Tilting Movements of the Japanese Islands Inferred from Cretaceous and Early Tertiary Paleomagnetic Data

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Cretaceous and early Tertiary rocks have been collected, by many workers including the present authors, from about two hundred sites in the Japanese Islands and South Korea for paleomagnetic investigations. The area mean direction of magnetization for the Oshima Peninsula and Okushiri Island of Hokkaido was 30.0° in declination and 58.4° in inclination. It differs distinctly from the area mean direction for granitic rocks from the Kitakami and Abukuma mountains. The area mean direction of magnetization obtained from the northern Kitakami belt was extremely westerly ($D=-81.1^\circ$, $I=22.3^\circ$) and that from the southern Kitakami belt was northwesterly ($D=-44.4^\circ$, $I=51.7^\circ$). The area mean from the Abukuma belt was also northwesterly ($D=-31.9^\circ$, $I=54.6^\circ$). The site mean directions of magnetization for granitic rocks in the Uetsu Province were not significantly grouped in the area. In Southwest Honshu, the area mean direction of the normal samples from various kinds of Cretaceous rocks was 50.2° in declination and 60.5° in inclination and that of the reversed ones was -114.8° and -55.8° , respectively. The normal and reversed magnetizations of early Tertiary rocks have shown similar directions to those of the Cretaceous rocks. The area mean of the normal samples was $D=37.6^\circ$, $I=52.3^\circ$ and that of the reversed ones was $D=-131.4^\circ$, $I=-44.8^\circ$, respectively. The site mean directions of magnetization for Cretaceous rocks in South Korea appear to be slightly northeasterly at each sampling site. The remarkable discrepancy between these area mean directions of magnetization is interpreted as being due to regional tilting movements which occurred in the Japanese Islands since the Cretaceous.

1. Introduction

Paleomagnetic directions of rocks may have been affected by various tectonic movements, such as folding, faulting or tilting, and evidences of these tectonic movements will still remain on the remanent vectors of rocks. Therefore, the paleomagnetic directions of rock masses would provide useful pieces of information about the form and timing of deformation of the rock masses followed by tectonic events.

In England, CLEGG *et al.* (1954) suggested, on the basis of paleomagnetic results of Triassic red sandstones, that England had rotated about 30° clockwise and drifted northward since the Triassic, and they successfully explained the deflection in paleomagnetic directions. In Japan, the bending hypothesis of the Honshu Island proposed by KAWAI *et al.* (1961) is well known. KAWAI *et al.* (1961, 1962, 1971) noticed that there was the remarkable discrepancy in declination between pre-Tertiary rocks collected from Southwest and Northeast Japan, and they pointed out

that it would be well interpreted by clockwise and anti-clockwise rotations of Southwest Japan and Northeast Japan. On the other hand, SASAJIMA *et al.* (1968) suggested that Southwest Japan had drifted northeastward from a lower latitude and rotated clockwise by about 20° since the Cretaceous by using the paleomagnetic data obtained from Southwest Japan. On the contrary, a possibility of southward drifting of Southwest Japan from a higher latitude has been discussed by YASKAWA (1973, 1975). In these cases, it is assumed that the geomagnetic field has always been the same dipole field as it is now and that the geomagnetic poles since the Cretaceous were situated near the present geographic poles. Recently, investigations of rotational deformations or drifting of land masses have been reported from East and Southeast Asia by several workers (e.g., MCELHINNY, 1973; SASAJIMA *et al.*, 1979; OTOFUJI *et al.*, 1981; OTOFUJI and MATSUDA, 1983; ACHACHE *et al.*, 1983).

The deviation in paleomagnetic declination from the present geomagnetic declination is usually explained by rotation about a vertical axis and that in inclination by latitudinal drift of a land mass sampled. In general, it is thought that regional tectonic movements were produced by rotations about inclined axes. However, rotation mechanisms about the inclined axes are not so simple, and such mechanisms are hard to relate to the paleomagnetic results. Two rotational movements about the vertical and horizontal axes which are well known are particular cases of rotations about the inclined axes. We assumed that regional tectonic deformations were produced by rotations about the horizontal axes from some paleomagnetic results described below.

Granitic rocks in the Oshima Peninsula and Kitakami Province have nearly the same ages according to KAWANO and UEDA (1967), but a area mean paleomagnetic direction of the Oshima Peninsula was north-easterly and that of the Kitakami region was northwesterly. The area mean directions of these two areas are obviously discordant with each other (ITO and TOKIEDA, 1974; ITO *et al.*, 1980). On the other hand, remanent magnetizations of Cretaceous and Paleogene granitic rocks in the Uetsu Province of Northeast Honshu showed apparently different directions among individual rock masses. This result suggests that more local tectonic deformations than the Kitakami region occurred in the Uetsu region. Accordingly, as we described in previous papers (ITO and TOKIEDA, 1974; ITO *et al.*, 1980), we supposed that there was little possibility of anti-clockwise rotation of Northeast Honshu including the southwestern part of Hokkaido and that the paleomagnetic directions of the Oshima Peninsula, Kitakami and Abukuma regions were mostly caused by regional rotational movements about the horizontal axes in each area. In this paper, a probability of tilting deformations of the Japanese Islands will be discussed from paleomagnetic data of granitic rocks which we mainly collected and also the published paleomagnetic data of igneous and sedimentary rocks in the Cretaceous and early Tertiary.

2. Remanent Magnetization of Granitic Rocks

The depth of emplacement of granitic intrusions is considered to be of the order of hundred or thousand meters below the original cover and overall crystallization temperatures of such intrusions appear to be usually in the range $900^\circ - 600^\circ\text{C}$ (e.g., BIRTH, 1962; RAGUIN, 1965). The natural remanent magnetization (NRM) of granitic

rocks is almost the thermo-remanent magnetization acquired when they were cooled through the Curie temperature of ferromagnetic minerals contained therein. After the acquisition of remanent magnetizations, it is considered that some formations overlying the granitic rocks should have been gradually removed and consequently the granitic rocks are considered to have been uplifted to present positions of the surface.

Paleomagnetic data for granitic rocks in Japan and South Korea indicated that directions of stable component of magnetization obtained from a number of sites within a single body cluster about a mean direction of magnetization. The between-site consistency in direction within a body has been repeatedly observed from Cretaceous and early Tertiary granitic rock masses with the stable NRM in Japan. The absence of remarkable difference in paleomagnetic directions between sampling sites within a body implies that no intensive plastic deformations which disturb the paleomagnetic directions at each site occurred in the body. The remanent vectors of granitic rocks should show no change in directions of NRM by simple vertical displacements of the blocks without rotational movements. Therefore, the between-site consistency in NRM directions within a rock mass suggests that the mass have moved as a block for some tectonic movements after the emplacement.

On the other hand, granitic rock masses having unstable NRM or exhibiting within-site scatter in magnetic directions are frequently observed from various regions of Japan, but such paleomagnetic data have always been dropped like a hot potato. It seems to us that granitic bodies showing unstable or within-site inconsistency have undergone intensive local tectonic distortions or excessive weathering after the emplacement. Thus, paleomagnetic data of granitic rocks in the Cretaceous and early Tertiary in Japan suggest that granitic masses showing the stable magnetization and between-site consistency in directions are useful for the study of tectonic movements using paleomagnetic techniques.

3. Geological Setting and Sampling

Cretaceous and early Tertiary granitic rocks are widely exposed in Hokkaido, Honshu, Shikoku, Kyushu and the other small islands in Japan, and radiometric ages of their rocks have been reported by many workers (NOZAWA, 1975). On the other hand, magnetic susceptibility of Japanese granitic rocks is measured on about 1200 samples by Ishihara and his co-workers (KANAYA and ISHIHARA, 1973; KANAYA, 1974; ISHIHARA, 1979; ISHIHARA *et al.*, 1979). Magnetic susceptibility is converted to magnetite content and the amount of magnetite decreases from quartz diorite or tonalite to granite in general. According to ISHIHARA (1979), high values of magnetic susceptibility are found in granitic rocks of the Kitakami belt, San-in belt and northern Kyushu belt. The magnetic susceptibility of granitic rocks in the Abukuma belt is usually lower than that in the Kitakami belt. Most of the granitic rocks in southwestern Hokkaido, Okushiri Island and the Uetsu region have magnetically similar character to that of the Abukuma region.

3.1. Oshima Peninsula and Okushiri Island of Hokkaido

The area sampled is in between latitude 42°05'–42°35'N and longitude 139°45'–140°15'E in the Oshima Peninsula. The K–Ar ages of the Setana and

Imagane granodiorite masses are 111 Ma and 124 Ma according to KAWANO and UEDA (1966a). The K–Ar biotite ages of 114 Ma and 133 Ma are recently given to the Yurappu-dake granodiorite mass (ISHIDA, 1981). The K–Ar age of a granodiorite sample taken from the west coast of the Okushiri Island is 95.8 ± 3.1 Ma (SHIBATA and YAMADA, 1978). Oriented hand samples were collected from the Imagane, Setana and Yurappu-dake masses in the Oshima Peninsula and a few small granodiorite bodies in the Okushiri Island.

3.2. *Uetsu Province*

The sampling area in the Uetsu Province is in between latitude $38^{\circ}00' - 40^{\circ}30'N$ and longitude $139^{\circ}35' - 140^{\circ}50'E$. The main masses of granitic rocks sampled in this area are exposed in the Asahi highland and its vicinity, Taiheizan, Shirakami-dake and Tazawa-ko areas. We collected granitic rock samples from more than 20 sites in the area. The ages of granitic rocks sampled in this area range mainly from 100 to 55 Ma (KAWANO and UEDA, 1966a; NOZAWA, 1975).

3.3 *Kitakami Province*

The Kitakami Province has been divided into six zones by petro logic and petro-chemical investigations (KATADA *et al.*, 1971; KATADA and KANAYA, 1980). However, we conveniently divided it into two parts, northern and southern Kitakami blocks, whose divider corresponds to the Morioka-Goyozan tectonic line, because a significant difference in NRM directions of granitic rocks is found between their two blocks (ITO and TOKIEDA, 1980). Some of the granitic rocks are associated with lower Cretaceous volcanic formations and are thought, therefore, to be of relative high-level emplacement (NOZAWA, 1983). The northern part of the Kitakami mountains sampled is in between latitude $39^{\circ}40' - 40^{\circ}15'N$ and longitude $141^{\circ}10' - 142^{\circ}00'E$ and the southern part in between $38^{\circ}15' - 39^{\circ}30'N$ and $141^{\circ}10' - 141^{\circ}50'E$. The ages of granitic rocks collected fall in about 125 to 100 Ma (KAWANO and UEDA, 1964, 1965a; NOZAWA, 1975). The Kitakami granitic rocks exposed in Kinkasan Island are dated at 120 to 84 Ma by KAWANO and UEDA (1964, 1965a).

3.4 *Abukuma Province*

Cretaceous granitic rocks of the Abukuma mountains are composed of two facies. The earlier facies comprises mainly quartz diorite, tonalite and granodiorite, intruding the Abukuma metamorphic rocks concordantly. The latter facies is composed mainly of granite and granodiorite, forming discordant intrusions. Both facies have nearly the same K–Ar age of mid-Cretaceous (NOZAWA, 1983). The area sampled is in between latitude $37^{\circ}10' - 37^{\circ}40'N$ and longitude $140^{\circ}35' - 141^{\circ}00'E$ in the northern part of the Abukuma Province. The K–Ar ages of granitic rocks sampled in this area are 100 to 90 Ma (KAWANO and UEDA, 1965b, 1966a).

3.5 *Southwest Honshu*

Felsic intrusive and extrusive rocks are widely exposed in the Chugoku district, and granite-rhyolite association is also found in the northern Kinki region on a relatively small scale (NOZAWA, 1983). Granitic rocks in the Chugoku district are divided into two zones (MURAKAMI, 1974). The southern zone contains a large batholith associated with upper Cretaceous volcanic rocks and small bodies of quartz

syenite are found in this batholith. The radiometric ages indicate mostly 90 to 75 Ma. The northern zone contains granitic masses of batholithic dimensions and sporadic, minor, high-level intrusive masses. They have K–Ar ages of 65 to 40 Ma (NOZAWA, 1983). The area sampled is widely ranging and in between latitude $33^{\circ}50'–36^{\circ}55'N$ and longitude $130^{\circ}50'–137^{\circ}40'E$ in the Kinki and Chugoku Provinces. More than 2000 samples were collected from granitic rocks of the Mesozoic and early Tertiary ages in Southwest Honshu. The ages of granitic rocks sampled fall in 90 to 25 Ma (KAWANO and UEDA, 1966b).

3.6 Northern Kyushu

Various kinds of Cretaceous granitic rocks are widely exposed in the northern Kyushu region (mainly Fukuoka Prefecture) and they are unconformably overlain by Paleogene formations (NOZAWA, 1983). Most of their granitic rocks belong to the magnetite series, according to ISHIHARA *et al.* (1979). The sampling area is in between latitude $33^{\circ}20'–33^{\circ}55'N$ and longitude $130^{\circ}05'–130^{\circ}50'E$. The ages of samples collected are 100 to 80 Ma (KAWANO and UEDA, 1966b; NOZAWA, 1975).

3.7 South Korea

Jurassic to Cretaceous granitic rocks are widely exposed in the southern part of the Korean Peninsula (LEE, 1981; TSUSUE *et al.*, 1981). The radiometric ages of granitic rocks in the Korean Peninsula are compiled by the Section of Mineralogy, GEOLOGICAL SURVEY OF KOREA (1972). We collected 128 samples from 13 sites in seven granitic bodies showing 121 to 71 Ma, according to the radiometric age map. The area sampled is in between latitude $35^{\circ}15'–37^{\circ}00'N$ and longitude $127^{\circ}35'–129^{\circ}30'E$. Recently, LEE and UEDA (1977) and LEE (1980) reported the K–Ar age data of granitic rocks from the southern Gyeongsang basin. The granitic rocks in this basin mostly have the K–Ar ages of 115 to 41 Ma.

4. Results of Measurements

Oriented hand samples collected have been drilled in the laboratory and core samples with 2.3 cm in diameter and 2.3 cm high have been made. All core samples were measured with a spinner magnetometer and examined by alternating field demagnetization of peak field of 10 to 120 mT. Results of measurements of the NRM of granitic rocks which we examined and the paleomagnetic data used in this paper are listed in Tables 1 to 8. Figures 1 and 2 show the site mean directions of NRM at each sampling site from the seven provinces in Japan and South Korea.

4.1 Oshima Peninsula and Okushiri Island

The Cretaceous granitic rocks in the Oshima Peninsula and Okushiri Island of Hokkaido are normally magnetized and directions of NRM were found to be almost northeasterly as shown in Fig. 1 and Table 1 (ITO and TOKIEDA, 1974; NOTSU and ITO, 1982). Site mean directions obtained from these two regions are distributed in the range from slightly northeasterly to easterly (Fig. 1).

4.2 Uetsu Province

A few granitic bodies which have negative inclination were found in this region

Table 1. Paleomagnetic data for granitic rocks in the Oshima Peninsula and Okushiri Island of western Hokkaido.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°) I(°)	α_{95} (°)	Age (Ma)	References
1 Imakane	42.50	140.08	Granodiorite	5	38	36	11.7	Cretaceous
2 Tomankeshi-gawa	42.48	140.01	Granodiorite	12	6	45	6.4	Cretaceous
3 Tomankeshi-gawa	42.47	140.01	Granodiorite	10	52	44	7.1	Cretaceous
4 Gorota	42.37	139.81	Granodiorite	14	-34	43	5.6	Cretaceous
5 Udomari	42.35	139.79	Granodiorite	11	-13	49	8.7	110, 111
6 Midare-misaki	42.35	139.78	Granodiorite	10	3	69	5.3	110, 111
7 Midare-misaki	42.35	139.78	Granodiorite	5	41	68	14.7	110, 111
8 Midare-misaki	42.35	139.78	Granodiorite	5	70	62	18.5	110, 111
9 Kudo	42.25	139.80	Granodiorite	5	65	30	9.2	Cretaceous
10 Kenichi-onsen	42.17	140.05	Granodiorite	4	82	55	10.0	114
11 Kenichi-onsen	42.15	140.05	Granodiorite	5	71	54	8.3	114
12 Ōiwaai-gawa	42.22	139.59	Granodiorite	9	23	68	6.6	Cretaceous
13 Ōiwaai-gawa	42.22	139.49	Granodiorite	10	-37	64	5.0	Cretaceous
14 Akaishi-misaki	42.15	139.52	Granodiorite	10	-26	73	11.7	Cretaceous
15 Kamoishi Tunnel	42.15	139.42	Granodiorite	10	29	35	13.1	Cretaceous
16 Tsukidashi	42.13	139.43	Granodiorite	12	70	43	11.0	95.8
17 Tsukidashi	42.13	139.43	Granodiorite	13	58	52	8.5	95.8
18 Matsue	42.07	139.48	Granodiorite	12	-13	34	6.3	Cretaceous

12: Ito and TOKIEDA (1974). NI: NORTSU and Ito (1982).

12-18: Okushiri Island.

Fig. 1. Site mean directions of the Oshima Peninsula and Okushiri Island, Kitakami mountains, Uetsu Province and Abukuma mountains. Closed symbols indicate to be the lower hemisphere (positive inclination) and open symbols to be the upper hemisphere (negative inclination). Cross mark is the present geomagnetic field direction at sampling area.

(Table 2 and Fig. 1). However, most of the samples measured had positive inclination. The NRM directions from the Uetsu Province were well grouped at each sampling site or within a single body, but between-body directional scatter was remarkable. Therefore, we were unable to estimate the area mean direction for this region. Such an inconsistency in directions between individual granitic bodies may imply that more local tectonic deformations occurred in the Uetsu Province. The Uetsu Province, by the paleomagnetic data, is definitely separated from the Kitakami block. Its boundary is likely to be the volcanic front by SUGIMURA (1960).

4.3 Kitakami Province

Granitic rocks from the Kitakami Province were mostly normally magnetized, and the NRM directions were found to be almost northwesterly to westerly (Table 3 and Fig. 1). Only gabbroic rocks taken at Ichinohe were reversely magnetized. The Kitakami region was divided into two parts, northern and southern Kitakami blocks, from the significant difference in NRM directions (ITO and TOKIEDA, 1980). The area mean direction for the northern Kitakami block was -81.1° in declination and 22.3° in inclination and that for the southern Kitakami block was -44.4° and 51.7° , respectively. The area mean of the reversed samples in the northern Kitakami block is $D=105.3^\circ$, $I=-20.0^\circ$. Thus the difference in declination between these two blocks is

Table 2. Paleomagnetic data for granitic rocks in the Uetsu Province.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°) I(°)	α_{95} (°)	Age (Ma)	References
1 Mokurenji	40.45	139.95	Granodiorite	11	-160 85	5.7	93	
2 Mokurenji	40.45	139.95	Granodiorite	7	112 79	6.1	93	
3 Mokurenji	40.45	139.95	Granodiorite	5	90 76	19.5	93	
4 Mokurenji	40.43	139.95	Adamellite	5	-21 21	8.2	63	
5 Sannai-gawa	39.78	140.40	Granodiorite	8	110 -17	4.7	88, 89	
6 Omata-gawa	39.73	140.42	Granodiorite	7	-50 5	3.3	88, 89	
7 Tazawako	39.78	140.65	Granodiorite	5	-35 64	18.1	102	
8 Obonai-gawa	39.70	140.77	Granodiorite	8	89 51	4.3	103	
9 Kinomata	38.57	139.68	Granodiorite	8	118 -9	5.7	61	
10 Sekigawa	38.52	139.65	Granodiorite	7	131 12	4.4	55	
11 Sekigawa	38.52	139.67	Granodiorite	7	-6 55	16.0	55	K
12 Ohari	38.53	139.80	Quartz diorite	5	-24 21	4.0	59	
13 Ohari	38.55	139.82	Quartz diorite	11	-23 23	5.0	59	K
14 Ōtori-gawa	38.45	139.78	Quartz diorite	6	13 55	6.0	63	K
15 Hondoji	38.45	140.03	Granodiorite	6	-63 -22	4.0	Cretaceous	
16 Hondoji	38.45	140.03	Granodiorite	5	-68 -7	9.0	Cretaceous	
17 Kijiyama Dam	38.13	139.93	Adamellite	5	-28 52	15.0	85	
18 Sugano Dam	38.12	139.93	Adamellite	4	45 31	20.0	85	

K: KAWAI *et al.* (1971).

very remarkable and the northwesterly to westerly declinations of the blocks are evidently opposed to the northeasterly ones of the Oshima Peninsula and Okushiri Island of Hokkaido.

4.4 *Abukuma Province*

All samples measured were normally magnetized (Table 4 and Fig. 1), and the area mean direction for this block was -31.9° in declination and 54.6° in inclination. The mean is close to that for the southern Kitakami block, but it is apparently different from the area mean for the Oshima Peninsula and Okushiri Island.

4.5 *Southwest Honshu*

The NRM directions of granitic rocks from Southwest Honshu are well consistent with those of Cretaceous or early Tertiary volcanic and sedimentary rocks reported by many workers (NAGATA *et al.*, 1959; KAWAI *et al.*, 1961; SASAJIMA and SHIMADA, 1966; SASAJIMA *et al.*, 1968; KAWAI *et al.*, 1971; DOMEN, 1971; KONO *et al.*, 1974). Site mean directions of magnetization for normally magnetized rocks were found to be almost northeasterly (Tables 5 and 6 and Fig. 2). Furthermore, there are many reversely magnetized rocks whose NRM directions are nearly antipodal to those of normal samples. The area mean direction of magnetization for the normal samples of the Cretaceous was 50.2° in declination and 60.5° in inclination and that for the reversed ones was -114.8° and -55.8° , respectively. The normal samples in the Paleogene have the area mean direction of magnetization of $D=37.6^\circ$, $I=52.3^\circ$ and the reversed ones have the mean of $D=-131.4^\circ$, $I=-44.8^\circ$, respectively.

4.6 *Northern Kyushu*

Paleomagnetic data for Cretaceous rocks are very scarce in the northern Kyushu region. The Cretaceous granitic rocks collected from this region were normally magnetized, except for one site at Wakinoura (Table 7 and Fig. 2). The magnetic directions of samples taken at Wakinoura were northward and negative inclination. The declinations of the normal samples were northeasterly or easterly. The area mean direction was 75.6° in declination and 58.1° in inclination. This mean value is slightly easterly than that for the Cretaceous rocks in Southwest Honshu.

4.7 *South Korea*

All samples of Cretaceous granitic, volcanic and sedimentary rocks taken from South Korea were normally magnetized and site mean directions of magnetization deviated slightly from the present direction of the geomagnetic field at each sampling site, as shown in Table 8 and Fig. 2 (KIENZLE and SCHARON, 1966; ITO and TOKIEDA, 1980; OTOFUJI *et al.*, 1982). The area mean direction of South Korea was $D=16.0^\circ$, $I=-57.4^\circ$.

5. Tectonic Movements and Paleomagnetic Pole

Reports of tectonic rotation deduced from paleomagnetic results have been steadily increasing (e.g., MACDONALD, 1980; WILSON and COX, 1980; OTOFUJI *et al.*, 1981; OTOFUJI and MATSUDA, 1983; ACHACHE *et al.*, 1983; and many others). However, translation and rotational movement about the vertical axis have been

Table 3. Paleomagnetic data for granitic rocks in the Kitakami Mountains.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°) I(°)	α_{95} (°)	Age (Ma)	References
1 Ichinohe	40.22	141.28	Gabbro	4 (4)	-72 47	5.9 20.0	100-116	I5
2 Ichinohe	40.23	141.28	Gabbro	8	101 -30			I5
3 Numabukuro	40.15	141.60	Granodiorite	8	109 -10	10.2	100-116	I5
4 Kosode-kaigan	40.18	141.83	Granodiorite	10	-72 26	8.5	120	I5
5 Kosode-kaigan	40.17	141.83	Granodiorite	8	-83 31	9.8	120	I5
6 Shimoakka	40.05	141.85	Granodiorite	11	-102 -17	3.9	120	I5
7 Ōtanabe	40.02	141.90	Granodiorite	10	-81 19	13.6	112, 117	I5
8 Kurumihata	39.80	141.93	Monzonite	9	-91 0	5.1	112, 117	I5
9 Ōkawa	39.80	141.63	Granodiorite	11	-60 20	7.4	114	I5
10 Kamiuge	39.75	141.82	Granodiorite	6	-85 47	7.6	Cretaceous	I5
11 Oginohora	39.37	141.77	Quartz diorite	10	20 50	9.3	112	I5
12 Ōkuchi	39.35	141.72	Quartz diorite	10	-40 47	11.0	115, 122	I5
13 Yamaya	39.58	141.25	Granodiorite	12	-33 43	7.9	120, 126, 129	I5
14 Tono	39.33	141.55	Granodiorite	5	-35 51	7.7	109	K
15 Akabane-toge	39.23	141.60	Granodiorite	12	-63 53	12.0	110	K
16 Akabane-toge	39.23	141.60	Granodiorite	13	-60 44	4.1	119	I5
17 Akabane-toge	39.23	141.60	Granodiorite	5	-63 43	8.0	119	K
18 Hitokabe	39.25	141.32	Granodiorite	10	-39 74	13.0	119	KM
19 Akagane Mine	39.17	141.35	Granodiorite	57	-63 63	16.1	114	K
20 Akagane Mine	39.17	141.35	Gabbro	33	-57 66	5.0	Cretaceous	NA
21 Akagane Mine	39.17	141.35	Quartz porphyry	29	-35 67	6.0	Cretaceous	NA
22 Akagane Mine	39.17	141.35	Granite porphyry	60	-18 66	8.0	Cretaceous	NA
23 Yoshihama	39.13	141.83	Granodiorite	5	-29 57	4.0	Cretaceous	NA
24 Ōkirai	39.12	141.82	Granodiorite	11	-73 34	16.0	107, 116	K
25 Ōkirai	39.12	141.83	Granodiorite	11	-73 36	5.7	107, 116	I5
26 Setamai	39.12	141.58	Granodiorite	14	-76 44	7.0	107, 116	I5
27 Yokota	39.08	141.58	Quartz diorite	11	-51 66	4.3	112	I5
28 Ōyo	38.97	141.68	Granodiorite	10	-65 35	4.8	112	I5
29 Nesaki	38.95	141.72	Granodiorite	15	-57 49	5.1	Cretaceous	I5
30 Murone-san	38.97	141.45	Granodiorite	10	-23 51	3.8	Cretaceous	I5
						8.2	Cretaceous	I5

31 Kiyota	38.93	141.40	Quartz diorite	11	-34	43	6.2	114, 119	I5
32 Senmaya	38.90	141.33	Quartz diorite	12	-38	43	4.9	114, 119	I5
33 Senmaya	38.90	141.33	Quartz diorite	8	-31	51	8.0	114, 119	K
34 Senmaya	38.90	141.33	Quartz diorite	5	-45	43	13.0	114, 119	KM
35 Tabashineyama	39.00	141.18	Granodiorite	10	17	48	5.3	Cretaceous	I5
36 Tabashineyama	39.00	141.18	Granodiorite	10	-26	78	5.2	Cretaceous	I5
37 Tabashineyama	39.00	141.20	Granodiorite	11	-71	54	6.4	Cretaceous	I5
38 Kinkasan	38.28	141.55	Quartz diorite	5	-25	41	14.7	119, 120	I5
39 Kinkasan	38.28	141.55	Quartz diorite	12	-35	24	10.0	119, 120	K
40 Kinkasan	38.28	141.57	Granodiorite	10	-54	29	5.4	109	I5
41 Kinkasan	38.28	141.57	Granodiorite	4	-35	51	17.0	109	KM

I5: ITO and TOKIEDA (1980) K: KAWAI *et al.* (1971). KM: KATO and MUROI (1965). NA: NEDACHI *et al.* (1970).
1-10=Northern Kitakami.
11-41=Southern Kitakami.

Table 4. Paleomagnetic data for granitic rocks in the Abukuma Mountains.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°)	I(°)	α_{95} (°)	Age (Ma)	References
1 Yamakiya	37.58	140.68	Diorite	10	-42	54	3.0	Cretaceous	
2 Tazawa	37.57	140.67	Diorite	10	-37	51	3.6	Cretaceous	
3 Shiobite	37.57	140.80	Adamellite	6	-33	49	6.3	100	
4 Shiobite	37.57	140.80	Adamellite	16	-49	61	4.0	100	K
5 Tsushima	37.57	140.77	Granodiorite	9	-29	57	6.0	95	K
6 Hirusone	37.53	140.87	Adamellite	10	7	45	12.0	92	K
7 Tamanoyu-onsen	37.42	140.92	Granodiorite	9	-45	48	3.8	Cretaceous	
8 Abukuma	37.17	140.50	Granite	24	-33	62	7.0	101	KM

K: KAWAI *et al.* (1971). KM: KATO and MUROI (1965).

Table 5. Paleomagnetic data for Cretaceous rocks in Southwest Hoshu.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°) I(°)	α_{95} (°)	Age (Ma)	References
1 Taki	34.52	136.27	Gabbro	5	9 56	4.0	Triassic	K
2 Sakurai	34.53	135.87	Gabbro	7	52 43	12.0	Triassic	K
3 Yono	34.92	135.50	Quartz diorite	10	90 49	9.6	75.6	I3
4 Kirihiata	34.92	135.52	Quartz diorite	5	-92 -74	6.0	75.6	I3
5 Zenihara	34.92	135.53	Quartz diorite	5	9 59	6.7	75.6	I3
6 Kamimura	34.85	135.55	Quartz diorite	15	-121 -32	7.7	75.6	I3
7 Daimonji	34.87	135.57	Quartz diorite	3	-135 -68	9.6	75.6	I3
8 Saho	34.87	135.53	Granodiorite	10	82 71	3.9	73.8-75.6	I3
9 Saho	34.87	135.53	Granodiorite	16	-114 -58	4.2	73.8-75.6	I3
10 Shimootowa	34.90	135.55	Granodiorite	32	-92 -56	3.0	73.8-75.6	I3
11 Minoyama	34.88	135.55	Granodiorite	10	-123 -56	19.3	73.8-75.6	I3
12 Tarumi	34.90	135.53	Adamellite	16	59 67	8.9	73.8	I3
13 Izuhara	34.88	135.52	Adamellite	5	-127 -51	6.4	73.8	I3
14 Noma-toge	34.93	135.48	Adamellite	11	22 69	11.4	74.0	I3
15 Noma-ohara	34.95	135.48	Adamellite	5	40 53	18.3	74.0	I3
16 Mimasaka-kamo	35.15	134.07	Granodiorite	6	60 42	7.4	78.2	I3
17 Renjaku	34.97	134.07	Quartz diorite	11	78 69	3.0	Cretaceous	I6
18 Nibori	34.87	134.02	Granite	16	52 63	5.0	79.9	I6
19 Myoken-zan	34.90	134.12	Granodiorite	16	83 65	4.4	75.7	I6
20 Myoken-zan	34.90	134.12	Granodiorite	14	53 70	5.4	75.7	I6
21 Myoken-zan	34.88	134.12	Granodiorite	15	24 66	10.5	75.7	I6
22 Myoken-zan	34.88	134.13	Granodiorite	15	77 59	2.5	75.7	I6
23 Myoken-zan	34.85	134.15	Tonalite	10	18 48	8.8	75.7	I6
24 Myoken-zan	34.85	134.17	Tonalite	8	61 63	6.5	75.7	I6
25 Nariwa	34.77	134.55	Andesite	10	67 42	8.9	Cretaceous	S1
26 Nariwa	34.77	134.55	Red shale	45	58 65	2.0	Cretaceous	S1
27 Kamochi	35.22	133.47	Granodiorite	5	-101 -56	7.8	Cretaceous	I6
28 Yumura	35.23	132.90	Diorite	10	-145 -45	5.3	Cretaceous	I6

29 Sanbe	35.10	132.63	Granodiorite	9	-20	39	7.0	Cretaceous	Sl
30 Sakugi	34.88	132.67	Andesite	8	55	46	18.1	Cretaceous	Sl
31 Kisa	34.78	133.05	Andesite	12	80	53	7.4	Cretaceous	Sl
32 Iwami-yanase	35.03	132.57	Andesite	7	47	66	8.6	Cretaceous	Sl
33 Akana	35.00	132.72	Granodiorite	6	59	64	10.1	Cretaceous	sl
34 Hashi	34.89	132.16	Quartz diorite	14	-86	-47	3.4	Cretaceous	
35 Mimata-onsen	34.89	132.27	Granodiorite	10	52	48	6.1	Cretaceous	
36 Haza	34.80	132.20	Granodiorite	14	28	64	2.4	81.4	
37 Masuda	34.68	131.87	Granodiorite	15	34	38	14.5	Cretaceous	K
38 Kibeshimo	34.43	131.58	Granodiorite	15	-4	73	4.1	Cretaceous	
39 Fukushima	34.44	131.49	Granodiorite	15	23	59	2.5	Cretaceous	
40 Fukushima	34.43	131.51	Diorite	9	55	66	6.0	Cretaceous	
41 Hagi	34.43	131.45	Granite	16	60	56	3.7	Cretaceous	
42 Kawakami	34.35	131.47	Diorite	12	60	60	3.4	Cretaceous	
43 Juraku	34.37	131.15	Welded tuff	8	74	61	8.0	Cretaceous	Sl
44 Chomonkoyo	34.32	131.57	Andesite	8	118	-30	5.0	Cretaceous	Sl
45 Chomonkoyo	34.32	131.57	Welded tuff	6	55	54	7.8	Cretaceous	Sl
46 Chomonkoyo	34.32	131.57	Welded tuff	15	64	73	6.8	Cretaceous	Sl
47 Niho-kamigo	34.23	131.58	Andesite	13	70	50	2.2	Cretaceous	Sl
48 Niho-kamigo	34.23	131.58	Welded tuff	9	49	63	10.3	Cretaceous	Sl
49 Ofuku	34.23	131.22	Red shale	23	43	46	7.0	Cretaceous	N
50 Okochi	34.23	131.12	Red shale	24	81	54	4.0	Cretaceous	N
51 Imozia	34.08	131.17	Red shale	15	50	46	4.0	Cretaceous	N
52 Misumi	34.37	131.25	Inkstone	14	11	71	7.0	Cretaceous	D
53 Mine	34.17	131.22	Inkstone	11	54	67	18.0	Cretaceous	D
54 Maqura	34.10	131.23	Andesite	26	48	63	5.0	Cretaceous	D
55 Yoshimi	34.07	130.92	Inkstone	13	27	61	15.0	Cretaceous	D
56 Ogori	34.10	131.38	Welded tuff	6	59	66	9.9	Cretaceous	Sl
57 Hikoshima	33.93	130.92	Andesite	16	45	50	7.2	Cretaceous	Sl
58 Hikoshima	33.93	130.92	Red shale	7	88	59	6.1	Cretaceous	Sl

D: DOMEN (1971). 13: ITO and TOKIEDA (1978). 16: ITO *et al.* (1982). K: KAWAI *et al.* (1971). N: NAGATA *et al.* (1959). Sl: SASAJIMA and SHIMADA (1966).

Table 6. Paleomagnetic data for Paleogene rocks in Southwest Honshu.

Locality	Latitude (°N)	Longitude (°E)	Rock type	N	Mean direction D(°) I(°)	α_{95} (°)	Age (Ma)	References
1 Asahi	36.90	137.60	Welded tuff	13	46 59	10.3	59	S2
2 Sabae	35.98	136.22	Rhyolite	10	33 50	6.3	Paleogene	S2
3 Tsuruga	35.60	136.12	Granodiorite	4	18 28	20.0	59	K
4 Tanigami	34.77	135.17	Welded tuff	8	65 55	11.2	Paleogene	S1
5 Tanigami	34.77	135.17	Rhyolite	11	40 50	10.4	Paleogene	S2
6 Aioi	34.82	134.47	Welded tuff	34	-134 -53	7.1	Paleogene	S1
7 Aioi	34.82	134.47	Rhyolite	46	-167 -61	3.4	Paleogene	S2
8 Ishigoshi	35.28	133.95	Granodiorite	10	-6 42	7.0	64	K
9 Kamisaibara	35.27	133.92	Granodiorite	4	-6 48	15.9	63	I1
10 Sangenya	35.27	133.82	Granodiorite	4	-152 -48	15.9	50	I1
11 Otani	35.15	133.07	Granodiorite	9	-150 -41	11.8	46	I1
12 Mitoya	35.32	132.90	Granodiorite	4	-122 -32	10.7	63	I1
13 Daito	35.28	132.98	Adamellite	5	-144 -50	7.5	51	
14 Asuna	34.87	132.62	Granodiorite	5	44 56	5.4	34, 40.3	
15 Kawachi	35.03	132.50	Andesite	5	-21 55	10.0	Oligocene	
16 Kirohara	35.00	132.52	Granodiorite	5	90 42	13.7	25	
17 Kawamoto	34.98	132.50	Granodiorite	5	32 61	4.3	25	
18 Kawakudari	34.97	132.47	Granodiorite	4	64 30	6.3	25	
19 Inbara	34.95	132.47	Granodiorite	5	50 51	4.2	25	
20 Kitani	34.97	132.47	Granodiorite	5	58 23	3.8	25	
21 Kitani	34.97	132.47	Granodiorite	4	-108 -18	14.1	25	
22 Obara	34.97	132.47	Granodiorite	5	-99 -41	10.5	25	
23 Mihara	34.98	132.42	Granodiorite	5	-131 -42	4.1	Paleogene	S2
24 Okami	34.77	131.90	Andesite	5	33 24	10.1	Paleogene	S2
25 Okami	34.77	131.90	Granodiorite	29	45 48	5.0	24, 29, 32, 36	S2
26 Okami	34.77	131.90	Granodiorite	10	51 63	14.7	24, 29, 32, 36	
27 Shimoozawa	34.60	131.71	Granite	12	13 54	7.5	39.3	
28 Katsurahira	34.57	131.73	Granodiorite	15	48 60	2.3	31.8	
29 Tanisako	34.57	131.64	Granite	12	48 61	3.3	39.3	
30 Tsuo	34.42	131.07	Andesite	10	45 63	4.5	Paleogene	S2
31 Imamisaki	34.42	131.13	Basalt	10	32 59	8.2	Paleogene	S2
32 Sakamoto	34.40	131.10	Andesite	8	31 56	13.1	Paleogene	S2

II: Ito and TOKIEDA (1972). K: KAWAI *et al.* (1971). S1: SASAJIMA and SHIMADA (1966). S2: SASAJIMA *et al.* (1968).

Fig. 2. Site mean directions of Southwest Honshu, northern Kyushu and South Korea. Solid circle indicates to be the lower hemisphere (positive inclination) and open circle to be the upper hemisphere (negative inclination). Cross mark is the present geomagnetic field direction at sampling area.

chiefly discussed in these papers. In general, local tectonic movements are considered to be produced by rotations about inclined axes, but rotation mechanisms about the inclined axes are difficult to relate to the paleomagnetic data. Two rotations about the vertical and horizontal axes are fortunately included, as particular cases, in rotations about the inclined axes. These particular cases are very important to elucidate tectonic movements, so that we consider only the two rotations about the vertical and horizontal axes in order to relate to the paleomagnetic data.

In Fig. 3, m_0 indicates an original direction of paleomagnetic vector for the normal polarity, and m'_0 indicates that for the reversed polarity. Fig. 3(A) shows that the original directions m_0 and m'_0 were rotated through angle δ about the vertical axis A to the present directions m and m' . In this case, the inclination of remanent vector is unchanged through rotation process, but the declination changes to angle δ . The bending hypothesis of the Japanese Islands by KAWAI *et al.* (1961) is based on the assumption that original paleomagnetic vectors changed their directions through tectonic rotations about the vertical axes.

On the other hand, rotations about the horizontal axes produce both declination and inclination anomalies in paleomagnetic vectors except an example of B_1 shown in Fig. 3(B). If original directions m_0 and m'_0 were rotated through angle δ about each of the horizontal axes B_1, B_2, B_3 and B_4 , or B'_1, B'_2, B'_3 and B'_4 , then present directions

Table 7. Paleomagnetic data for granitic rocks in northern Kyushu.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°)	I(°)	α_{95} (°)	Age (Ma)	References
1 Wakinoura	33.92	130.75	Granodiorite	14	7	-48	9.5	89	
2 Shikanoshima	33.68	130.30	Diorite	11	104	46	3.0	Cretaceous	
3 Shikanoshima	33.67	130.29	Diorite	14	76	56	5.3	Cretaceous	
4 Shikanoshima	33.66	130.30	Granodiorite	14	45	52	3.4	Cretaceous	
5 Kota	33.62	130.24	Granodiorite	12	44	73	7.1	80, 89, 90	
6 Kota	33.64	130.23	Granodiorite	13	84	63	5.9	80, 89, 90	
7 Sakurai	33.64	130.19	Granodiorite	11	87	26	5.9	80, 89, 90	
8 Nokita	33.60	130.16	Granodiorite	13	77	55	3.2	90	
9 Fukaehama	33.51	130.12	Granodiorite	17	40	79	10.5	89	

Table 8. Paleomagnetic data for Cretaceous rocks in South Korea.

Locality	Latitude (°N)	Longitude (°E)	Rock Type	N	Mean Direction D(°)	I(°)	α_{95} (°)	Age (Ma)	References
1 Chungju	36.93	127.93	Biotite granite	5	3	61	8.7	121	I4
2 Eumseong	36.87	127.63	Biotite granite	10	8	51	6.9	112	I4
3 Yeonpung	36.78	128.03	Biotite granite	5	-18	62	13.5	89, 90	I4
4 Daegu	35.95	128.73	Adamellite	5	29	62	11.1	73, 82	I4
5 Yangsan	35.30	129.08	Adamellite	10	8	51	10.0	71	I4
6 Masan	35.27	128.63	Granodiorite	10	-8	52	4.7	84.8, 104	I4
7 Pohang	36.20	129.30	Rhyolite	6	19	60	8.8	Cretaceous	KS
8 Shin-Lee	35.90	127.50	Andesite	8	15	46	10.0	Cretaceous	KS
9 Gyeongsan	35.80	128.70	Andesite	6	21	39	6.6	Cretaceous	KS
10 Anjong-dong	35.40	128.90	Dacite	9	43	62	11.4	Cretaceous	KS
11 Kimhae	35.20	128.80	Andesite	6	15	54	13.3	Cretaceous	KS
12 Yuchon	35.72	128.74	Andesite	22	21	58	19.4	Cretaceous	OT
13 Hagbong	35.89	129.03	Basalt	6	7	66	5.1	68.1	OT
14 Chilgog	35.17	128.16	Shale	27	28	59	1.9	Cretaceous	OT
15 Jinju	35.16	128.10	Sandstone	31	53	60	7.5	Cretaceous	OT
16 Hansandong	35.17	128.03	Sandstone	20	19	59	7.5	Cretaceous	OT

14: ITO and TOKIEDA (1980). KS: KIENZLE and SCHARON (1966). OT: OTOFUJI *et al.* (1982).

Fig. 3. Rotations about a vertical axis and horizontal axes. m_0 is the original paleomagnetic direction at the time of the normal field and m'_0 the original one at the time of the reversed field. (A) Rotation about a vertical axis. m and m' indicate magnetic directions after rotation about axis A . (B) Rotations about four horizontal axes: $B_1 = \text{NE } 0^\circ$, $B_2 = \text{NE } 30^\circ$, $B_3 = \text{NE } 60^\circ$, $B_4 = \text{NE } 90^\circ$. m_1, m_2, m_3 and m_4 indicate directions of the normal magnetization after rotations about horizontal axes B_1, B_2, B_3 and B_4 . m'_1, m'_2, m'_3 and m'_4 indicate directions of the reversed magnetization after rotations.

should be indicated by m_1 , m_2 , m_3 and m_4 , or m'_1 , m'_2 , m'_3 and m'_4 , respectively. Rotation about a horizontal axis indicates that the paleomagnetic vector moves on a small circle including both the original direction m_0 and the present direction m . The face of the small circle is always perpendicular to the horizontal axis.

It is not so easy to detect an original direction at sampling localities, so that the present geomagnetic field direction is usually used as indicating the original direction. We can find no other way than using the paleomagnetic pole estimated from the paleomagnetic data available for our purpose. If the original direction m_0 was determined by using the paleomagnetic pole, we can draw a small circle from both the original and present directions and detect an orientation perpendicular to the face of the small circle as the most probable rotational axis in the horizontal.

The Cretaceous paleomagnetic poles from Eurasia have fortunately been calculated by several workers (MCELHINNY, 1973; IRVING, 1977; ACHACHE *et al.*, 1983; TARLING, 1983). Many of the paleomagnetic poles from Eurasia appear to lie in a region near 70° N, 180° E, and the Cretaceous paleomagnetic poles estimated from North America is also located near the region (HARRISON and LINDH, 1982; TARLING, 1983). In this paper, we would use the paleomagnetic mean pole (lat. = 72.5° N, long. = 177.5° E) in the upper Cretaceous calculated by ACHACHE *et al.* (1983) as the Cretaceous paleomagnetic mean pole for Eurasia. This mean pole position for Eurasia is shown in Fig. 4. Virtual geomagnetic poles calculated from the area mean directions of NRM of the Japanese Cretaceous rocks are listed in Table 9 and also shown in Fig. 4. From the figure, it is clear that positions of their virtual poles are inconsistent with each other. It appears, however, that the poles are systematically situated along a great circle. The virtual pole for the South Korea is close to the paleomagnetic mean pole for Eurasia.

6. Discussion

Assuming that the geomagnetic pole in the upper Cretaceous had been located at 72.5° N, 177.5° E as described previously, the geomagnetic field directions at each sampling locality calculated by using the mean pole position. The geomagnetic field direction at 39.0° N, 141.5° E in Northeast Honshu is $D=16.6^\circ$, $I=68.8^\circ$, and that at 33.0° N, 133.5° E in Southwest Honshu is $D=17.6^\circ$, $I=64.5^\circ$, respectively. On the other hand, the present geomagnetic field directions at the same localities in the Northeast and Southwest Honshu blocks are $D=-7.5^\circ$, $I=53.0^\circ$ and $D=-6.7^\circ$, $I=48.3^\circ$, respectively.

In the Uetsu Province, it was impossible to find a significant area mean direction of the NRM for Cretaceous granitic rocks, because the scatter in NRM directions was very remarkable as seen in Fig. 1 and Table 2. However, between-site consistency in directions within a rock body was observed in several granite bodies. The scatter in site mean directions in this region is likely to show that more local and complicated tectonic movements than the southwestern part of Hokkaido or the Kitakami region was substantial. Such local movements are considered to have provided complicated and/or intensive tilting for individual granite bodies. From this unexpected paleomagnetic results of the Uetsu Province, it is thought that Northeast Honshu has not been uniformly bent as a single block relative to Southwest Honshu or the southwestern part of Hokkaido. Therefore, we concluded that Northeast Honshu has

Fig. 4. Virtual geomagnetic pole. Closed symbols indicate north-seeking pole and open symbols south-seeking pole. OH=Oshima Peninsula and Okushiri Island, KNN=normal sample of northern Kitakami, KNR=reversed sample of northern Kitakami, KS=southern Kitakami, A=Abukuma mountains, MN=normal sample of Cretaceous rocks in Southwest Honshu, MR=reversed sample of Cretaceous rocks in Southwest Honshu, TN=normal sample of Tertiary rocks in Southwest Honshu, TR=reversed sample of Tertiary rocks in Southwest Honshu, F=northern Kyushu, SK=South Korea, P=paleomagnetic mean pole for Eurasia calculated by ACHACHE *et al.* (1983).

undergone regional tectonic deformations without simple anti-clockwise rotation about the vertical axis. One of their regional deformations is rotation about the horizontal axis, i.e., tilting movement.

The area mean direction of NRM for granitic rocks in the Oshima Peninsula and Okushiri Island of Hokkaido was 30.0° in declination and 58.4° in inclination. From this area mean direction, the Oshima and Okushiri region should have been tilted toward the Japan Sea side, and its rotation axis and the amount of rotation are $B_1 = \text{NW } 34^\circ$, $\delta = 18^\circ$ as seen in Table 10. This rotation axis is likely to be parallel to "Old Trench" running through the nearly north-south trend along the west-side of the Hidaka mountains in Hokkaido, which has been expected from the free-air anomaly (TOMODA and SEGAWA, 1971). If tilting had been produced by lateral compression and it was downward, the direction of compressional stress would be perpendicular to

Table 9. Virtual geomagnetic poles for Hokkaido, Honshu, Kyushu and South Korea.

Area	Latitude (°N)	Longitude (°E)	N*	N	Mean Direction D(°)	I(°)	α_{95} (°)	Age (Ma)	Latitude (°N)	VGP Longitude (°E)	dp	dm
Oshima and Okushiri Is. (OH)	42.2	140.0	18	162	30.0	58.4	11.6	125-95	67.1	225.7	12.7	17.2
Uetsu	39.1	140.0	18	120	-	-	-	100-55	-	-	-	-
N. Kitakami (KNN)	40.0	141.5	8	71	-81.1	22.3	17.7	125-110	14.2	54.9	9.9	18.7
N. Kitakami (KNR)	40.2	141.2	2	12	105.3	-20.0	-	116-100	-18.3	229.6	-	-
S. Kitakami (KS)	39.0	141.5	31	441	-44.4	51.7	5.8	125-110	53.7	54.1	5.4	7.9
Abukuma (A)	37.5	140.5	8	94	-31.9	54.6	8.5	100-90	64.3	55.3	8.5	12.0
SW. Honshu (MN)	35.0	133.5	48	597	50.2	60.5	4.1	100-65	50.6	198.5	4.8	6.2
SW. Honshu (MR)	35.0	133.5	10	115	-114.8	-55.8	9.9	100-65	-38.1	21.9	10.2	14.2
SW. Honshu (TN)	35.0	133.5	23	205	37.6	52.3	7.8	64-25	58.9	216.2	7.4	10.7
SW. Honshu (TR)	35.0	133.5	9	116	-131.4	-44.8	12.9	64-25	-47.7	40.2	10.3	16.3
N. Kyushu (F)	33.6	130.2	8	119	75.6	58.1	14.1	90-80	30.6	191.5	15.4	20.8
South Korea (SK)	36.0	128.5	16	186	16.0	57.4	5.3	120-70	77.1	205.1	5.7	7.8

N*: Number of sites.
N: Number of samples.
 α_{95} : Semi-angle of cone of 95 percent confidence.
dp: $I/2(1+3\cos^2 p)\alpha_{95}$.
dm: $\alpha_{95}\sin p/\cos I$.

Table 10. Orientations of horizontal axes and rotation angles.

	λ ($^{\circ}$ N)	λ_0 ($^{\circ}$)	B	H ($^{\circ}$)	δ ($^{\circ}$)
Oshima and Okushiri Is. (OH)	42.2	54.8	B_1	-34	18
N. Kitakami (KNN)	40.0	53.1	B_2	-11	77
N. Kitakami (KNR)	40.0	-	B_2'	(-6)	77
S. Kitakami (KS)	39.0	52.2	B_3	13	35
Abukuma (A)	37.5	50.5	B_4	22	29
SW. Honshu (MN)	35.0	46.4	B_5	18	19
SW. Honshu (MR)	35.0	-	B_5'	(24)	26
N. Kyushu (F)	33.6	44.6	B_6	36	29
S. Korea (SK)	36.0	46.0	-	-	-

λ : Present latitude of sampling locations.

λ_0 : Paleolatitude of sampling locations based on Cretaceous mean pole (72.5°N, 177°E) for Eurasia (ACHACHE *et al.*, 1983).

B: Horizontal axis.

H: Orientation of horizontal axis.

δ : Rotation angle.

each rotation axis. If so, stress appears to have acted toward the east from the Japan Sea side in this region.

In case of the Kitakami and Abukuma belts, the area mean directions for the northern Kitakami and southern Kitakami blocks were $D=-81.1^{\circ}$, $I=22.3^{\circ}$ and $D=-44.4^{\circ}$, $I=51.7^{\circ}$, respectively, and the area mean for the Abukuma block was $D=-31.9^{\circ}$, $I=54.6^{\circ}$. The paleomagnetic data indicate that these blocks have tilted toward the Pacific Ocean side. The orientation of rotation axis B_2 in the northern Kitakami block is NW 11° and B_3 in the southern Kitakami block NE 13° (Table 10). The rotation axis in the northern Kitakami block seems to us to be partially dependent on "Old Trench" by TOMODA and SEGAWA (1971), because the tilting axis is rather parallel to "Old Trench" than the Japan Trench. From the area mean direction for the Abukuma belt, the Abukuma block is thought to have also tilted toward the Pacific Ocean side under circumstances similar to the southern Kitakami block. The orientation of the rotation axis B_4 is NE 22° in the horizontal.

The amounts of tilting in the northern Kitakami, southern Kitakami and Abukuma regions are about 77° , 35° and 29° , respectively. It should be noted that the value of the northern Kitakami block is distinctive as compared with two others. This suggests that the northern Kitakami block has undergone more intensive deformations than the southern Kitakami or Abukuma block. The northern Kitakami block may indicate to have been under the influence of "Old Trench". On the contrary, the southern Kitakami and Abukuma blocks are likely to have been affected only by the formation of the Japan Trench. Thus, if tilting deformations have taken place in Northeast Honshu and the southwestern part of Hokkaido, we can assume a tectonic line parallel to the tilting axes, which runs through the nearly north-south trend. This

Fig. 5. Rotations about horizontal axes. B_1, B_2, B_3, B_4, B_5 and B_6 are horizontal axes for normal magnetizations of OH, KNN, KS, A, MN and F. B'_1 and B'_2 are horizontal axes for the reversed magnetizations of KNR and MR. Square is the geomagnetic field direction calculated from the Cretaceous mean pole (72.5°N, 177.5°E).

Fig. 6. Directions of horizontal axes and compressional stress. Arrow indicates the area mean direction of NRM and dotted line the direction of horizontal axis. Blank arrow indicates the direction of stress taken perpendicular to the horizontal axis.

hypothetical tectonic line is nearly parallel to the volcanic front of the Quaternary proposed by SUGIMURA (1960).

In Southwest Honshu, the stable directions of NRM represent almost uniform orientation seemingly, as shown in Fig. 2. The existence of many reversed polarities which are approximately antiparallel to the normal ones indicates positively that Southwest Honshu, as a whole, was subjected to substantially similar tectonic deformations. In this case, the rotation axis B_5 in Southwest Honshu is the orientation of NE 18° in the horizontal, and B'_5 is SW 24° (Fig. 5(B)). Southwest Honshu is to have tilted westward as shown in Figs. 5 and 6, and the amount of tilting is estimated to be about 19° (Table 10). It is unlikely, however, that Southwest Honshu has uniformly tilted westward as a single block. A possibility is that Southwest Honshu had tilted as numerous small blocks which were divided by tectonic lines or faults. It is expected, of course, that there occurred regional vertical movements without rotational deformations in addition to simple tilting deformations of the small blocks.

The paleomagnetic data of the Cretaceous granitic rocks belonging to the Ryoke belt in the Inner Zone of Southwest Japan have been reported by NISHIYAMA *et al.* (1984). According to their result, the NRM directions of the granitic rocks exposed in the Takanawa Peninsula, Ehime Prefecture, Shikoku, are slightly northeasterly, but the NRM directions are obviously inconsistent with those of the Cretaceous rocks in the Chugoku Province. The difference in NRM directions between the Ryoke belt and

the northern zone in the Chugoku Province suggests that the southern zone in the Chugoku region has undergone dissimilar tectonic deformations to the northern zone.

The area mean direction for granitic rocks in the northern Kyushu region was 75.6° in declination and 58.1° in inclination and it is similar to that of Southwest Honshu. The orientation of the rotation axis B_6 is taken NE 36° and the amount of tilting is about 29° (Table 10). The tilting is westward in the same sense with Southwest Honshu. In these cases, the amount of tilting is simply given by an angle between the reference field and present NRM directions.

The horizontal axes for the individual regions can be drawn as shown in Fig. 6, on the assumption that rotations about the horizontal axes were predominant in the Japanese Islands since the Cretaceous. If such tilting deformations of the Japanese Islands had been produced by lateral compression which may be caused by plate movements, the directions of compressional stress would be perpendicular to each rotation axis. However, there remains a possibility of tilting deformations caused by positive vertical movements (upheaval) of the crust. It is impossible, for the present, to determine whether tilting deformations of the Japanese Islands were produced by lateral compression or by positive vertical movements of the crust.

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