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# Preliminary Report of the Palaeomagnetic and Seismic Studies on the Ryukyu Islands

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## Abstract

Preliminary study of the palaeomagnetism on the Ryukyu Islands has been carried out and results obtained together with the relating seismic considerations are described with special reference to the Miyako Depression. From the palaeomagnetic results obtained, it may be assumed that a considerable counterclockwise rotational movement of the southwestern sub-arc was presumably accompanied by the simultaneous tectonic movement during or/and after Miocene epoch to which bearings of the Miyako Depression may be related. On the other hand, the zonal density distribution of epicentres and energy release of earthquakes near the island arc suggest also a relative sagging in the Miyako Depression. Using the well-known GUTENBERG-RICHTER's formula, an annual magnitude-frequency relation and an energy release of earthquakes occurred near the Ryukyu Islands are determined. The seismotectonic coefficients obtained from the formula show a close relation with the geological development of the island arc.

## Introduction

The Ryukyu Islands are one of the prominent island arcs in circum-Pacific orogenic belt, intersecting the Japan Arc and the Taiwan-Philippine Arc in its respective terminal. The geophysical studies concerning the Ryukyu Islands are too incomplete to discuss in detail, in comparison with the Japan and Kuril-Kamtchatka arcs which have been most extensively investigated from many geophysical points of view.

The "Miyako Depression" was originally recognized upon the most notable bathymetric feature traversing the Ryukyu Islands between Okinawa- and Miyako-jima by B. KOTO (1897), who claimed it to be a major rift or fault system intersecting his Ryukyu Cordillera. S. HANZAWA (1935), S. EHARA (1950) and others supported this interpretation. Recently the structural zonation of the islands has been proposed by K. KONISHI (1963, 1965) basing on his structural studies of the pre-Miocene basement complex, and he introduced the term "Miyako Depression".

In such a situation, we had carried out a preliminary palaeomagnetic survey of the islands in summer of 1964. With the aim of estimating, first of all, the differential movement, if occurred, between Japan and Ryukyu arcs throughout geological times, we had intended to take rock-samples covering a whole geological age as far as possible. This report describes the palaeomagnetic results obtained from the islands with special reference to the Miyako Depression, and some seismological considerations in connection with the geotectonic development of the arc as well.

## Locality of samples and the obtained palaeomagnetic results

Sampling plans for the palaeomagnetic research have been arranged after the suggestion of K. KONISHI, who has extensively studied the geology of the islands.

The localities, site numbers, rock kinds and their assumed geological times are illustrated in the next Table 1.

Unfortunately, we failed to measure a reliable natural remanent magnetization

Table 1. List of localities, site numbers and rock kinds.

| Geological time | Ishigaki-jima | Kume-jima | Okinawa-jima |
|---|---|---|---|
| Pliocene | | | Shinzato-tuff near Shinzato-village (No. 1) |
| Miocene | Hypersthene-bearing augite andesite (Nosoko Formation) near Ibarama-village (No. 10-1, 10-2, 10-3)<br>Greenish lapilli-tuff near Ōno-village (No. 9)<br>Biotite granite Arakawa-village (No. 11) Kabira-village (No. 12) | Hypersthene-bearing augite andesite Mt. Ōdake (No. 13-14) near Maja-village (No. 15-17) | Andesite porphyry dike north of Yabu-village (No. 18)<br>Biotite quartz-porphyry a quarry near Yohuke-village (No. 2) near the waterfall of Todoroki (No. 3) |
| Cretaceous | | | Sandstone and shale (Kayo Formation) near Kayo-town (No. 4-7) near Henoko-village (No. 8) |
| Jurassic Triassic | | | Slate (Nago Formation) near Yohuke-village (No. 19-20) |

(n.r.m.) for palaeomagnetic purpose, of rock-specimens taken from Triassic-Jurassic and Cretaceous formations, because they showed, more or less, heterogeneous magnetization which might be due to the alteration subsequent to the heavy folding after their deposition. Besides these, n.r.m. of Miocene granite collected from Ishigaki-jima indicated an anisotropic and unstable character being useless for palaeomagnetism. In addition, those specimens of biotite bearing quartz-porphyry dike and of Shinzato-tuff which collected from Okinawa-jima possessed a n.r.m. of too weak intensity to be measured, say less than $10^{-7}$ cgs/gr. Only Miocene andesite lava flows in Kume- and Ishigaki-jima, and an andesite porphyry dike in Okinawa-jima of which age was presumed to be also Miocene had a reliable n.r.m. showing a fairly good grouping in their remanent directions. The rock-specimens were subjected to the A.C. demagnetization experiments in order to wash out a soft viscous components acquired after their solidification. As a result of vector change in n.r.m. of specimen against the increasing A.C. field ($\tilde{H}$) up to 400 Oe, it was ascertained that a peak field amounting to 120 Oe was sufficient to find out the original n.r.m. of rocks.

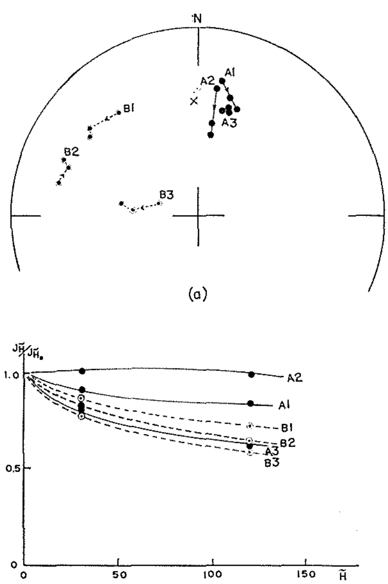


Fig. 1. The changes of the direction (a) and the intensity (b) of n.r.m. by A.C. demagnetization on Schmidt equal-area projection.
—●— ; specimen of Kume-jima (A1, A2 and A3).
--⊙-- ; specimen of Ishigaki-jima (B1, B2 and B3).

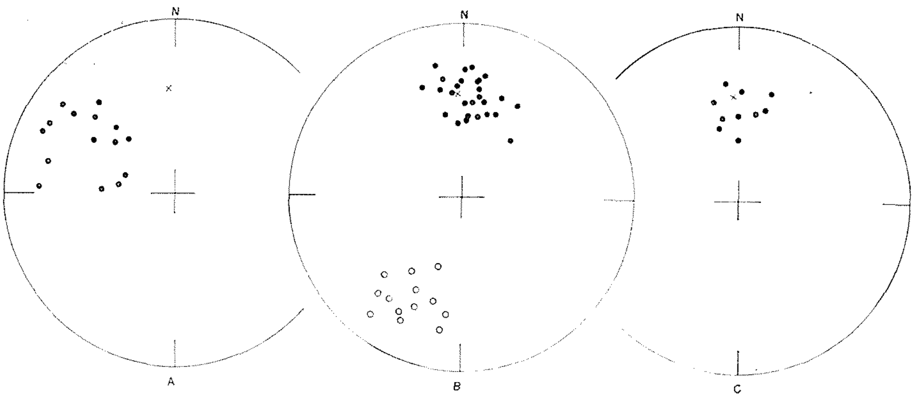


Fig. 2. Direction of n.r.m. after the demagnetization experiments showing on Schmidt equal-area projection.
A ; Ishigaki-jima. B ; Kume-jima. C ; Okinawa-jima.
× ; Direction of the present geomagnetic field.
● ; lower hemisphere ○; upper hemisphere.

Table 2. Results of N.R.M. for Miocene andesite taken from the Ryukyu Islands.

| Locality | Site-number | Number of Specimens | Mean Direction | | Virtual pole position | | Fisher's error angle ($\alpha_{95}$) |
|---|---|---|---|---|---|---|---|
| | | | D | I | Lat. | Long. | |
| Ishigaki-jima (124.2°E 24.4°N) | 10-1 | 5 | N45.0°W | 36.1° | 53.0°N | 40°E | 12.3° |
| | 10-2 | 4 | N52.0°W | 33.5° | 51.0°N | 78°E | 14.0° |
| | 10-3 | 7 | N40.5°W | 37.4° | 58.9°N | 39°E | 6.3° |
| | | | *N45.3°W | 36.0° | 53.2°N | 40°E | 7.8° |
| Kume-jima (126.8°E 26.2°N) | 13 | 11 | S 25.8°W | −26.1° | 72.6°N | 119°W | 3.8° |
| | 14 | 2 | S 28.0°W | −51.0° | 68.5°N | 163°W | |
| | | 8 | N 7.7°E | 46.2° | 85.0°N | 151°W | 5.8° |
| | 15 | 8 | N 4.3°E | 37.8° | 83.0°N | 83°W | 7.2° |
| | 16 | 9 | N10.9°E | 42.9° | 82.5°N | 140°W | 5.7° |
| | 17 | 7 | N 9.0°E | 45.3° | 81.0°N | 146°W | 7.0° |
| ** Okinawa-jima (127.9°E 26.6°N) | 18 | 10 | N 2.0°E | 46.9° | 87.5°N | 178°W | 5.0° |
| | | | *N 7.9°E | 43.1° | 84.6°N | 108°W | 4.9° |

* Mean of sites mean in each locality.
** Assumed direction of the present geomagnetic field: D=2.0°W, I=39°.

An example is illustrated in Fig. 1; the directional change of n.r.m. is shown in the upper diagram (a) on schmidt equal-area projection, and the corresponding intensity change in normalized values *vs* applied A.C. field up to 120 Oe is seen in the lower (b). The results of n.r.m. after the above-mentioned magnetic washing are illustrated in Table 2 and Figure 2.

The andesite lavas near the summit of Mt. Ōdake (326m) in Kume-jima possess a reversed n.r.m. covering nearly 135m in thickness with the direction antipodal to that of the normal n.r.m. revealed in lavas exposing in the southern hill-side about 140m below in height of the same mountain. Further below these localities, there develope several lava flows in the coastal cliffs of north Maja-village, possessing the normal n.r.m. quite similar to the direction in lavas of the hill-side mentioned above. These Miocene lava flows in Kume-jima and porphyritic dike in Okinawa-jima of which age is presumably Miocene are all magnetized in the direction close to the present geomagnetic field.

On the other hand, the "Nosoko andesite" in Ishigaki-jima to which the "Kume-jima andesite" may be correlative is magnetized in a quite different direction from that of the axial dipole. Of this difference in direction described above, angular deviation of 50° on the average may be estimable as seen in Table 2 and Fig. 2.

The angular difference of n.r.m. between those rocks taken from two adjacent sub-arcs may be most simply interpreted by the fact that the southwest sub-arc (or at least Ishigaki-jima) had undergone counterclockwise horizontal movement amounting to 50° in degree relative to the central sub-arc (or at least Kume- and Okinawa-jima), which is divided by the presence of the Miyako Depression from the southwest sub-arc. When such is the case, during or after Miocene epoch the movement might be simultaneously followed by the generation of the Miyako Depression.

Another interpretation of the fact is that if the axis of dipole had undergone angular displacement of limited amplitude comparatively rapidly, for example, say 40-50° in several millions of years during Miocene epoch, the difference between those two directions may be explained to give only other picture of the orientation of the dipole at two different times of Miocene epoch respectively; as samples collected from each individual islet do not necessarily belong to quite the same age. The reversed polarization of n.r.m. included only in the "Kume-jima andesite" seems to give considerable support to this view point.

The latter interpretation, however, is considered by the present authors as less likely than the former, because during Miocene epoch no such a large angular migration of the geomagnetic dipole amounting to 50° around the present rotational axis has been so far reported, with the exception of a very short duration of transient stage converting the polarity of dipole, if occurred, that is, from normal to reversed and its *vice versa* (H. Ito: 1965, and S. Nomura: 1963).

**Zonal variation in the distribution of epicentres and energy release of earthquakes along the arc in relation to geotectonics of the islands.**

The authors' attentions have been put upon the clarification of geophysical significance of the Miyako Depression since the palaeomagnetic results mentioned-above brought a light on further investigation. As a first step, we have taken up the seismological examination so far available. Partly for a political reason and partly for a disadvantage situation against neighbouring seismic observatory net, the long years' seismological data available for the statistic treatment are somewhat limited in number around the Ryukyu Islands. Prior to entering into our seismic considerations, we denote the following authentic issues to which are referred in this paper;

1. The Magnitude Catalogue of Major Earthquakes which occurred in Vicinity of Japan (1926-1956).
2. Preliminary determination of epicentres (U.S.C.G.S.; 1957-1964).
3. "Seismicity of the Earth" by GUTENBERG & RICHTER (1900-1948).

As is well known, the near Ryukyu Islands are regarded as one of the representative earthquake zone in the circum-Pacific, and accompanying characteristic features of the island arc have been pointed out by several authors such as B. GUTENBERG and C. F. RICHTER (1949), V. V. BELOUSSOV and E. M. RUDITCH (1961), G. S. GORSHKOV (1962) and so on. But these studies gave only too qualitative or outlined descriptions about the Ryukyu Arc, therefore, it is intended here to go into further details.

As a distribution map, the epicentres of 420 important earthquakes which took place from 1900 through 1964 near the Ryukyu Islands are plotted in Figure 3. For lack of the exact depth determination of the hypocentres, a rough classification is adopted in the figure; i.e. shallow shocks ($h \leqq 60$ km) and the intermediate shocks ($60 \leqq h \leqq 300$ km).

Considering from the figure, it is noted that the zone of shallow shocks is situated as a whole between the ocean trench and the island arc, while the zone of intermediate shocks lies inner side of the island arc. These regularities of the zonal distribution of epicentres are not so sharp as compared with that of Japanese Islands, although the yearly density of epicentres in the Ryukyu Islands is a little less than that in the former.

On the other hand, the density or frequency of epicentres is seen to vary considerably along the island arc. At several areas, the epicentres are much grouped, while at other several areas less grouped. The Ryukyu Islands appear to be lying in a circular arc with a good approximation, the center being located at a point near Shanghai (about 121° E, 32.5° N). In order to get more detailed views in the distribution of epicentres along the Ryukyu Islands, the whole concerned area were divided into equally spaced 13 sectors having 14 radial straight lines normal to the imaginary central circle of the arc,

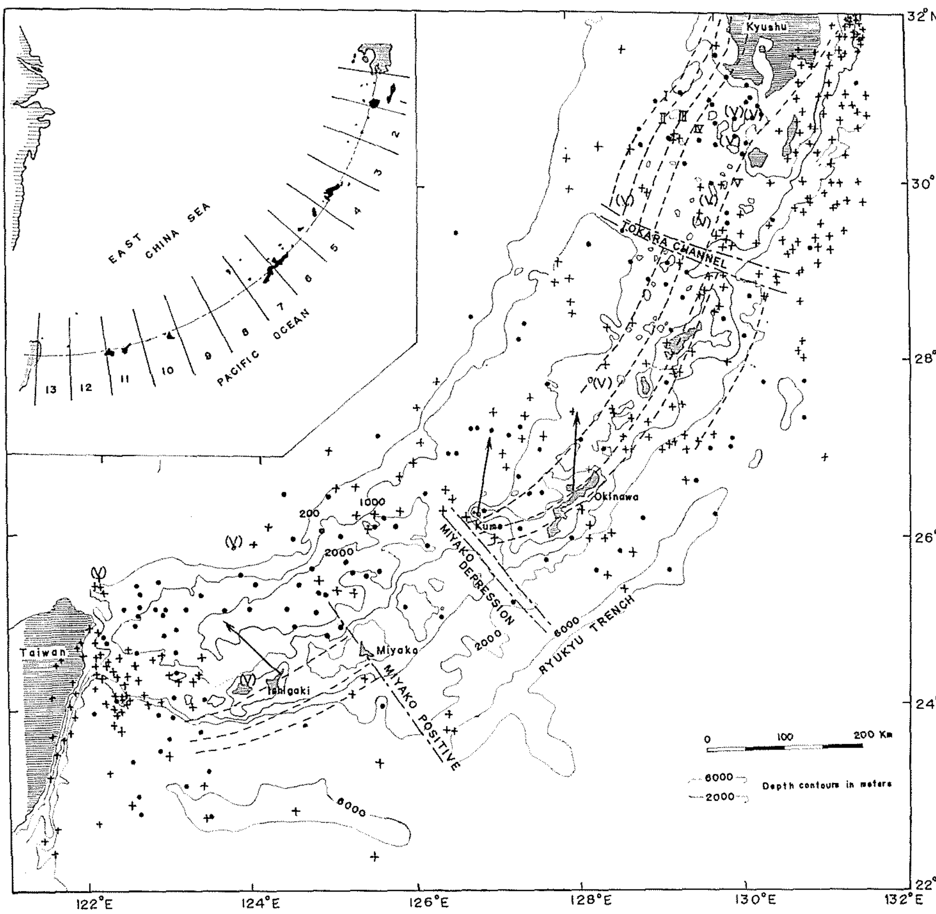


Fig. 3. Map showing the distribution of epicentres and the palaeomagnetic results plotted on the transcription from K. KONISHI (1965).

+; shallow shock ($h \leqq 60$ km). ●; intermediate shock ($60 \leqq h \leqq 300$ km). (V); site of recorded volcanic eruption.

⟶; the mean horizontal vector of n.r.m. obtained from Miocene andesite. I; Koshiki-jima belt. II; Ishigaki-jima belt. III; Motobu belt. IV; Kunigami belt. V; Shimajiri belt. VI; Kumage belt.

as is shown at a corner of Figure 3. The width of a sector is roughly 100 km long as measured longitudinally along the imaginary central circle.

As seen in Figure 4, the zonal variations in frequency of epicentres and released energy of earthquakes are respectively represented by sectors along the arc.

As to the released earthquake energy, the GUTENBERG-RICHTER's formula (1956) of $\log E = 11.8 + 1.5\ M$ is referred to. It is probable that the weak shocks such as

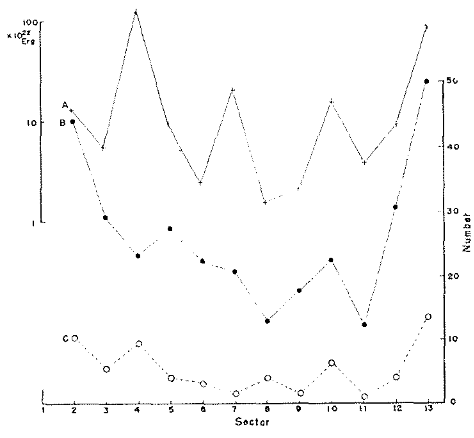


Fig. 4. Zonal variation along the arc of both frequency and released energy for earthquakes belonging to each sector.
A; Released energy of earthquakes.
B; Total numbers of earthquakes.
C; Number of earthquakes having magnitude greater than 6.0.

having the magnitude less than 6.0 were insufficiently recorded in data of the area. Therefore, the frequency variation curve of the total numbers of shocks is not so trustworthy as compared with that of the heavy shocks having their mangitude more than 6.0, which also shows nearly similar tendency to the former in its frequency curve. Of both frequency curves, there exist considerably higher values at each terminal in near Taiwan (sector 13 in Fig. 4) and Kyushu of Japan (sector 1), where the Ryukyu Arc intersects respective another arc.

Anyway, in this diagram, it is noted that the Miyako Depression, belonging to the sector 8-9 in this diagram, is situated in the minima of both frequency and energy release curves, despite of the complex variation of seismic activity along the arc.

According to A. V. GORYATCHEV (1962), who has extensively studied on some geophysical phenomena of the Kuril-Kamtchatka Arc, it is obvious that several areas of relatively low and high seismic activities show a fairly good accordance respectively with the regions of transverse relative saggings and uplifts separating them. Such a quite similar relationship between earthquake activities and geotectonic situation of the Miyako Depression probably reflects also the other accompanying geophysical and geotectonic characters which control the Miyako Depression.

The other character found in the Miyako Depression is a discontinuous distribution in epicentres of shallow shocks, which is superimposing, for the major parts, upon the general region of the epicentres of intermediate shocks. If the shallow shocks can simply be referred to the crustal earthquakes, it may be said with some exaggerations that the crustal structure in the Miyako Depression is dislocated far into the inner region of the intermediate shocks.

## Annual energy release for earthquakes in and around the Ryukyu Islands.

Annual energy release near the Ryukyu Islands is expressed by an equation $\log NE = 15.6 + 0.84\,M$ combining the two equations; GUTENBERG-RICHTER formula (1956) $\log E = 11.8 + 1.5\,M$ and $\log N = -1.48 + 0.66\,(8-M)$ obtained by the present authors. From the equation, the annual rate of energy release near the Ryukyu Islands will be determined to be $5.4 \times 10^{22}$ erg. If the concerned area is taken to be $2.9 \times 10^{15}$ $cm^2$, the mean rate of energy release for unit area will be $1.9 \times 10^7$ $erg/cm^2 \cdot year$.

It is plausible fact that the obtained value is very similar to the energy release of $1.5 \times 10^7$ $erg/cm^2 \cdot year$ obtained from the vicinity of Japan, where the concerned area is taken to be $1.5 \times 10^{16}$ $cm^2$ (C. TSUBOI, 1965).

## Magnitude-frequency relation for earthquakes near the Ryukyu Islands with special reference to their geotectonics.

As to the relation between mean annual number of earthquakes N and those magnitude M, GUTENBERG-RICHTER's formula $\log N = a + b\,(8-M)$ is well known. Here the coefficients $a$ and $b$ in the formula are variable with respect to the time interval used for statistics even in the same area under consideration (C. TSUBOI, 1952). According to the same author, however, the values of $a$ and $b$ may be regarded to tend to their respective asymptotic values when the time interval beyond 15 years is taken for statistics. The seismic data near the Ryukyu Islands having much more range than the criterion mentioned above, saying 33 years in total from 1926 through 1956 and 1963-1964, were selected from the issues mentioned in the previous section. The numerical values of the coefficients $a$ and $b$ were determined by means of the method of the least squares, taking into account the fact that the listed 191 heavy earthquakes having greater magnitude than 6.0 can only be trusted upon. Then, the following relation corresponding to 1/4 class interval of magnitude is obtained (Figure 5):

$$\log N = -1.48 + 0.66\,(8-M).$$

Recently C. TSUBOI (1965) has introduced a new formula concerning annual magnitude-frequency relation of earthquakes from 1926 through 1963 for the vicinity of Japan which was determined by the Seismological Section of the Japan Meteorological

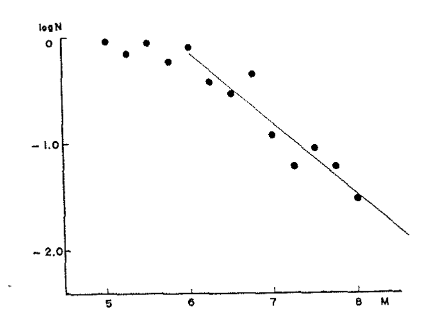


Fig. 5. Mean annual number of earthquakes (N) in and near the Ryukyu Islands according to magnitude (M).

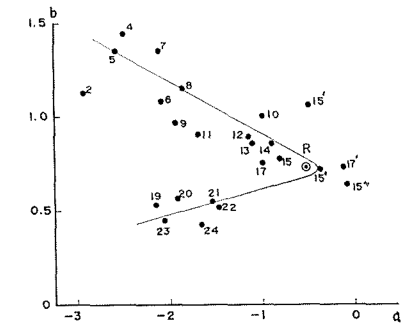


Fig. 6. Relation of the coefficients a′ and b for various earthquake regions; additional result on the Ryukyu Islands is drawn on the transcription from MIYAMURA (1962).
15 ; Japan-Kamtchatka.
15′ ; N.E. Japan-Pacific side.
15″ ; S.W. Japan-Pacific side.
15‴; Inner Japan-Japan Sea side.
R ; Ryukyu Islands.

Agency (1956 with additional material for later years). That is as follows:

$$\log N = -1.47 + 0.87\,(8 - M)\,.$$

A very interesting and plausible fact is that the present writers' results obtained from the Ryukyu Islands show a fairly good approximation to the formula mentioned above.

Recent MIYAMURA's hypothesis (1962) gave a light on the particular relationship between geotectonic development and a regular variation of reduced $a'$ and $b$ in a number of seismic zones in the world. If we determine the reduced value of coefficient $a'$ concerning the Ryukyu Islands on the basis of his new criterion, the following value may be given; $a' = -0.47$. By plotting this reduced $a'$ and $b$ relation of the Ryukyu Islands on the diagram transcribed from S. MIYAMURA, the Figure 6 may be obtained. As is plotted in the figure, the point representing seismic situation of the Ryukyu Islands is located near the turning point of the curve drawn by the original author. The Ryukyu Islands (mark **R** of the figure) shows much more association with both the Pacific side of Southwest-Japan (15″ of the figure) and the Japan Sea side of the whole Japan (15‴ of the figure) than the Pacific side of Northeast-Japan (15′ of the figure).

Furthermore, S. MIYAMURA has pointed out that the value of $b$ differs with the age of the arc, suggesting a seismotectonic explanation on the different $b$ values corresponding to the three major seismic belts in and near Japan which were studied by C. TSUBOI (1952). It is a significant fact that the seismotectonic characters of the Ryukyu Islands show a good approximation to those of Southwest Japan, since the Ryukyu Arc as a whole is likely to be distinctly connected with Southwest Japan from a standpoint of zonal classification of geotectonics (K. KONISHI: 1963, 1965).

So far as the numerical value of $b$ obtained from the near Ryukyu Islands is concerned, it may be inferred that the Ryukyu Islands is related rather to the older stage of arc as well as Southwest Japan. In other words, according to the present study, the Ryukyu Island Arc may be ascribed to the first type of island arc and not to the second type, even though V. V. BELOUSSOV and E. M. RUDITCH (1961) attributed the Ryukyu Arc to the latter probably basing on their geological understanding of the arc which, they believe, differs from the Japan Arc of the first type.

## Conclusion

From the results and discussions presented in the previous sections, the followings may be concluded.

1) As the results of the palaeomagnetic measurements on the Miocene andesites collected from each island bordering the Miyako Depression, a relative counterclockwise rotational movement through 50 in degrees may be reasonably assumed to have occurred during and/or after Miocene epoch at the eastern wing of the southwest Ryukyu subarc.

2) In the Miyako Depression, the anomalous distributions are found not only of the epicentres of shallow shocks, but also of earthquake activities characterizing region of sagging.

3) Annual magnitude-frequency relation for earthquakes near the Ryukyu Islands which was determined by the present authors shows a significant approximation to that newly reported for earthquakes in and near Japan. (C. TSUBOI, 1965)

4) Making use of a combined equation of GUTENBERG-RICHTER's formula of energy release and the annual magnitude-frequency relation of earthquakes, the annual energy released near the Ryukyu Islands was estimated. It is significant that the obtained value, $1.9 \times 10^7$ erg/cm$^2$·year, is comparable with the value of $1.5 \times 10^7$ erg/cm$^2$·year which was reported for the vicinity of Japan (C. TSUBOI, 1965).

5) Considering from the relationship between reduced coefficient $a'$ and $b$, it may be recognized that the Ryukyu Islands is much more closely associated with the Pacific side of Southwest-Japan and the Japan Sea side of the whole Japan than the Pacific side of Northeast-Japan. Accordingly, it may be assumed also from seismic evidences that the Ryukyu Arc is likely to be an extension of the older orogenic sequences of Chichibu and Shimanto geosynclines.

Finally, referring to the palaeomagnetic and seismic evidences mentioned above, it may be said that much more emphasis must be put upon the nature of Miyako Depression than ever from the view points of not only geotectonics but also geophysics. For further comprehensive understanding of the matter, other geophysical investigation giving informations about the crustal and sub-crustal structures are urgently desired.

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