の間隔で行なわれた 2 回の一等三角測量の結果を解析して，北海道をのぞく日本列島の三角点の水平移動を求めた．彼らの方法は，いくつかの固定点を設定する多固定点法といわれるもので，その結果は，地方的変動をかなり忠実にあらわしていると思われる．このような変位の分布図は，その地域の応力状態を知る手掛りを与えるものとして重要である．

一方，日本列島のような弧状列島での地変の最も著しいものは，海溝生成によつて象徴されるもので，海溝沿いの大地震の発生もそれに伴なう変動現象の一つであり，その原因は，太平洋底からの圧縮力によると考えられる．このような見地から，想定される外力の方向の変位ベクトルの成分に着目して検討した結果，日本列島の変位分布は，島弧に直角な方向への一様な圧縮と大地震の発生によるその局所的な解放として大体説明されることが知られた．著しい圧縮をうけているいくつかの地域が認められるが，これらの地域では，将来，大きい地震が起こる可能性が考えられる．実際，第 2 回測量以降発生した大きい地震は主にこのような地域やその周辺で起こつている．