Quaternary Paleomagnetic Studies in Japan¹⁾

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Various geomagnetic phenomena have been revealed by paleomagnetic and archeomagnetic studies on the Japanese Quaternary. Archeo-secular variations of the geomagnetic field in Japan are clarified for the past 2,000 years. Fairly big local gradients in the geomagnetic direction are found within Japan.

Studies on tephra layers and marine and lake sediments, revealed that several geomagnetic events or excursions occurred during the Brunhes normal polarity epoch. These events and excursions will provide very good time markers to correlate with the middle and late Quaternary strata.

Age of paleo-earthquakes can be determined by using remanent direction of sediments squeezed out by ancient earthquakes, because their magnetization recorded the geomagnetic field at the time when the earthquakes occurred.

I. Introduction

There are various time constants in the variation of the earth's geomagnetic field. The geomagnetic phenomena which are the main targets of paleomagnetic research on the Quaternary are the secular variations in direction and intensity of the geomagnetic field, the geomagnetic excursions and the geomagnetic reversals. Various paleomagnetic approaches have been carried out to clarify these geomagnetic phenomena as recorded in the Japanese Quaternary system.

The first is the archeomagnetic approach. For archeological and historic times, geomagnetic secular variation has been investigated by measuring the directions of thermoremanent magnetization (TRM) of ancient baked clays which have been preserved in archeological sites. Such a paleomagnetic study using the archeological objects and remains is called archeomagnetism.

The second approach uses sediments. The past geomagnetic field direction is recorded in sedimentary strata. Tiny magnetic grains contained in the sediments aligned their magnetic moments parallel to the ambient geomagnetic field at the time of deposition, so that the

sediments have remanence which is defined as detrital remanent magnetization (DRM). Marine and lake sediments with high sedimentation rates are suitable for the study of secular variation in the geomagnetic field direction because they not only give a high resolution but also provide a continuous time series record.

The third approach is the study of tephra layers. Tephra sediments are strongly magnetized as compared with the ordinary sediments because of the high magnetic mineral content. There are many tephra layers which are widely distributed in the Japanese Islands. Some of the late Pleistocene tephra layers are well dated and correlated with each other. Air fall tephra layers have magnetic remanence which was acquired just after their deposition. Fine magnetic grains in the tephra rotated, so as to orient their magnetic moments parallel to the ambient geomagnetic field, when rain water percolated through the loosely bedded tephra layers.

The fourth approach is the study of volcanic rocks. Thermoremanent magnetization of volcanic lava flows and bombs is very stable, which enables us not only to clarify the

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Fig. 1 Archeo-secular variation curves obtained in Japan

1. HIROOKA (1971), 2. WATANABE (1977), 3. WATANABE (1959), 4. KAWAI *et al.* (1965b), 5. YUKUTAKE *et al.* (1964), 6. MOMOSE *et al.* (1964), 7. SHIBUYA (1980)

directional changes of the geomagnetic field, but also to estimate the past geomagnetic field intensity. Volcanic rocks have often been used to make up for deficiencies in paleomagnetic and archeomagnetic studies of sediments or archeological materials.

II. Archeomagnetism

Studies of the secular variation of the Japanese geomagnetic field direction have been carried out by many workers, such as WATANABE (1959, 1977), MOMOSE *et al.* (1964), YUKUTAKE *et al.* (1964), KAWAI *et al.* (1965b), HIROOKA (1971) and SHIBUYA (1980). Secular variation curves of declination and inclination obtained in Japan are summarized in Fig. 1. All except one were obtained from measurements of archeological baked clays. The only exception is the data on the volcanic lava flows of Mt. Mihara in Oshima Island (YUKUTAKE *et al.*, 1964). A complete secular

variation record for the last 2,000 years is obtained from the measurements of thermoremanent magnetization of archeological baked clays, such as old kilns and hearths in southwestern Japan (HIROOKA, 1971, 1977a, 1983). According to the curve, the geomagnetic declination variation ranges from 17°W to 14°E, and the inclination variation from 35° up to 60° as seen in Fig. 2. It is now possible to date archeological sites of unknown age by using this secular variation curve when baked clays remain untouched in the archeological sites.

The results of spherical harmonic analyses of the instrumental records of the geomagnetic field for the periods of 1905 ~ 1945 (VESTINE *et al.*, 1947) and 1907 ~ 1945 (BULLARD *et al.*, 1950) show no movement of the main dipole component. Most researchers, therefore, believe that geomagnetic secular variation originated not from dipole wobbling but from the westward drift of the non-

Fig. 2 Geomagnetic secular variation in southwestern Japan for the last 2,000 years

(after HIROOKA, 1977)

dipole components. An hypothesis on dipole axis wobbling was proposed after analysis of the global archeomagnetic data so far obtained. KAWAI *et al.* (1965a) compared the virtual geomagnetic pole (VGP) positions indicated by archeomagnetic results from Arizona, England and Japan for 900 AD, 1300 AD and 1500 AD, and found that the three indicated pole locations at each time cluster together at locations that are very distant from the present magnetic pole position. The VGP position is calculated on the assumption that the geomagnetic field consists only of the dipole. Consequently, the agreement in pole locations between the three data sets indicates that the main dipole axis inclined in other directions in the past, and has been wobbling. KAWAI and his colleagues (KAWAI and HIROOKA, 1967; KAWAI *et al.*, 1967) concluded from these results that the main geomagnetic dipole axis is wobbling counterclockwise with a period of 1,500 years. Whether such a short period of wobble for the geomagnetic dipole axis really exists or not is still a bone of contention.

As archeomagnetic data accumulates, the regional difference in the geomagnetic field direction is recognized as being much greater than that estimated from the present field

Fig. 3 Secular variation in paleointensity in Japan

(after SAKAI and HIROOKA, 1986)

distribution. For example, HIROOKA (1989) suggested that the declination in the 17th Century AD differed by 5° between the northern part of the Kyushu District in western Japan and the Kanto District in central Japan, in spite of both districts being located in almost the same latitude. Such a large local gradient in the geomagnetic field in East Asia seems to be caused by a predominantly non-dipole anomaly called the "Mongolian Anomaly" which has been at the same location, without drifting, since 300 years ago (YUKUTAKE and TACHINAKA, 1969).

The intensity of the geomagnetic field also undergoes a secular variation. The TRM intensity of ancient baked clays such as pottery, bricks and roof tiles, is proportional to both the geomagnetic field intensity in ancient times, when the clays were baked, and the amount of magnetic mineral contained in them. We can therefore estimate the intensity of the ancient geomagnetic field by comparing the natural remanent magnetization (NRM) intensity of the archeological objects with the TRM intensity that is artificially given to them in the laboratory. The estimated intensity of the past geomagnetic field is called the "paleointensity".

Paleointensity studies in Japan were carried out by NAGATA *et al.* (1963), SASAJIMA and MAENAKA (1966), KITAZAWA (1970), TANAKA (1980, 1982), and SAKAI and HIROOKA (1986). The results of TANAKA (1980, 1982) were obtained by studying volcanic rocks.

Fig. 4 Holocene paleomagnetic orientations observed in Japan

(after HIROOKA and SAKAI, 1984)

As the paleointensity variation is considered to have originated mainly in the change of the main dipole moment, the paleointensity results can be compared globally to clarify the history of variation of the geomagnetic dipole moment. Fig. 3 shows the paleointensity variation in Japan as compiled by SAKAI and HIROOKA (1986). It is very clear that the intensity of the geomagnetic field was low in period between 7,000 and 5,000 years BP, and a high peak is seen at about 1,800 years BP.

III. Paleomagnetism of lake and marine sediments

The oldest archeomagnetic datum is reported by HIROOKA and TOKIEDA (1979) from Sempukuji, a prehistoric cave site, in Nagasaki Prefecture. A Ryusenmon type potsherd from the very beginning of the Jomon Period was excavated. In the same horizon was found a baked sandstone which was a part of a hearth. The sandstone has a very stable TRM direction. Three thermoluminescent ages for the hearthstone are $12,170 \pm 1,170$, $11,980 \pm 280$ and $11,370 \pm 760$ years BP (ICHIKAWA and HAGIWARA, 1978).

Furthermore samples are collected from 6 horizons of sedimentary strata overlying the hearth. The magnetic data cover the period between 11,800 to 1,000 years BP.

Studies of DRM of the submarine sediments of the Osaka Bay extended the geomagnetic secular variation curves to an older age. MUROI and YASKAWA (1977) collected oriented samples from 43 horizons in a sub-bottom hole that was dug for the construction of a bridge. A boring core of 7 m length penetrated the bottom of the Osaka Bay. Continuous sampling at 3 cm intervals was carried out on this core (HYODO and YASKAWA, 1980; HYODO *et al.*, 1985). Paleomagnetic results of the Osaka Bay samples revealed the geomagnetic secular variation back to 5,000 years BP.

HIROOKA and SAKAI (1984) collected oriented samples of Holocene sediments from 12 horizons on the wall of a trench which was excavated to investigate the past earthquake activity of the Atotsugawa Fault (EXCAVATION RESEARCH GROUP OF THE ATOTSUGAWA FAULT, 1983; OKADA, 1986). The secular change obtained from paleomagnetic measurements covers the age range of 12,000 to

Fig. 5 Changes in inclination and intensity in the upper 60 m of a 200 m core from Lake Biwa

(after KAWAI *et al.*, 1975)

5,000 years BP. The Holocene paleomagnetic results so far reported in Japan are compiled by HIROOKA and SAKAI (1984) as shown in Fig. 4.

A 200 m boring core was taken from Lake Biwa in 1971 (HORIE, 1973). 2 cm×2 cm×2 cm paleomagnetic specimens were collected continuously through the core from the top to the bottom. KAWAI *et al.* (1972) made reconnaissance measurements on the specimens at 5 m intervals, and found anomalous magnetic directions at 5 horizons of 13 m, 50~55 m, 80.5~85 m, 130~132.5 m and 155~160 m in depth. Two more anomalous horizons at 25 m and 33~35 m were found by a later precise measurement. The sedimentation rate was calculated by YASKAWA (1973) based on the compaction rate of sediments, radiometric ages of ^{14}C , and fission-track methods, and the age of the Blake Event (SMITH and FOSTER, 1969). According to the calculated sedimentation rate,

the age of the core bottom is about 500 thousand years (ka) BP. Ages of the 7 horizons showing anomalous directions are estimated to be 18, 49, 60~80, 110, 170, 290 and 380 ka BP. The 110 ka event is correlated to the Blake Event. In Fig. 5 are plotted the inclination and intensity of all the specimens against their subbottom depth for the upper 60 m (KAWAI *et al.*, 1975). Newly found 170, 290 and 380 ka events are named the Biwa I, II and III Events respectively. Although these are named "Events", they should be called geomagnetic "excursions" because the paleomagnetic directions during these "Events" do not stay reversed but oscillate with very short periods. Recently, KAWAI (1984) revised the respective ages of the Biwa I, II and III Events to 160, 310 and 380 ka.

IV. Paleomagnetism of tephra sediments

The middle to late Pleistocene time is the most

difficult period to do precise age determination for. This fact makes it difficult for us to clarify the authentic geomagnetic variation in this period.

Tephra layers provide very good material for the paleomagnetic study of the middle to late Pleistocene because not only are they strongly magnetized, but also many of them are very well correlated with each other. Few researchers, however, carried out studies on such tephra layers. It was HIROOKA *et al.* (1977a) who first reported paleomagnetic results for tephra layers. They measured tephra layers of the so-called "Kanto Loam", and proved that the remanent magnetization of tephra is so stable that we can trace even small geomagnetic secular variations.

Paleomagnetic results for the Ontake Tephra layers in Ina City, Central Japan, show two anomalous directions during the last 100 ka (HIROOKA *et al.*, 1977b, 1978). The ages of these anomalous geomagnetic field directions are about 80~70 ka and 60~50 ka BP. Since they do not undergo complete reversals, they are assumed to be not geomagnetic events but geomagnetic excursions. HIROOKA *et al.* (1978) proposed to name the younger and older ones the Ina I and II Excursions respectively. Similar records of excursions are observed in tephra layers of the same age, such as the tephra layers in Shimane Prefecture whose origins are Mt. Sambe and Mt. Daisen (HIROOKA *et al.*, 1982), the Omachi Tephra in Omachi City (HIROOKA *et al.*, 1988), tephra layers distributed on the eastern flank of Mt. Yatsugakate (AIDA, 1978), and tephra layer in Tokachi, Hokkaido (HIROOKA *et al.*, 1988). The younger excursion is found not only in tephra layers but also in the coastal sand dune sediments of the late Pleistocene (HIROOKA, 1977b). This excursion might be correlated with the 49 ka event found in Lake Biwa sediments (YASKAWA *et al.*, 1973).

In Fig. 6 are shown the reported virtual geomagnetic pole (VGP) paths corresponding to the Ina I and II Excursions. It is found that all these VGP paths show strikingly similar features in spite of their remote locations.

Reversals which correlated to the Blake Event are found on the northern coast of Fukui Prefecture, central Japan (NAKAJIMA and MIURA,

1983) and in the Tsukahara Formation, Fukushima Prefecture (MANABE, 1980a). MANABE (1988) reported from the study of sedimentary formations in Fukushima and Yamagata Prefectures, that the anomalous directions occurred three times between 35 to 80 ka.

All these excursions are reviewed by HIROOKA *et al.* (1988) and NAKAJIMA (1988). Although some disagreements still remain about the ages of the excursions seen in Japan, these will provide very good time markers or key beds for the middle and late Pleistocene when they are correlated with each other and their chronology is established.

By using the geomagnetic reversals many good magnetostratigraphic studies of early to middle Pleistocene formations such as the Osaka, the Kobiwako and the Tokai Groups (ISHIDA *et al.*, 1969; MAENAKA *et al.*, 1977; MAENAKA, 1983), the Quaternary formations in the Boso Peninsula (NITSUMA, 1976) and the Yamato and the Sendai Groups (MANABE, 1979, 1980b) have been carried out. These studies contributed greatly to correlating formations of the Japanese Quaternary System.

V. Paleomagnetic applications in Quaternary research

It is often observed at the time of earthquakes that sediments are squeezed out from underground layers up to the ground surface along a fault plane. SAKAI and HIROOKA (1983) found that such sediments were remagnetized in the direction of the ambient geomagnetic field at the time when the earthquake occurred.

There is an historical document which described a disaster in an area near the Atotsugawa Fault which was brought about by an earthquake in 1858 AD. According to the disaster damage pattern, it is assumed that the earthquake was resulted from movement of the Atotsugawa Fault. In 1982, a trench excavation was carried out across the Atotsugawa Fault to investigate its past activities. In the side walls of the trench, a silt layer of 3 m depth is distorted near the fault and thrust up along the fault plane. Directions of magnetization in the most distorted part of the silt layer, however, are convergent on a direction close to that of the

Fig. 6. Virtual geomagnetic pole (VGP) paths seen in Japanese late Pleistocene sediments, corresponding to the Ina I and II Excursions

A : Tephra from Mt. Daisen and Mt. Sambe in Shimane Prefecture (after HIROOKA *et al.*, 1982), B : The 49 ka sediments of Lake Biwa (after YASKAWA *et al.*, 1973), C : Coastal sand dune sediments in Fukui Prefecture (after HIROOKA, 1977), D : The Ontake Tephra at Ina, Nagano Prefecture (after HIROOKA *et al.*, 1978), E : The Omachi Tephra at Omachi, Nagano Prefecture (after HIROOKA *et al.*, 1988), F : The tephra at Tokachi, Hokkaido (after HIROOKA *et al.*, 1988)

present geomagnetic field. The magnetization is considered to have been acquired at the time of or a little after, the distortion of the layer. When we look at the direction of magnetization more closely and compare it with the archeosecular variation curve, the remanent orientation corresponds to the direction of the geomagnetic field at 1880 ± 60 AD. This age coincides with the age of the 1858 earthquake. TAKEUCHI and SAKAI (1985) observed the same direction in samples collected at different places along the fault. Such sediments reset their magnetization in the direction of the geomagnetic field, by a special composite mechanism of DRM and SRM (shock remanent magnetization), when the earthquake occurred. In cases like this, the age of paleo-earthquakes can be determined by comparing the magnetic direction of distorted or squeezed out sediments with the archeosecular variation curve (HIROOKA, 1971) as long as the earthquakes are assumed to have occurred within the past 2,000 years.

Recently, stone implements which are assumed to be of early paleolithic age were found at sites in the Tohoku District (OKAMURA, 1986). Dating by fission-track and thermoluminescence methods was carried out to determine the age of horizons where paleoliths were preserved. At the Babadan A Site, a magneto-stratigraphic study was applied together with fission-track and thermoluminescence dating. According to the age estimated from tephrochronology the Ina I and II Excursions, Blake Event, and Biwa I Event may be expected in some horizons in the vertical section, where soil layers divide into 30 strata. Paleomagnetic samples were taken from all of the layers. Finally, three layers were found showing anomalous magnetization orientations, at Stratum 22 and Substrata 23a and 29c (HIROOKA and KITA, 1986; HIROOKA and TERASAKI, 1988). From both the VGP characteristics and radiometric ages, the upper two and the lower layers are assumed to be 110 ka (Blake Event) and 160 ka (Biwa I Event) respectively.

A similar attempt was made on the Nishiyagi Coast, Hyogo Prefecture. This is a famous place, where a fossil bone of "Akashi Man" was found. HARUNARI (1987) carried out an excavation at the site in an attempt to find other fossil

bones, or any indication of human activities. He found no fossil bone, but obtained a wooden artifact on which artificial carving is seen. A magnetostratigraphic study of the Nishiyagi Formation was performed, at the excavated section. The anomalous direction of magnetization indicates that Layer IV at the excavation site (ITIHARA and INADA, 1987) corresponds to the Ina I Excursion (HIROOKA and YUDA, 1987).

Records of the VGP paths, during events and excursions of the Japanese geomagnetic field, will greatly ease estimation of the age of geologic formations and paleolithic archeological sites.

References

- AIDA, N. (1978) Natural remanent magnetizations and ferromagnetic minerals of the Late Pleistocene volcanic ash ("Younger Loam") of the Yatsugatake Volcanoes, Central Japan. *The Quaternary Research (Daiyonki-Kenkyu)*, **16**, p. 86-94. (in Japanese)
- BULLARD, E. C., FREEDMAN, C., GELLMAN, H. and NIXON, J. (1950) The westward drift of the earth's magnetic field. *Phil. Trans. Roy. Soc. London, A*, **243**, p. 67-92.
- EXCAVATION RESEARCH GROUP OF THE ATOTSUGAWA FAULT (1983) Trench excavation research at Atotsugawa Fault (A short report). *Gekkan Chikyū (The Earth Monthly)*, **5**, p. 335-340. (in Japanese)
- HARUNARI, H. (1987) The significance of the investigations of the Nishiyagi Coast. *Bull. National Museum of Japanese History*, **13**, p. 291-304. (in Japanese with English abstract)
- HIROOKA, K. (1971) Archaeomagnetic study for the past 2,000 years in southwest Japan. *Mem. Fac. Sci., Kyoto Univ.*, Ser. Geol. Mineral., **38**, p. 167-207.
- HIROOKA, K. (1977a) Recent trend in archaeomagnetic and palaeomagnetic studies in Quaternary research. *The Quaternary Research (Daiyonki-Kenkyu)*, **15**, p. 200-203. (in Japanese)
- HIROOKA, K. (1977b) On the possibility of palaeomagnetic study of coastal sand dune sediments. *Paleolimnology of Lake Biwa and Japanese Pleistocene*, **5**, p. 102-106.
- HIROOKA, K. (1983) Archaeomagnetism of baked clays, results from Japan. in K. M. CREER, P. TUCHOLKA and C. E. BARTON (eds.): *Geomagnetism of baked clays and recent sediments*. Elsevier, Amsterdam, p. 150-157.
- HIROOKA, K. (1989) Scientific investigation of the archeological remains of ancient handicraft production in Hokuriku District. in RESEARCH GROUP OF HISTORY OF ANCIENT HOKURIKU HANDICRAFT PRODUCTION (ed.): *Ancient handicraft production in Hokuriku District*. Shin-yo-sha, Kyoto, p. 255-284. (in

- Japanese)
- HIROOKA, K., SAKAI, Y. and YOKOYAMA, T. (1977a) Paleomagnetic study of "Kanto Loam", the late Pleistocene volcanic sediments. *Rock Magnetism and Paleogeophysics*, **4**, p. 88-94.
- HIROOKA, K., TOBITA, C., YOKOYAMA, T. and NAKAYA, S. (1977b) On the excursion of the latest Pleistocene recorded in Ontake Tephra, Ina, Central Japan. *Rock Magnetism and Paleogeophysics*, **4**, p. 81-87.
- HIROOKA, K., HASEGAWA, E., HIROTA, T., NAKAYA, S. and YOKOYAMA, T. (1978) On the geomagnetic excursions in the late Pleistocene found in Ontake Tephra, Ina, Central Japan. *Paleolimnology of Lake Biwa and Japanese Pleistocene*, **6**, p. 101-114.
- HIROOKA, K. and TOKIEDA, K. (1979) Archaeomagnetic results of Sempukuji Remains, the cave site, and the Holocene paleosecular variation in Japan. *Rock Magnetism and Paleogeophysics*, **6**, p. 18-24.
- HIROOKA, K., NAGAI, N. and NAKAJIMA, T. (1982) Geomagnetic excursions of the late Pleistocene inferred from Palaeomagnetic study of tephra sediments in Japan. *Paleolimnology of Lake Biwa and Japanese Pleistocene*, **10**, p. 200-213.
- HIROOKA, K. and SAKAI, H. (1984) Geomagnetic secular variation in prehistoric time. in THE EDITORIAL COMMITTEE OF KOBUNKAZAI (ed.): *Scientific approaches to the study of cultural property*. Dohosha, Kyoto, p. 812-816. (in Japanese)
- HIROOKA, K. and KITA, J. (1986) Magnetostratigraphy of Babadan A Site. in TOHOKU HISTORIC MUSEUM (ed.): *Babadan A Site, I*, p. 139-145. (in Japanese with English abstract)
- HIROOKA, K. and YUDA, O. (1987) Paleomagnetic age of the Nishiyagi Formation in Akashi. *Bull. National Museum of Japanese History*, **13**, p. 163-175. (in Japanese with English abstract)
- HIROOKA, K. and TERASAKI, N. (1988) Magnetostratigraphic study of Strata 18-23, 29-31a in the Babadan A Site. in TOHOKU HISTORIC MUSEUM (ed.): *Babadan A Site, II, —Research of Japanese earlier Palaeolithic age—*, p. 70-76. (in Japanese with English abstract)
- HIROOKA, K., NAGAI, N. and ISHIHARA, A. (1988) Paleomagnetic dating in the middle and late Pleistocene. *Mem. Geol. Soc. Japan*, No. 29, p. 295-304. (in Japanese with English abstract)
- HORIE, S. (1973) An outline of the paleolimnological works of Lake Biwa-ko, Japan. *Japanese Jour. Limnol.*, **34**, p. 49-54. (in Japanese with English abstract)
- HYODO, M. and YASKAWA, K. (1980) Geomagnetic secular variation in the stable magnetic remanence of the young sediments collected from Osaka Bay. *Jour. Geomag. Geoelectr.*, **32**, p. 581-584.
- HYODO, M., MORINAGA, H., NISHIMURA, H., INOKUCHI, H. and YASKAWA, K. (1985) Paleomagnetism of a core from Osaka Bay. *Jour. Geomag. Geoelectr.*, **37**, p. 729-737.
- ICHIKAWA, Y. and HAGIWARA, N. (1978) Thermoluminescence dating of burnt stone and burnt soil. *Kokogaku to Sizenkagaku (Archaeology and Natural science)*, **11**, p. 1-7. (in Japanese with English abstract)
- ISHIDA, S., MAENAKA, K. and YOKOYAMA, T. (1969) Paleomagnetic chronology of volcanic ash of the Plio-Pleistocene series in Kinki District, Japan —The research of younger Cenozoic strata in Kinki District, Part 12—. *Jour. Geol. Soc. Japan*, **75**, p. 183-197.
- ITIHARA, M. and INADA, T. (1987) Geology of the Nishiyagi Coast. *National Museum of Japanese History*, **13**, p. 45-54. (in Japanese with English abstract)
- KAWAI, N. (1984) Paleomagnetic study of the Lake Biwa sediments. in S. HORIE and W. JUNK (eds.): *Lake Biwa*. Dordrecht, Netherlands, p. 399-416.
- KAWAI, N., HIROOKA, K. and SASAJIMA, S. (1965a) Counterclockwise rotation of the geomagnetic dipole axis revealed in the world-wide archaeo-secular variations. *Proc. Japan Acad.*, **41**, p. 398-403.
- KAWAI, N., HIROOKA, K., SASAJIMA, S., YASKAWA, K., ITO, H. and KUME, S. (1965b) Archaeomagnetic studies in southwestern Japan. *Ann. Geophys.*, **21**, p. 574-577.
- KAWAI, N. and HIROOKA, K. (1967) Wobbling motion of the geomagnetic dipole field in historic time during these 2000 years. *Jour. Geomag. Geoelectr.*, **19**, p. 217-227.
- KAWAI, N., HIROOKA, K. and TOKIEDA, K. (1967) A vibration of geomagnetic axis around the geographic north pole in the historic time. *Earth Planet. Sci. Lett.*, **3**, p. 48-50.
- KAWAI, N., YASKAWA, K., NAKAJIMA, T., TORII, M. and HORIE, S. (1972) Oscillating geomagnetic field with a recurring reversal discovered from Lake Biwa. *Proc. Japan Acad.*, **48**, p. 186-190.
- KAWAI, N., YASKAWA, K., NAKAJIMA, T., TORII, M. and NATSUHARA, N. (1975) Voice of geomagnetism from Lake Biwa. *Paleolimnology of Lake Biwa and Japanese Pleistocene*, **3**, p. 143-160.
- KITAZAWA, K. (1970) Intensity of the geomagnetic field in Japan for the past 10,000 years. *Jour. Geophys. Res.*, **75**, p. 7403-7411.
- MAENAKA, K. (1983) Magnetostratigraphic study on the Osaka Group, with special reference to the existence of pre- and post- Jaramillo episodes in the late Matuyama polarity epoch. *Mem. Hanazono Univ.*, **14**, p. 1-65.
- MAENAKA, K., YOKOYAMA, T. and ISHIDA, S. (1977) Pa-

- leomagnetic stratigraphy and biostratigraphy of the Plio-Pleistocene in the Kinki District, Japan. *Quaternary Res.*, **7**, p. 341-362.
- MANABE, K. (1979) Magnetostratigraphy of the Yamato Group and Sendai Group, northeast Honshu, Japan (I). *Sci. Rep. Fukushima Univ.*, **29**, 51-65.
- MANABE, K. (1980a) Magnetostratigraphy and Middle Pleistocene chronology. *The Quaternary Research (Daiyonki-Kenkyu)*, **19**, p. 225-232. (in Japanese with English abstract)
- MANABE, K. (1980b) Magnetostratigraphy of the Yamato Group and the Sendai Group, northeast Honshu, Japan (II). *Sci. Rep. Fukushima Univ.*, **30**, p. 49-71.
- MANABE, K. (1988) Geomagnetic variation during the last glacial age. *Mem. Geol. Soc. Japan*, No. 29, p. 269-280. (in Japanese with English abstract)
- MOMOSE, K., KOBAYASHI, K., TSUBOI, K. and TANAKA, M. (1964) Archaeomagnetism during the old tomb and the Nara Periods. *1964 Annual Progress Report of the Rock Magnetism Research Group in Japan*, p. 33-38.
- MUROI, I. and YASKAWA, K. (1977) Palaeomagnetism of Osaka Bay sediments. *Rock Magnetism and Paleogeophysics*, **4**, p. 76-80.
- NAGATA, T., ARAI, Y. and MOMOSE, K. (1963) Secular variation of the geomagnetic total force during the last 5,000 years. *Jour. Geophys. Res.*, **68**, p. 5277-5281.
- NAKAJIMA, T. (1988) Reversals and excursions of the geomagnetic field. *Mem. Geol. Soc. Japan*, No. 29, p. 281-294. (in Japanese with English abstract)
- NAKAJIMA, T. and MIURA, S. (1983) Blake polarity event found in the Hamaji volcanic ash layer in Fukui Prefecture. *The Quaternary Research (Daiyonki-Kenkyu)*, **22**, p. 97-101. (in Japanese)
- NITSUMA, N. (1976) Magnetic stratigraphy in the Boso Peninsula. *Jour. Geol. Soc. Japan*, **82**, p. 163-181. (in Japanese with English abstract)
- OKADA, A. (1986) Trench investigation of the Atotsugawa Fault (Nokubi Site) in 1982. *Active Fault Research*, no. 3, p. 59-64. (in Japanese)
- OKAMURA, M. (1986) Babadan A Site and its stratigraphy. in TOHOKU HISTORIC MUSEUM, (ed.) : *Babadan A Site, I*, p. 1-25. (in Japanese with English abstract)
- SAKAI, H. and HIROOKA, K. (1983) Fault movement inferred from paleomagnetism and rock magnetism. *Gekkan Chikyu (The Earth Monthly)*, **5**, p. 394-399. (in Japanese)
- SAKAI, H. and HOROOKA, K. (1986) Archaeointensity determinations from western Japan. *Jour. Geomag. Geoelectr.*, **38**, p. 1323-1329.
- SASAJIMA, S. and MAENAKA, K. (1966) Intensity studies of the archaeo-secular variation in west Japan, with special reference to the hypothesis of the dipole axis rotation. *Mem. Coll. Sci. Univ. Kyoto*, Ser. B, **33**, p. 53-67.
- SHIBUYA, H. (1980) Geomagnetic secular variation in southwest Japan for the past 2,000 years by means of archaeomagnetism. *Master Thesis, Dept. Material Phys., Fac. Engineering Sci., Osaka Univ.*, p. 1-54.
- SMITH, J. D. and FOSTER, J. H. (1969) Geomagnetic reversals in Brunhes normal polarity epoch. *Science*, **163**, p. 566-567.
- TAKEUCHI, A. and SAKAI, H. (1985) Recent event of activity along the Atotsugawa Fault, central Japan —a paleomagnetic method for dating of fault activity—. *Active Fault Research*, no. 1, p. 67-74. (in Japanese)
- TANAKA, H. (1980) Paleointensities of the geomagnetic field determined from recent four lava flows of Sakurajima Volcano, west Japan. *Jour. Geomag. Geoelectr.*, **32**, p. 171-179.
- TANAKA, H. (1982) Geomagnetic paleointensities for the period 6,000 to 3,000 years B. P. determined from lavas and pyroclastic flows in Japan. *Jour. Geomag. Geoelectr.*, **34**, p. 601-617.
- VESTINE, E., LAPORTE, H. L., COOPER, C., LANGE, I. and HENDRIX, W. C., (1947) Description of the earth's magnetic field and its secular change, 1905-1945. *Carnegie Inst. Washington Publ.*, No. 578
- WATANABE, N. (1959) The direction of remanent magnetism of baked earth and its application to chronology for anthropology and archaeology in Japan : An introduction to geomagnetochronology. *Jour. Fac. Sci. Univ. Tokyo, Sect. V*, **2**, p. 1-188.
- WATANABE, N. (1977) Magnetic dating in archaeology. *Kagaku no Ryoiki (Jour. Japanese Chemistry)*, **31**, p. 683-691. (in Japanese)
- YASKAWA, K. (1973) Rate of sedimentation for young loose sediment. *Rock magnetism and Paleogeophysics*, **1**, p. 39-43.
- YASKAWA, K., NAKAJIMA, T., KAWAI, N. TORII, M., NATSUHARA, N. and HORIE, S. (1973) Palaeomagnetism of a core from Lake Biwa (I). *Jour. Geomag. Geoelectr.*, **25**, p. 447-474.
- YUKUTAKE, T., SAWADA, M. and YABU, T. (1964) Magnetization of ash-fall tuff of Oshima Volcano, Izu, I —Magnetization of ash-fall tuffs. *Jour. Geomag. Geoelectr.*, **16**, p. 178-182.
- YUKUTAKE, T. and TACHINAKA, H. (1969) Separation of the earth's magnetic field into the drifting and the standing parts. *Bull. Earthqu. Res. Inst.*, **47**, p. 65-97.