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RELATION BETWEEN CRUSTAL AND SUBCRUSTAL EARTHQUAKES INFERRED FROM THE MODE OF CRUSTAL MOVEMENTS

By

Yutaka TANAKA

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Abstract

Coincidentally with the occurrence of subcrustal earthquake, mean rates of secular tilting in the direction of horizontal displacement of the ground are changed, and moreover the sequences of crustal earthquake are alternated at the same time. According to these phenomena, the modes of crustal movements accompanied with individual crustal earthquake are also changed.

Furthermore, subcrustal earthquakes themselves are divided into some sequences from the modes of tilt variation as stepwise motion, at the peaks of which they occur, decreasing amplitude and period with time.

Drawing hypothetic inferences from these modes of crustal movements, it may be suggested that slow movements or state-processes of materials in the upper mantle cause the subcrustal earthquake at their periodic peaks and also change the impetus to the crust at the same time, thus alternations of crustal earthquake sequence may be derived.

1. Introduction

In the previous paper (Nishimura et al., [1963]), it was shown that the crustal movements observed continuously by tiltmeters at Makimine Observatory (Ref. Fig. 3) in Kyûshû Province behave characteristically accompanied by the seismic activities in the Hyûganada. Namely the Earth's surface near Makimine Area shows see-saw motions in the direction parallel to Median Line and shallow earthquakes (hereinafter called as Crustal Earthquake) occur at peaks of the movements. It was also suggested that the see-saw motion completes decreasing amplitude and shortening duration with time and then a new earthquake sequence begins. At the point of alternation in earthquake sequence, variation rate of secular tilting movements is also changed.

After that, it was confirmed that these phenomena repeat in the same manner and at the alternating time intermediate earthquakes (hereinafter called as Subcrustal Earthquake) occur without exception. The purpose of this paper is to investigate the relation between crustal and subcrustal earthquakes from the viewpoint of crustal movements.

Fig. 1 shows the vector diagram of tilt variation observed at Makimine. As shown in the previous paper, by resolving this vector diagram into several components, it may be concluded that characteristic changes connected with seismic activity are noticeable, especially in the direction parallel to Median Line throughout the whole period. The direction of the Median Line is coincident at Makimine with that of

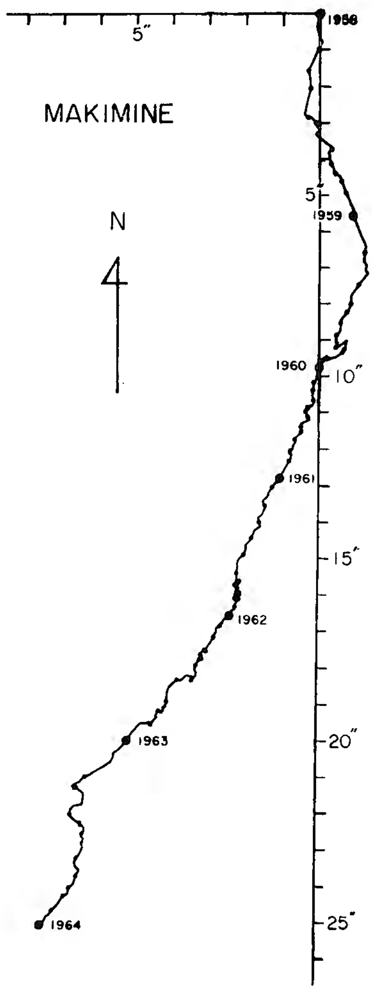

Fig. 1. Vector diagram of ground-tilt observed at Makimine.

horizontal displacement obtained by primary triangulation, so that it is impossible to estimate from one-station-observation, which is more effective, Median Line, horizontal displacement or both of them. Anomalous changes accompanied with individual earthquake were also recognized in other components according to nature and position of each earthquake, but the arguments of which will be found in other paper. In this paper, changes only in the direction parallel to Median Line shall be treated.

2. Peculiar modes of anomalous crustal movements accompanied with crustal earthquakes originated in the Hyûganada

It seems that anomalous crustal movements directly related to the individual crustal earthquakes in the Hyûganada behave always as elastic deformation at Makimine because the station is located more than 40 km far from the seismically active region. This elastic deformation superposes on secular movements in wide area and moreover, any sudden unrecoverable change was not observed at Makimine up to the present time.

Fig. 2 shows the state of tilt variation in the direction to horizontal displacement, by resolving the vector diagram in Fig. 1 only during seismically the most active

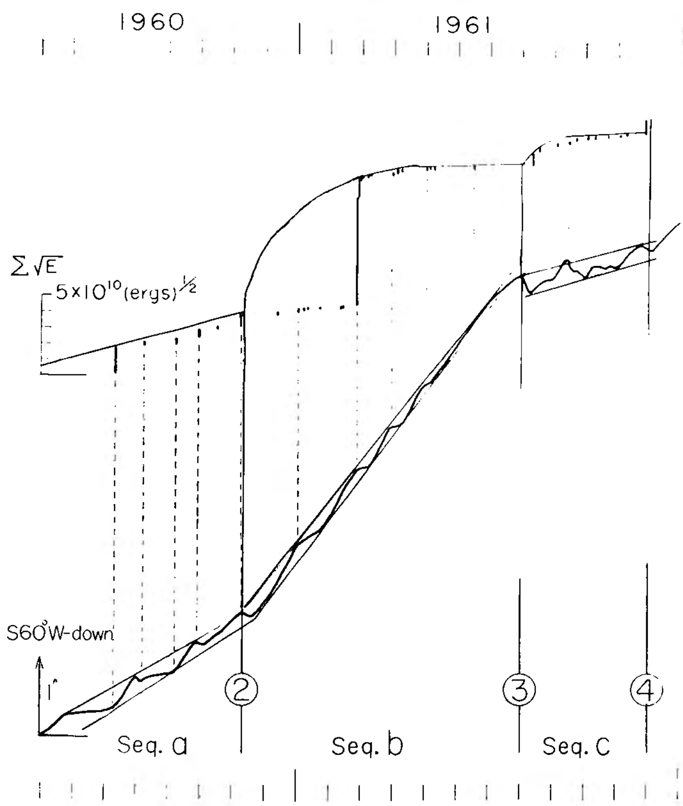

Fig. 2. Tilt variation in the same direction to the horizontal displacement near Makimine and the state of strain release caused by the crustal earthquake originated in the Hyûganada. Numbers show the same subcrustal earthquakes as in Fig. 4.

period in the Hyûganada. The state of energy release in the crust caused by the Hyûganada crustal earthquakes is also indicated in accumulated sum of square roots of energy (calculated by magnitude) of each earthquake (Benioff, [1951]). As seen in Fig. 2, the relations between these seismic activities and crustal movements are clearly confirmed, and these are as follows:

a) Judging from the state of energy release, a series of earthquakes occurred during the period May 1960 to December 1961 is divided into three sequences (Seq. *a*: untill Nov. 1960, Seq. *b*: Nov. 1960～July 1961, Seq. *c*: July～Dec. 1961). During the period of Sequence *a*, medium earthquakes occurred with frequent pause, on the other hand, of Sequence *b* minor earthquake swarms are generated four times. It is very interesting fact that the second swarm consist of the 1961-Hyûganada Earthquake (Magnitude=7.2) and its foreshocks and aftershocks. Sequence *c* is a compromise between Sequences *a* and *b*.

b) Earthquakes belonging to each sequence originate in the restricted area respectively, the extent of which is about the same as that of aftershock area of the 1961-Hyûganada Earthquake. With the alternation from Sequence *a* till *c*, the area concerned shifts southward. (Ref. Fig. 3)

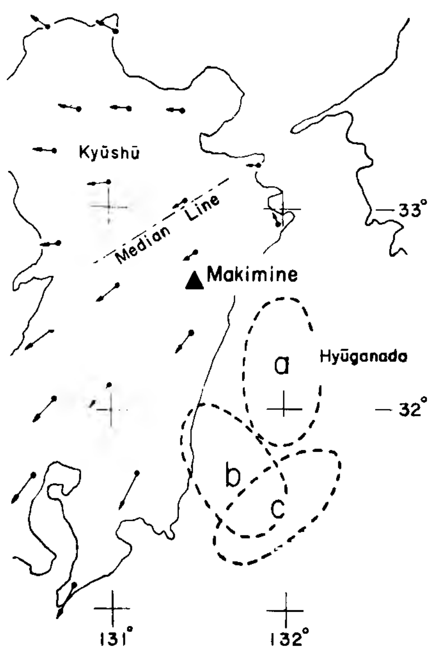

Fig. 3. Originated a eas of crustal earthquake sequences (*a*, *b*, *c*) and their shifts.
Arrows show the directions of horizontal displacements of primary triangulation points.

c) As seen in Fig. 2, earthquake swarms in Sequence *b* occur extending upper peak of saw-tooth shaped curve in tilt variation to lower one, on the contrary, in Sequences *a* and *c*, earthquakes occur at both upper and lower peaks.

d) In Sequence *b*, see-saw motion damps of itself, decreasing its amplitude and shortening its period with time and then alternates into that of next sequence, but in Sequence *a* these characters are not remarkable and in Sequence *c* its amplitude does not decrease.

e) Within each sequence velocity of secular tilting is constant, but it changes according to and simultaneously with alternation of sequence.

As mentioned above, nature of occurrence in the Hyûganada earthquakes, mode of crustal movements accompanied with individual or swarmed earthquakes and mean velocity of secular tilting suddenly change at certain turning point. It is a noticeable fact that a subcrustal earthquake occurs without exception at this turning point.

Though occurrence mechanisms of the Hyûganada earthquakes, having their origin in the sea region, are not clear because of difficulty in finding the push-pull distribution of initial motion, single (apparently) nodal line in every earthquake, without regard to sequences, may possibly be in the direction of NE-SW, and its NW side is almost push zone.

3. Secular behaviour of crustal movements connected with subcrustal earthquakes originated in the northern part of Kyûshû-Ryûkyû Arc

Fig.4 shows the tilt variation in the direction of horizontal displacement at Makimine, subtracted the constant rate of 2 ″/year from the real secular variation for conspicuity, over a long period of time, and the states of strain release caused by the crustal earthquakes in the Hyûganada and the subcrustal earthquakes in the northern part of Kyûshû-Ryûkyû Arc (intermediate earthquake zone) respectively. It is seen without exception in Fig. 4 that, in the time of alternation of crustal earthquake sequence, subcrustal earthquake occurs as mentioned in foregoing section.

The behaviour of tilt variations in longer periods connected with subcrustal earthquake, on the whole, is similar to the mode in the case of crustal earthquake, except difference in the scale, and the similarity between both may be characteristic of crustal deformation in this seismic region. Remarkable relations between the characteristic behaviour of crustal movements and the subcrustal earthquake concerned are as follows:

a) The Earth's surface near Makimine behaves a see-saw motion (Stepwise motion, to be more exact with due regard to secular movements) with natural period between several months and one year in similar mode as the case of crustal earthquake

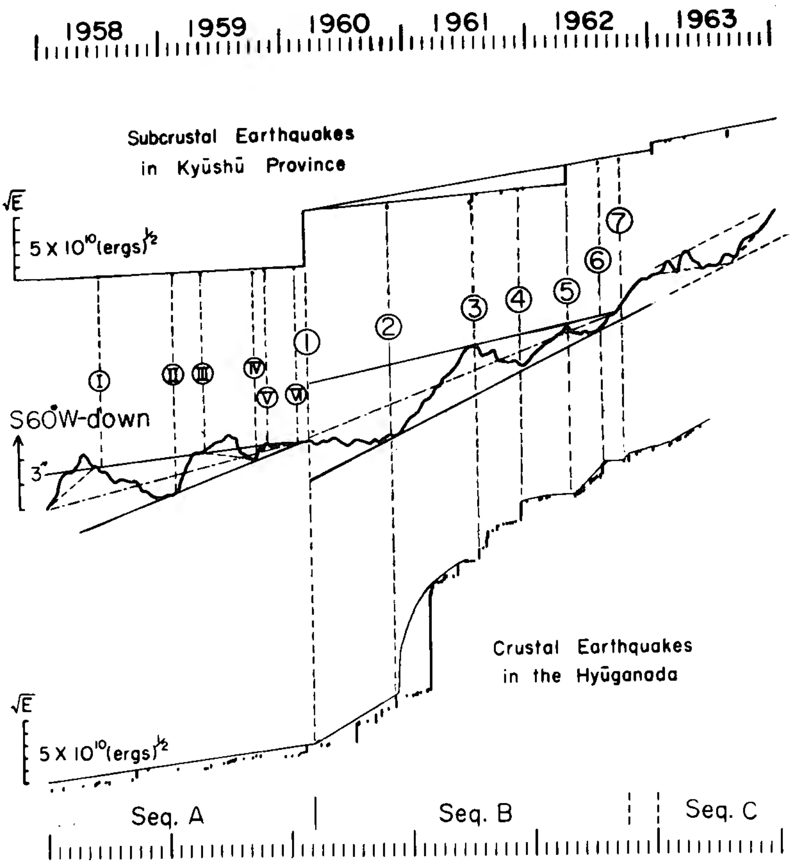

Fig. 4. Tilt variation in the direction of horizontal displacement at Makimine, the states of energy release caused by the crustal earthquakes in the Hyûganada (lower) and the subcrustal earthquakes in the northern part of Kyûshû-Ryûkyû Arc (upper) respectively.
Numerals indicate the number of subcrustal earthquake.

with shorter period, and subcrustal earthquake occurs at their upper and lower peaks.

b) A series of subcrustal earthquakes concerned during a period of 1958∼1963 may also be divided into three sequences (*A*, *B* and *C*) viewed from the mode of see-saw motion similar to the case of crustal earthquake and from the state of energy release caused by themselves, and their alternation times are in Feb. 1960 and in Oct. or Dec. 1962. The latest Sequence *C* is still under investigation.

c) In both cases of Sequences *A* and *B*, amplitudes and periods of the see-saw motions decrease with time, especially it is regular in Sequence *B* but in Sequence *A* time intervals from lower peaks to upper are shorter than from upper to lower as if Earthquakes II-III and IV-V made a pair respectively.

d) Mean rate of tilt variation (shown by chain line in Fig. 4) differs with every sequences as same to the case of crustal earthquake sequences.

e) It is very interesting matters that earthquake origins in Sequences *A* and also *B* distribute systematically, that is, as seen in Fig. 5 referring to Fig. 4, the first (No. 1) and the last (No. 7) earthquakes in Sequence *B* lie on the center line passed through the active area of Sequence *B* from NNE to SSW and on the one side even numbered earthquakes occurred at lower peaks of variation curve are situated on the eastern side line, having the focal depth of 80 km$\sim$100 km, on the other side odd numbered ones at upper peaks, having the focal depth of 100 km$\sim$200 km, are on the western. On the contrary, earthquakes in Sequence *A* are generated in the southern adjacent area, odd numbered earthquakes I, III and V at upper peaks are on the southern side line and even numbered ones II, IV and VI are on the northern.

The above mentioned characteristics in subcrustal earthquake are more remarkable and on larger scale rather than in the case of crustal earthquake. It seems that the crust moves slowly over a wide area complying with turning pionts by the occurrence of subcrustal earthquake, but never suddenly and macroscopically as in fracture zone of great crustal earthquakes.

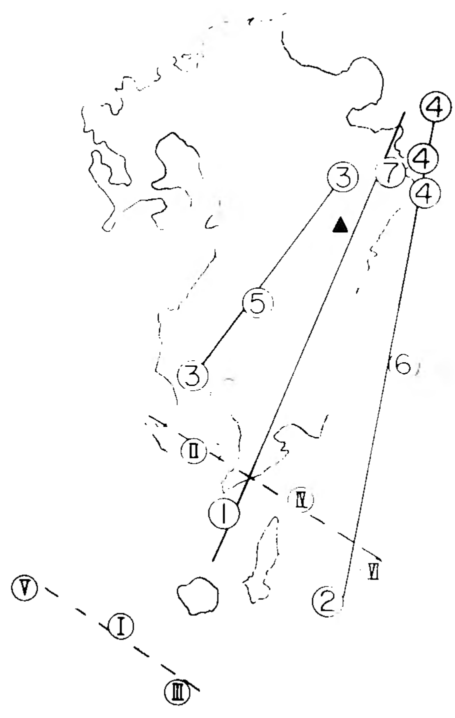

Fig. 5. Systematic distribution of epicenters in subcrustal earthquake sequences.

4. The correlations between crustal and subcrustal earthquakes through the mode and behaviour of crustal movements

It is the interesting fact that in the both cases of crustal and subcrustal earthquakes the modes of crustal movements have much in common, only differ in their scale. Nevertheless it must be suggested that these phenomena arise only in the region of elastic deformation far from the seismically active area, but in the region of plastic deformation these modes may get out of their shapes.

The most important points are not only the similarity of the modes, but also that according to the occurrence of subcrustal earthquake the sequences of crustal earthquake are alternated, namely, the state of generation of crustal earthquakes, the mode of anomalous crustal movements related to individual crustal earthquake, and mean velocity of secular tilting, these all are changed at the same time, besides simultaneously with the occurrence of subcrustal earthquake.

From these phenomena, it may be supposed the view that the occurrence of subcrustal earthquake, namely the change of the state in the upper mantle, regulates the generation mechanism of crustal earthquake. However, within the Sequence *A* of subcrustal earthquake, as seen in Fig. 4, crustal earthquakes are not active and the

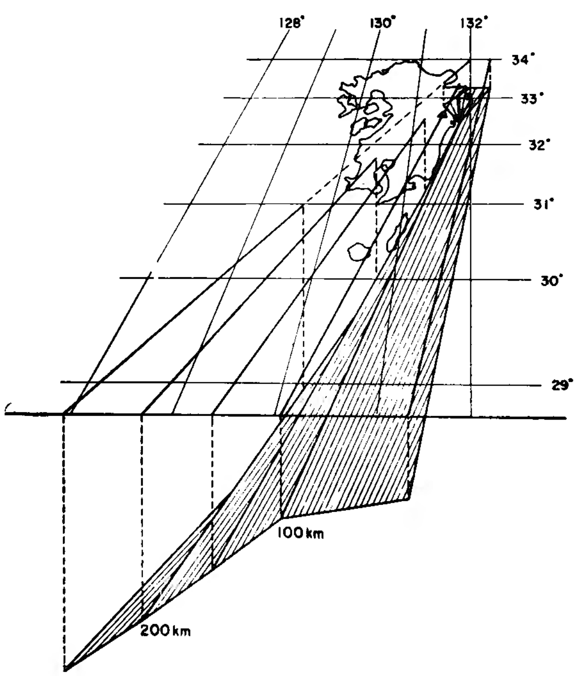

Fig. 6. Supposed surface originating subcrustal earthquake in the northern part of Kyûshû-Ryûkyû Arc (shown by perspective drawing method).

mode of crustal movements accompanied with these are also not clearly systematic. These cannot be explained by only the fact that Makimine is located far from the originated area of subcrustal earthquake Sequence *A*, but may be explained by supposing that focal depth of subcrustal earthquakes become deeper as origin shift toward south. The foci of subcrustal earthquake originated in Kyûshû-Ryûkyû Arc lie approximately upon a surface dipping westward. As seen in Fig. 6, this surface is distorted, having easier dip of 35° in the south and more sharp dip of 60° in the north, and is terminated completely by the active region of shallower (depth of 70～80km) subcrustal earthquake, as if to screw diagonally upward a gigantic knife into the crust. Accordingly if foci are far deeper in the south against crust-mantle interface, they give little influence directly to the crust. On the contrary, in northern parts vertical distribution of foci of both crustal and subcrustal earthquakes unite continuously, so that energy accumulation in the upper mantle and energy release caused by generation of subcrustal earthquake produce a powerfall effect on the state in the crust. Existence of seismically active area of the Hyûganada seems to be significant from above inference.

Almost all of crustal and subcrustal earthquakes may have the occurrence mechanism of quadrant type such as polar axis of focal nuclear is inclined or parallel to the Earth's surface in a vertical nodal plane striking SW from the epicenter. Therefore one nodal line runs in the direction of nearly NE-SW, and in the case of crustal earthquake its NW side is almost push zone, but in the case of subcrustal earthquake there is a tendency that the direction of nodal line turn anticlockwisely with the northward shift of origin and NW side is not always push zone. Though these are not clear because of insufficient seismic data, it is expected that some relations on the generation mechanism between crustal and subcrustal earthquakes may be existent, considering connection with slippage on the previously mentioned surface.

5. Conclusive remarks

The crustal movement connected with subcrustal earthquakes must be interpreted as the following. Namely, it is not directly connected with and does not correspond to individual subcrustal earthquakes, of course, it is also not caused by them. But it is only a reflection (over a wide area because of depth) of change in movement of material as plastic flow and deformation under high pressure and high temperature or in state of strain-accumulation and -release within the mantle. Subcrustal earthquake occurs merely at the peak of the change, so that the amount of crustal deformation is not related to the magnitude and epicentral distance of individual earthquake. The changes in states of slow movement or of strain energy in the mantle, however, must have a great influence on the crust over a wide area and it is enough to give an impetus to the brittle crust and to cause a series of crustal earthquake. When the conditions of impetus are changed according to the generation of subcrustal earthquake, the state in the crust and variation rate of secular ground-tilt are also changed, in this manner alternation of crustal earthquake sequence may be carried out.

Besides, the relation between the time variation of earth tidal amplitude observed at Makimine and seismic activity in the Hyûganada, investigated by the late Professor Eiichi Nishimura who had been always taking a great interest in this problem, in other words, change in elasticity of the crust as he supposed, may be closely connected with alternations of earthquake sequence and change of mean velocity of secular tilt variation.

Acknowledgements

As this study was made before and after the Professor Eiichi Nishimura's decease, it is a great regret this was not completed before the sad event. This paper is dedicated to the memory of the late Professor Nishimura, responding to his former kind instruction and continuous guidance with a deep sense of gratitude.

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