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Archaeomagnetic Study for the Past 2,000 Years in Southwest Japan*

By

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Abstract

To clarify the secular variation of the geomagnetic field in the Kinki District, about 2,600 samples were collected from some 150 kilns and hearths excavated in the Kinki District and its vicinity. The age of these samples covers a time range from 100 A.D. to the present. As a result of the magnetic measurements of these samples, the secular variation of the geomagnetic field in the Kinki District was brought to light in detail in this time range. In the same time range, the positions of the virtual geomagnetic north pole were calculated by using the values of the declination and inclination of the geomagnetic field thus obtained. The aspect of the secular variation of the virtual pole position seems to show that the movement of the virtual pole consists of two kinds of motion, that is, one is a basic counter-clockwise rotation of the period of about 1,500 years and the other is three clockwise rotations of the period of about 500 years.

Introduction

Since historic lava flows, baked soils, bricks, pieces of pottery and other earthenware, when they were fired in the past, acquired respective thermoremanent magnetism whose vector was parallel in its direction to that of the past ambient geomagnetic field and proportional in its magnitude to the intensity of the field, they make it possible for us to reconstruct the geomagnetic field of the time when they were erupted or baked. Therefore, if a number of those proprietors of fossil magnetism of great antiquity are widely collected and if there is archaeological or historical information about the time when they were erupted or baked, it is possible to expand the time range of the geomagnetic secular variation hitherto recorded at various observatories on the earth's surface. The record thus obtained will yield a good deal of informations regarding the origin of the geomagnetism, and therefore, contribute much to geophysics. The record, on the other hand, offers a good archaeometric standard without which many relics might so far have remained undatable.

It was MERCANTON (1918a, b) who attempted the first trial of archaeomagnetism. He measured the magnetization of an ancient ceramic sinker for a fisherman's net

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which was found in Switzerland as representing the geomagnetic field of the Bronze Age. His *a priori* assumption that baked earth should have been magnetized in the direction parallel to the ambient magnetic field while it was hot should be greatly appreciated.

Next, CHEVALLIER (1925) attempted to clarify the past geomagnetic field by measuring the magnetization of a number of samples from a sequence of historic lava flows in Mt. Etna. His result demonstrated that the secular variation of a geomagnetic field could reasonably be traced backward in the past, even back to 1300 A.D.

Then THELLIER (1937) established an elegant method of determining the direction of remanent magnetism remaining in many old kilns of known age. He also established an excellent procedure with which one can reproduce the intensity of past geomagnetic fields in the laboratory. From his studies it was found that a geomagnetic field quickly changed its total field intensity, actually reducing the field strength from its ancient value of about 1.5 times greater than that of the present field. Together with this intensity variation, the changes in both the declination and the inclination of the field were measured.

Almost at the same time, in Japan, NAGATA (1943) started his famous study on rock magnetism by using lava flows whose eruptions were well recorded in literature. The lava flows, belonging to Mt. Fuji and to the volcano in Ooshima Island, were sampled and their magnetization was measured. The same line of the study was also initiated by KATO (KATO and NAGATA, 1953; KATO, TAKAGI and KATO, 1954) who attempted to collect much older lava flows. The two studies mentioned above were unfortunately left abandoned owing to the commencement of the Second World War. Recently an archaeomagnetic study was reopened in the Ooshima volcanic area by YUKUTAKE (1961) who elucidated archaeosecular variation in the period from 500 A.D. to 1700 A.D. in the Kanto District of central Japan.

Quite independently from the above-mentioned studies, a special trial was done by WATANABE (1958, 1959) who wanted to utilize secular geomagnetic variations for chronological frames on which the ages of many antique potsherds and pieces of earthenware can be determined. He, therefore, started measuring the magnetization of many baked clays of known age as correctly as possible to set up the standard scale of the secular variation. He quoted several sources in literature describing direct instrumental, geomagnetic observations undertaken by many foreign navigators, such as Saris and Perry and some Japanese, such as INŌ, ARAI, TANI etc. For example, Saris visited Japan about 350 years ago and made geomagnetic observations, and TANI made a measurement of geomagnetic declination about 270 years ago. These data were added to his result of measurements to complete the secular change from 300 A.D. to the present time.

Shortly after WATANABE's investigation, KAWAI, KUME, YASKAWA, ITO, SASAJIMA, and the present author (Archaeomagnetic research group in Kansai, 1963; KAWAI *et al.*, 1965) began to make an investigation similar to that which THELLIER was carrying out in Europe. The samples from kilns and hearths and of earthenwares excavated in the Kansai District, Southwest Japan, were measured (KAWAI *et al.*, 1968; HIROOKA, 1968; HIROOKA *et al.*, 1971). The study to be reported in this paper is the continuation of this archaeomagnetic investigation.

When the above-mentioned authors were carrying out their investigations, COOK and BELSHE (1959) started their study of the past geomagnetic field, collecting baked clays from several Roman kiln remains in southern England. Slightly later, a study standing more on the side of archaeology than on that of geophysics was initiated by AITKEN (AITKEN and WEAVER, 1962; AITKEN *et al.*, 1964) in Oxford, England. A number of baked clays were sampled at several kiln sites having different ages. As a result, a record of the archaeosecular variation in England for nearly two thousand years was completed. A similar study to that made in England was carried out in Iceland using a sequence of historic lava flows and reported by BRYNJOLFSSON (1957). Likewise, in turn a series of reports on the study of archaeomagnetism appeared from Russia (BURLATSKAYA, 1961, 1962; BURLATSKAYA and PETROVA, 1961a, b, c; BURLATSKAYA *et al.*, 1965). For example, BURLATSKAYA *et al.* (1965) investigated many old potteries found in their country and in Bulgaria, and clarified how the inclination of the geomagnetic field had varied in Russia to the present day. As a conspicuous result, the aspect of variation obtained from Tbilisi, Caucasas, and that from Bulgaria, not only resemble each other, but also agree remarkably with the hypothetic aspect which derived from the wobbling dipole model proposed by KAWAI and the present author (1967).

Sample Collection

Kiln and baked earth

The baked earths with which the present author has investigated geomagnetic secular variations in historic times are distributed widely in the Kinki, Tokai, Chugoku, and Kyushu Districts as seen in Fig. 1. The number of sites from which oriented samples were collected for measurement are 105 in the Kinki, 26 in the Tokai, 13 in the Chugoku and 8 in the Kyushu Districts respectively.

As will be described later in detail, the pottery relics excavated from these kilns have been studied mainly by a number of archaeologists in Kyoto University, Nagoya University, Okayama University and associated with Osaka Prefectural Board of Education. Relatively accurate dating of those kilns were established by them. The dates were directly confirmed in some cases where the establishment of the kilns was

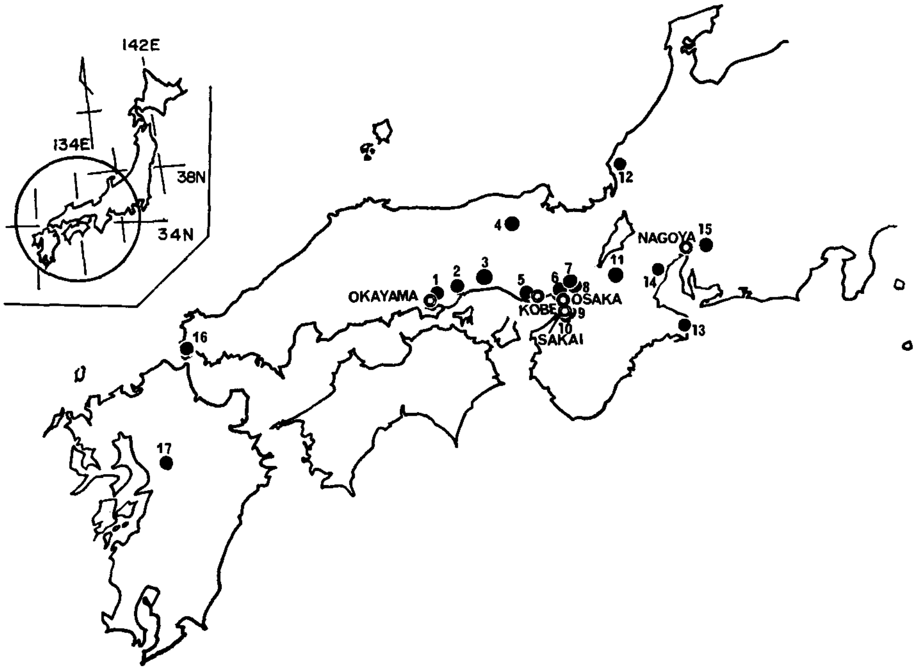

Fig. 1. Map of southwest Japan. Sampling sites are shown by numbers. Corresponding site to each number is as follows:
1. Tsudaka Cho 2. Bizen Cho 3. Tatsuno City
4. Wadayama Cho 5. Akashi City 6. Amagasaki City
7. Ikeda City and Toyonaka City 8. Takatsuki City and Suita City
9. Kanan Cho and Habikino City
10. Izumi City, Tondabayashi City and Kawachinagano City
11. Sigaraki Cho 12. Ota Cho 13. Isobe Cho
14. Yokkaichi City and Suzuka City 15. Toki City
16. Shimonoseki City 17. Kikusui Cho

fortunately recorded in literature. There existed some special cases in which the date of firing had been written directly on the pottery surface. It was, however, the more common case that the age was indirectly inferred from a general trend of the development in ceramic technology. For example, for specialists who are familiar with changes in the styles of pottery, it is quite easy to arrange a random mixture of new and old earthenware in a perfect chronological order on the basis of their archaeometric standard. This method of making a relative correlation of dates is quite successful in application.

According to the archaeologists' interpretation, the dates of the kilns used in this study were found to range from 420 A.D. to about 1700 A.D.

Almost all these baked earths used in the present experiments were collected from kilns of the so-called "Noborigama" type. The techniques used in this ancient ceramic industry were imported from ancient Korea first to Sue Village, Kinki District, and evolved there for about half a century and then spread rapidly over to the other districts. The kilns were constructed usually in a hilly area where both clay and firewood were abundant. An inclining and ascending draft and a vertical chimney as shown in Fig. 2 were made in a hill side. The draft was about 1.5 meters in diameter so that technicians could easily bring unfired pots in and fired ones out of the chamber occupying the lowest part of the kiln. Instead of digging a hole for making a draft along a slope, frequently the slope was gouged out, and covered over with a roof.

Besides the above-mentioned Noborigama type, special kilns for firing roof-tiles were built in antiquity. Samples of baked earths taken from these kilns were also employed in this study. Such kilns were called Hiragama by archaeologists. To demonstrate their construction, a vertical section of Hiragama is drawn in Fig. 3. It was recently discovered that kilns similar to but larger than Hiragama were used for a mass production of pottery or for firing large-sized ceramics. Such a large firing space and a longer vertical chimney as shown in Fig. 4 were employed in these particular kilns. A new type of kiln appears in the later half of 16th century. This is a kind of improved type of Noborigama. The chamber of the kiln was divided into several sub-chambers (sometimes the number exceeded ten) with intersecting walls. The contiguous chambers were connected with each other by holes which were made in the intersecting wall. Firewood was supplied not only from the front fuel hole of the lowest chamber but also from the fuel holes built in the side of each. This type of kiln has a very high thermal efficiency and therefore was more suitable for mass production. In this paper this kiln is designated Ogama. Fig. 5 shows an example of an excavated Ogama.

No kilns have been found which antedate those of the time of import from Korea of firing techniques, i.e. Noborigama type kilns. Archaeologists, therefore, consider that pottery was fired on the surface of the ground without using any special kiln during the Jomon and Yayoi periods. So that for the studies in the period from about 1 A.D. to 400 A.D. many baked soil samples obtained from hearths which were found in ancient dwelling pits were used. As one special case in this paper, samples were taken from a furnace which had been fired in the past to condense sea water to salt.

In the following four tables (Tables 1, 2, 3 and 4), there are some descriptions of those kilns and hearths which were mainly excavated in the above-mentioned four districts, that is, the Kinki, Tokai, Chugoku and Kyushu Districts respectively. The name or identification of those kilns and hearths, the locality of the sampling site, the type of kilns, the estimated age, the number of the oriented samples collected from each kiln were tabulated in turn together with the magnetic data obtained.

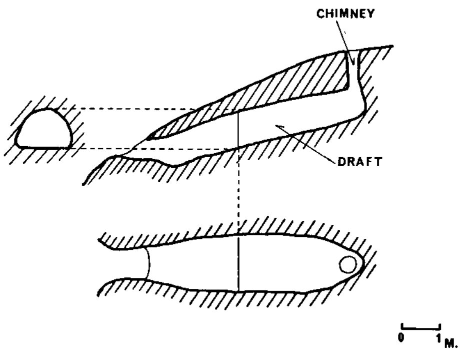

Fig. 2. Noborigama (After TANABE, 1966)

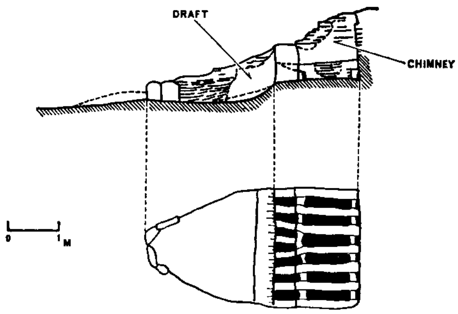

Fig. 3. Hiragama (or Kawaragama), Kishibe-H-1 (After FUJISAWA, 1968)

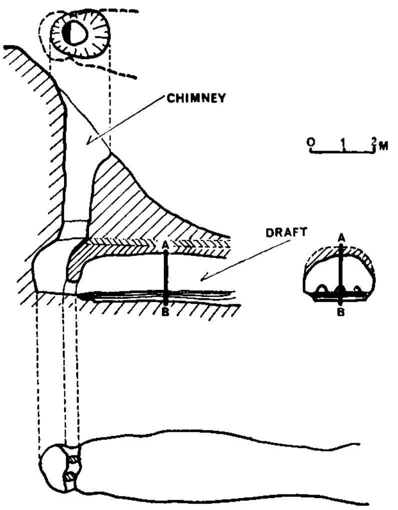

Fig. 4. Hiragama, KM-38-II (After Osaka Prefectural Board of Education, 1967)

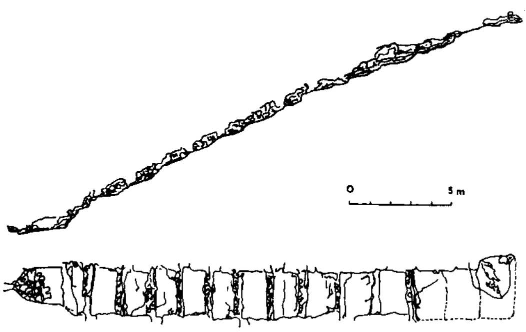

Fig. 5. Ogama, Kiln Motoyashiki (After NARASAKI *et al.*, 1967)

Table 1. KINKI DISTRICT

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
*Tano-TN-5-L60	Amagasaki City	Hearth	0±50	10	2.3	34.9	7.6	41.5
*Tano-T4-4-3-6	Amagasaki City	Hearth	50±80	10	−18.7	50.4	10.8	20.9
*Miyanomae-GI-51	Ikeda City	Hearth	50±80	10	−11.2	60.4	8.0	37.2
Miyanomae-GP-49-II	Ikeda City	Hearth	100±50	10	− 5.3	46.0	4.7	105.8
*Miyanomae-GP-49-I	Ikeda City	Hearth	150±50	15	− 1.5	26.1	3.8	105.3
Miyanomae-GE-49	Ikeda City	Hearth	150±50	20	1.7	67.6	6.0	27.7
Takatsukayama	Hirakata City	Hearth	200±30	12	6.2	59.9	4.0	118.1
*Benitakeyama-7	Takatsuki City	Hearth	250±50	22	12.7	63.6	4.2	54.5
Ichisuka-B7	Kanan Cho	Hearth	250±50	22	28.0	63.4	6.6	23.0
Daishiyama-B	Kawachinagano City	Noborigama	250±50	9	29.9	58.8	10.9	23.0
*Benitakeyama-6	Takatsuki City	Burnt Floor	300±50	10	− 9.1	58.3	6.6	53.7
Ama-B9-P7A	Takatsuki City	Hearth	330±35	22	23.0	53.7	5.1	38.1
Ama-B9-P7B	Takatsuki City	Hearth	335±35	9	0.8	33.5	8.5	37.7
Ichisuka-2	Kanan Cho	Noborigama	440±15	31	2.2	47.0	2.2	135.9
Ama-B9-P7C	Takatsuki City	Hearth	440±35	10	2.2	40.8	12.5	15.9
Habikino-5	Habikino City	Noborigama	445±10	21	−10.3	46.0	2.8	128.5
*Habikino-1-1	Habikino City	Noborigama	445±10	17	− 4.9	61.4	4.5	68.8
*Habikino-1-2	Habikino City	Noborigama	445±10	27	− 9.1	40.9	3.9	51.0
*Habikino-3-1	Habikino City	Noborigama	445±10	9	−10.5	44.8	4.9	110.1
*Habikino-3-2	Habikino City	Noborigama	445±10	9	− 8.0	39.4	4.4	139.5
*Habikino-3-3	Habikino City	Noborigama	445±10	9	−10.0	43.3	3.5	217.4
Habikino-4	Habikino City	Noborigama	445±10	11	− 8.3	39.5	6.4	52.6
Habikino-8	Habikino City	Noborigama	445±10	20	− 9.1	49.9	2.7	146.0
Naniwanomiya	Osaka City	Hiragama	450±50	9	− 6.6	48.2	5.5	87.7
Habikino-W1	Habikino City	Noborigama	460±10	11	− 2.6	50.8	5.0	85.4
Shimomuramachi-3	Toyonaka City	Noborigama	480±15	15	5.2	43.7	8.1	23.1
Shimomuramachi-2	Toyonaka City	Noborigama	550±25	22	− 6.7	40.6	2.4	175.2
Shimomuramachi-1	Toyonaka City	Noborigama	665±35	30	−15.0	56.4	1.4	341.2
Shindo Haiji-V-3	Tondabayashi City	Noborigama	750±10	28	− 8.5	52.3	2.0	180.1
Shindo Haiji-V-2	Tondabayashi City	Noborigama	750±10	23	−13.2	51.2	1.9	269.0
Shindo Haiji-V-1	Tondabayashi City	Noborigama	750±10	28	−12.0	50.9	1.9	202.6
*Kishibe-H-1	Suita City	Hiragama	790±10	16	−14.3	47.9	2.7	182.0
*Kishibe-N-1	Suita City	Noborigama	790±10	15	−14.9	47.0	3.0	163.0
Mozuhachiman-W	Sakai City	Hiragama	1200±50	19	− 5.7	61.9	2.9	134.3
Mozuhachiman-E	Sakai City	Hiragama	1350±50	8	7.7	57.4	4.2	175.9
Sue Village (Komyoike Area)								
KM-2	Izumi City	Noborigama	490±10	31	−18.7	47.0	4.3	36.8
KM-3	Izumi City	Noborigama	610±10	30	−14.8	53.7	1.4	363.4
*KM-11-U	Izumi City	Noborigama	630±10	25	−17.9	59.7	1.9	244.2
*KM-11-L	Izumi City	Noborigama	630±10	7	−18.4	60.1	4.0	229.0
*KM-28-I-L	Sakai City	Noborigama	630±10	25	−13.2	58.1	6.3	23.0
*KM-28-II	Sakai City	Noborigama	650±10	28	−10.4	59.8	3.0	116.3
*KM-38-I	Sakai City	Noborigama	750±10	35	−28.4	56.7	3.9	39.6
*KM-38-II	Sakai City	Hiragama	750±10	40	−13.4	51.2	1.9	149.9

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
KM-102	Izumi City	Noborigama	750±10	25	− 9.1	57.3	2.2	171.3
KM-101	Izumi City	Noborigama	760±10	26	− 8.7	51.5	3.1	83.8
KM-60	Izumi City	Noborigama	770±10	29	−11.0	53.0	1.4	378.4
KM-31	Izumi City	Noborigama	780±10	30	−22.1	46.5	2.5	113.1
KM-33	Izumi City	Noborigama	780±10	31	−13.4	48.7	2.2	144.4
KM-22	Izumi City	Noborigama	780±10	32	−10.3	49.0	3.8	46.0
KM-51	Izumi City	Noborigama	780±10	29	− 6.9	44.4	2.5	116.2
Sue Vilage (Takakuradera Area)								
TK-87	Sakai City	Noborigama	410±20	11	14.4	52.0	5.2	78.6
TK-305-I-2	Sakai City	Noborigama	470±10	15	− 8.9	38.4	2.4	262.7
TK-305-I-L	Sakai City	Noborigama	470±10	14	− 9.1	40.2	2.0	369.3
TK-68-A	Sakai City	Noborigama	470±10	16	1.2	49.6	4.5	67.6
TK-68-B	Sakai City	Noborigama	470±10	23	0.8	42.4	6.4	23.6
TK-33-N	Sakai City	Noborigama	470±10	19	− 2.7	45.3	3.4	96.4
TK-50	Sakai City	Noborigama	470±10	27	− 3.4	50.9	3.0	87.5
TK-33-S	Sakai City	Noborigama	510±10	10	−14.1	47.8	3.8	166.1
TK-71	Sakai City	Noborigama	530±10	27	− 7.8	47.2	2.6	116.0
TK-85	Sakai City	Noborigama	530±10	7	− 8.7	43.4	5.6	119.3
TK-305-II	Sakai City	Noborigama	550±10	20	−10.4	53.6	4.5	53.0
TK-41	Sakai City	Noborigama	570±10	15	−18.2	50.5	2.7	201.5
*TK-43-D	Sakai City	Noborigama	570±10	8	− 9.8	61.9	6.7	69.1
*TK-43-C	Sakai City	Noborigama	570±10	13	−18.2	56.0	2.4	302.3
*TK-43-B3	Sakai City	Noborigama	570±10	13	−14.7	55.2	1.8	504.2
*TK-43-B2	Sakai City	Noborigama	570±10	7	−24.5	58.9	2.0	909.1
*TK-43-B1	Sakai City	Noborigama	570±10	8	−18.6	53.9	4.7	141.7
*TK-43-AL	Sakai City	Noborigama	570±10	13	−18.3	53.1	2.3	327.9
*TK-43-AM	Sakai City	Noborigama	570±10	15	−18.8	56.6	1.6	549.0
*TK-43-AU	Sakai City	Noborigama	570±10	19	−19.1	55.6	2.1	245.9
TK-212	Sakai City	Noborigama	580±10	28	−20.1	55.8	2.4	132.6
TK-312	Sakai City	Noborigama	590±10	19	− 6.3	57.0	3.2	109.8
TK-117	Sakai City	Noborigama	610±10	8	−11.0	45.6	2.9	360.8
TK-46	Sakai City	Noborigama	650±10	35	−15.6	63.5	2.1	129.7
TK-67	Sakai City	Noborigama	675±15	8	−11.2	59.3	2.8	348.3
TK-48	Sakai City	Noborigama	675±15	14	−24.3	66.3	2.8	196.1
TK-45	Sakai City	Hiragama	750±10	19	− 9.9	54.1	2.3	223.6
TK-57-O	Sakai City	Hiragama	760±10	20	−16.2	59.1	2.7	150.2
TK-53-O	Sakai City	Hiragama	760±10	22	−13.0	51.5	1.5	415.0
TK-57-N	Sakai City	Hiragama	760±10	10	−10.9	57.0	5.6	75.8
TK-53-N	Sakai City	Hiragama	760±10	19	−10.2	52.8	2.0	275.7
TK-33-SN	Sakai City	Noborigama	780±10	5	− 8.9	41.9	6.2	156.3
TK-314	Sakai City	Noborigama	925±25	20	−13.4	47.9	2.8	137.4
Sue Vilage (Tokiyama Area)								
MT-70	Sakai City	Noborigama	470±10	25	− 6.1	42.4	2.9	101.0
MT-84	Sakai City	Noborigama	490±10	22	− 7.9	55.0	2.6	145.0
MT-200-II	Sakai City	Noborigama	510±10	15	−14.5	44.5	5.3	52.6

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
MT-22-I	Sakai City	Noborigama	570±10	11	−18.5	59.0	3.2	199.6
MT-85-6	Sakai City	Noborigama	570±10	10	−12.9	48.3	2.7	332.1
MT-85-5	Sakai City	Noborigama	570±10	10	− 8.7	50.0	2.6	323.4
MT-85-4	Sakai City	Noborigama	570±10	14	−10.8	51.7	2.2	322.1
MT-85-3	Sakai City	Noborigama	570±10	14	−14.2	50.6	1.0	1616.9
MT-85-2	Sakai City	Noborigama	570±10	12	−16.4	52.4	1.7	650.5
MT-85-1	Sakai City	Noborigama	570±10	15	−12.3	53.3	2.1	325.4
MT-5-IC	Sakai City	Noborigama	825±25	19	−13.1	48.9	2.8	142.3
MT-5-IB	Sakai City	Noborigama	825±25	13	−11.7	47.4	3.7	126.8
MT-5-IA	Sakai City	Noborigama	825±25	14	− 6.2	46.1	4.0	98.7
MT-200-I	Sakai City	Noborigama	875±25	15	−12.1	46.0	2.6	223.2
Sue Vilage (Toga Area)								
TG-43-III	Sakai City	Noborigama	445±10	26	− 4.4	43.1	1.6	302.7
TG-43-II	Sakai City	Noborigama	470±10	29	− 5.4	44.6	2.6	106.7
TG-43-IV-L	Sakai City	Noborigama	490±10	8	− 9.4	50.2	4.6	147.8
TG-43-I	Sakai City	Noborigama	490±10	30	− 0.6	48.4	2.0	180.9
TG-40-I	Sakai City	Noborigama	530±10	22	− 3.0	53.3	6.7	22.1
TG-37	Sakai City	Noborigama	530±10	31	−11.1	41.0	2.3	129.1
TG-41-IV	Sakai City	Noborigama	650±10	43	−14.9	55.7	2.1	104.3
TG-15	Sakai City	Noborigama	750±10	23	−24.2	52.0	2.3	172.6

The asterisked sites are detailed in appendix.

Table 2. TOKAI DISTRICT

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
Hata	Suzuka City	Hearth	250±30	26	− 4.1	49.8	5.0	40.7
Nishi-Okane	Yokkaichi City	Noborigama	670±20	10	−24.9	55.9	6.2	61.6
Okayama-1	Yokkaichi City	Noborigama	780±10	14	−16.7	49.2	5.0	65.2
Maruishi-1	Toki City	Noborigama	1100±30	8	5.3	51.1	4.1	227.3
Maruishi-2	Toki City	Noborigama	1100±30	14	− 0.2	52.4	2.9	178.6
Okayama-4	Yokkaichi City	Noborigama	1120±10	11	−10.9	52.1	4.9	88.3
Kamioshidani	Ota Cho	Noborigama	1260±20	9	20.0	51.6	9.5	30.5
Maruishi-3-L	Toki City	Noborigama	1290±30	11	16.0	61.2	4.3	112.0
Maruishi-3-U	Toki City	Noborigama	1300±30	11	23.4	56.8	5.2	79.6
Magoemon-2	Yokkaichi City	Noborigama	1330±10	14	− 1.5	55.3	7.2	31.3
Magoemon-1	Yokkaichi City	Noborigama	1350±10	9	− 8.3	52.0	10.4	24.9
Anayama	Yokkaichi City	Noborigama	1350±10	10	15.0	52.0	3.9	153.1
Matsuo-1	Shigaraki Cho	Noborigama	1350±50	6	9.0	38.1	4.2	260.6
Matsuo-2	Shigaraki Cho	Noborigama	1350±50	14	4.0	39.7	5.2	58.0
Ogai	Isobe Cho	Salt Furnace	1380±50	20	1.0	41.3	4.8	47.1
Nakaide-1	Shigaraki Cho	Noborigama	1570±30	9	12.9	33.1	6.5	63.8
Nakaide-2	Shigaraki Cho	Noborigama	1600±30	21	12.3	35.4	3.5	81.4

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
Motoyashiki	Toki City	Ogama	1620±30	7	9.1	39.5	3.7	269.1
Maruishi-4	Toki City	Noborigama	1630±30	7	− 1.1	41.3	2.3	674.2
Jyorinji-1	Toki City	Noborigama	1630±30	21	4.9	42.7	2.8	123.4
Jyorinji-4	Toki City	Noborigama	1630±30	7	2.3	38.9	2.8	471.0
Jyorinji-2	Toki City	Ogama	1660±40	16	5.0	36.3	2.6	210.7
Kamagamine-2	Toki City	Ogama	1660±40	6	2.4	41.6	2.4	781.3
Jyorinji-3	Toki City	Ogama	1670±40	12	13.3	35.3	6.6	45.2
Ko-Kutani-1	Yamanaka Cho	Ogama	1670±30	19	7.5	49.3	3.0	122.7
Kamagamine-1	Toki City	Ogama	1760±50	7	1.9	33.3	4.7	163.0

Table 3. CHUGOKU DISTRICT

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	α_{95}	K
Takaoka-14	Akashi City	Noborigama	590±10	35	−22.2	51.7	1.3	364.0
Okada-1	Wadayama Cho	Noborigama	600±25	26	−19.8	53.9	2.8	107.0
Takaoka-3	Akashi City	Noborigama	675± 5	19	− 3.8	53.2	2.0	283.0
Takaoka-4A	Akashi City	Noborigama	675± 5	16	−13.4	57.2	2.8	171.9
Takaoka-4BN	Akashi City	Noborigama	675± 5	15	− 5.0	57.3	2.8	184.5
Takaoka-4BO	Akashi City	Noborigama	675± 5	5	− 4.9	63.0	3.7	664.5
Kaneiba	Tsudaka Cho	Noborigama	850±50	21	−14.0	46.6	2.1	230.7
Nakai	Tatsuno Cho	Hiragama	950±25	31	−19.8	53.4	2.0	169.5
Aigafuchi-N	Bizen Cho	Noborigama	1220±30	17	2.5	54.2	4.1	74.7
Aigafuchi-S1	Bizen Cho	Noborigama	1300±30	16	2.7	51.3	2.4	226.6
Furoyama-E	Bizen Cho	Noborigama	1330±30	27	2.9	40.6	2.7	104.9
Furoyama-W1	Bizen Cho	Noborigama	1330±30	27	13.6	52.7	1.6	301.6
Furoyama-W2	Bizen Cho	Noborigama	1550±30	32	8.1	36.0	1.6	239.4

Table 4. KYUSHU DISTRICT

Site	Locality	Type	Age (A.D.)	No. of Samples	D(°)	I(°)	σ_{95}	K
Ayaragi	Shimonoseki City	Hearth	1±50	17	−16.0	53.3	7.6	22.9
Suwanoharu-C-2	Kikusui Cho	Hearth	260±50	7	2.8	58.0	8.5	50.9
Suwanoharu-B-14	Kikusui Cho	Hearth	260±50	11	10.7	56.4	5.7	65.5
Suwanoharu-B-16	Kikusui Cho	Hearth	260±50	8	15.8	64.2	6.0	86.4
Suwanoharu-B-102	Kikusui Cho	Hearth	260±50	12	8.5	57.2	3.8	130.6
Suwanoharu-A-18	Kikusui Cho	Hearth	260±50	12	16.2	59.4	4.6	90.8
Suwanoharu-A-21	Kikusui Cho	Hearth	260±50	8	1.1	52.8	4.7	136.7
Suwanoharu-A-3	Kikusui Cho	Hearth	260±50	9	8.7	46.1	4.8	115.1

Orientation in situ and sampling

Since it is very important in an archaeomagnetic study to determine the direction of magnetization as accurately as possible, the method of orientation *in situ* at the sampling site has been considered very carefully and recently has undergone new developments. For this purpose the present author prepared a special plate made of non-magnetic metals such as duralumin or copper-beryllium. To this plate were attached three non-magnetic nails, each having equal length and a sharp point (A, B and C in Fig. 6). To the same plate was also fastened a magnetic compass as demonstrated in Fig. 6.

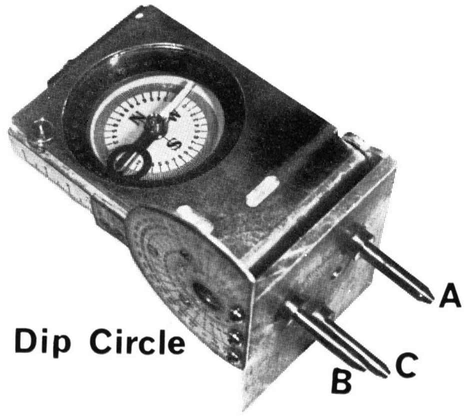

Fig. 6. Orientation apparatus.

By using this small apparatus the orientation of the baked earths was determined in the field. The actual procedure is described as follows: First, the three sharp points A, B and C are brought into contact with the surface of baked earth to be sampled (usually the surface is covered with a thin layer of plaster as will be mentioned later). Among these three points, two points A and B are placed on the line at which the surface of the baked earth intersects a horizontal plane. Then the angle between the straight line $\overrightarrow{AB}$ joining these two points and the geomagnetic meridian at the sampling site is measured by using the magnetic compass attached to the plate. Next, the angle between the plane determined by the three points A, B, C and the horizontal plane is measured by using a dip circle also attached to the plate as shown in Fig. 6. Finally the three points on the surface of the baked earth, with which the points of the three nails A, B and C are in respective contact, are carefully marked with a sharpened crayon. After the above four procedures are finished, the specimen is carefully removed from the fireplace.

In general the surface of baked earth is, however, so uneven that the error angle due to both reading and marking cannot be disregarded. To prevent this error, "Plaster de Paris" is applied on the uneven surface of baked earth. The surface of the thin layer of plaster is then made as flat as possible. On this flat and even surface are put the above-mentioned marks indicating the orientation.

Since baked earth has relatively weak remanent magnetism with mean intensity of magnetization being in a range from 10^{-4} to 10^{-5} e.m.u./gr, the local magnetic anomaly produced in the vicinity of the fireplace due to the baked earth to be sampled is indeed so small that there is no problem in using a magnetic compass to determine the orientation correctly. Therefore, the Sun compass employed in many other archaeomagnetic studies was not used in this study. The error angle made at the time of the orientation of a specimen could be kept to such a small value that it did not exceed 1.5 degrees. Besides this error in the orientation, one must consider the errors arising from measuring procedures in the laboratory and also the possible errors made in the course of plotting of the results on the equal area projection. Even taking these error angles altogether into account, 3 degrees was the largest error angle in each measurement encountered so far.

Usually about 20 oriented specimens of the baked earth were collected from one kiln. The size and shape of these specimens were approximately 38 mm cube. The floor of the chamber in the Noborigama was not fired so hard in general as compared to the roof or the lateral walls. Nevertheless, estimating its firing grade, to the depth about 100 mm below the surface of the floor the temperature of the soil was considered to have been elevated beyond the blocking temperatures of the magnetic compositions of the soil at which the soil could acquire an effective magnetization.

Sampling at kiln sites

It is needless to say that the baked earth is required to have kept the same constant orientation since the time of its final firing.

In the beginning of this study the inside lateral walls of the draft or the chimney of kilns were sampled and measured, and those walls were soon found to have significantly moved and tilted during the gradual burial of the kilns. In Fig. 7a is shown the Schmidt's equal area projection of the directions of the remanent magnetic vectors of those specimens which were taken from the walls of a kiln. The direction of the magnetic vectors of the specimens taken from the floor of the draft of this kiln is also shown in Fig. 7a. So it is interesting to compare them. It appears as if the left side wall and the right side wall of the draft have different directions of magnetization from each other. It is reasonable, however, to assume that they both originally possessed the same direction of magnetization, but, since both the walls tilted slightly inside the draft subsequently, their directions of magnetization have been discrepant. Being in contrast with this, the baked earth taken from the floor of the draft has the remanent magnetism whose direction lies between these two directions of the walls, and it seems to show that the floor has been stable since the kiln was built (see Figs. 7a and b). On the other hand, usually the ceiling of the draft chamber is quite unstable now, and in many cases it has sunk or sometimes completely collapsed into the draft. So, in the present study the data from the lateral walls and those from the upper portions of the draft were avoided.

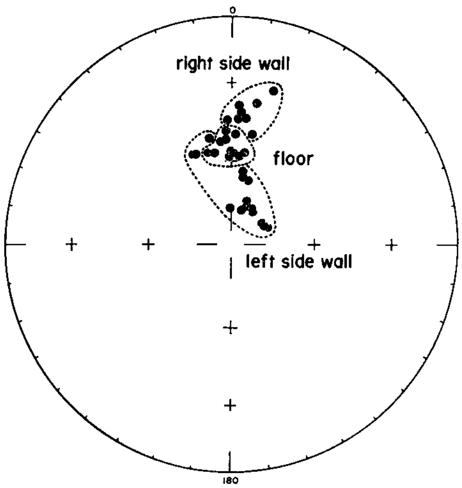

Fig. 7a. Schmidt's equal areal projection of the remanent magnetic vectors of the samples collected from the kiln whose schematic diagrams is shown in Fig. 7b.

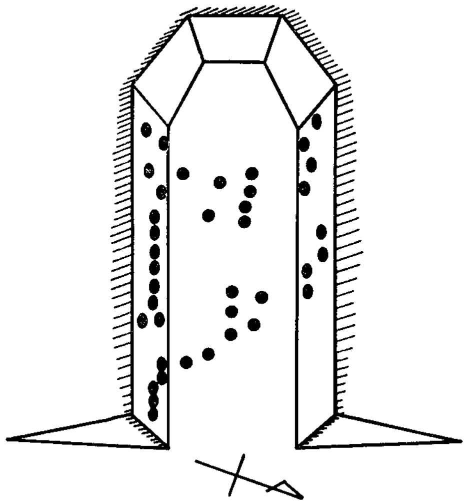

Fig. 7b. Distribution of samping places in a kiln.

It was often the case in the Noborigama kilns that probably these kilns had intermittently and repeatedly been used for more than 100 years. Many pieces of various kinds of earthenware with markedly different style and appearance were found at the so-called Haibara which was usually placed in the vicinity of a kiln and used as a dumping place for defective earthenware, suggesting that frequent stepwise advances of earthenware styles may have been made in the history of ceramic engineering. This implies that major repairs may have been made several times in these kilns. In fact these kilns seem to have minor repairs at each time of the major repairs, being plastered with new clay on their old inside surfaces. As the result of this, the inside diameter of the draft was reduced, and occasionally the layers of old clay would be scraped off from the walls of the draft to enlarge the draft before the new clay was plastered on the walls. So, except for this case, it is not impossible to find the successively different directions of remanent magnetism in the walls, since the remanent magnetism of the old walls could be kept safely under the protection of the new layer of clay over it.

Chronological divisions on pottery types

The Japanese pre-historic age is divided into three periods; namely pre-Jomon, Jomon, and Yayoi. The age of the oldest sample measured in this paper belongs to the middle of the Yayoi period.

The Yayoi period begins at about 300 B.C. and is divided into three stages of about 200 years each, that is; Early, Middle, and Late Yayoi periods. Beside this division, five pottery types from I to V are used in the Kinki District for expressing the dating of pottery. Type I corresponds to Early, Types II, III and IV to Middle, and Type V to Late Yayoi period respectively (KOBAYASHI, 1938; TANABE and SAHARA, 1966).

The time from about 300 A.D. to about 780 A.D. is called the Kofun period. The Kofun is a large mound burying the leader of tribe. Leaders made mounds for their burial place during their reign. Every leader wanted to make his mound as big as possible to demonstrate his powerfulness. The terms Asuka and Nara eras are also used for the late Kofun period, that is, 550 to 709 A.D. and 710 to 793 A.D. espectively. Buddhism was introduced in the middle of the 6th century and accompanying Buddhism, the technique of building temples was also imported. Accordingly, many huge temples came to be built in the Asuka and Nara eras. Roofs of these temples were covered with tiles. To supply the demand of a large number of roof tiles, many kilns were newly constructed for each temple. The chronology of roof tiles was very well studied in relation with many records concerning the construction of temples. Before that time buildings were thatched with straw or miscanthus.

The production of Sue type ceramics continued almost through all of the later three quarters of the Kofun period at Sue Village in the Kinki District. The technical development of Sue ceramics was investigated chiefly by TANABE and YOKOYAMA over a period of 15 years. They stated that it was possible for them to classify the history of Sue ceramic industry from the 5th century to the 10th century at least into five periods.

The classification was undertaken on the basis of an archaeometric standard that TANABE (1966) established. He succeeded in arranging various pairs of pot and lid named Tsuki in the chronological order because of their distinguishable technical evolution.

Period I starts from the beginning of the 5th century and comes to an end at the beginning of the 6th century. The "Nihonshoki", the earliest Japanese annals written in the 8th century records that Sue ceramic was initiated towards the end of the reign of Emperor Suinin. At this primitive stage, the typical style of the pair is such that the pot has a gently curving bottom under which there is no circular edged foot and has a nearly vertical and rather long fringe called Tachiagari on whose outer slope is to rest the lid having a gently curving top surface as shown in the diagram (Fig. 8). Another typical characteristic can be seen in the relatively short height of the pedestal of the earthenware, especially those referred to by the name, Takatsuki, as can be seen in Fig. 8b.

Period II ranges from the beginning of the 6th century to the beginning of the next century. In this period, the following modification in the shape of the pair of pot and lid can be seen. The curvature of the bottom surface is more gentle in general, and the vertical length of the fringe of the pot becomes appreciably shorter with a simultaneous decrease in the inclination of the outer slope as also shown in Fig. 8c. The above tendency is so clear that one can easily discriminate the older pots from the younger ones even if they belong to the same period. The elongation of the height of the pedestal, Takatsuki, is evident in this period.

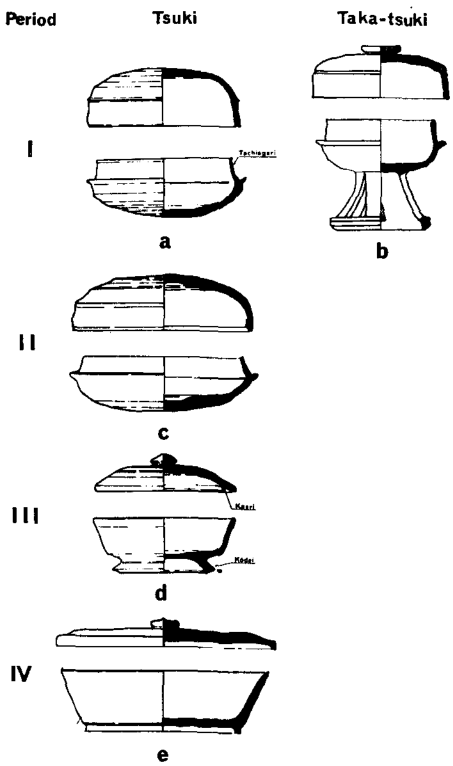

Fig. 8. The time change in the stylization of pot and lid pairs (Tsuki) and a pair with pedestal (Taka-tsuki). a, c, d and e are called by the name Tsuki and b named Taka-tsuki. (a, c and d : after Tanabe, 1967; b and e : after Osaka Prefectural Board of Education, 1967)

The shape of the pair changes greatly in Period III. Not only is the curvature of the surface of the pair more reduced than that of the previous period but also a small knob is attached on the top of the lid. The shortening of the fringe, Tachiagari, is so accelerated that it finally vanishes accompanying the appearance of a circular limb at the inner surface of the lid (Fig 8d). The brim of the pot rests on the groove between this limb and the edge of the lid. This circular limb is named Kaeri. This third period begins at about 640 A.D. and lasts for about 50 years.

As is shown in Fig. 8e, the circular limb, Kaeri, disappears from the inner surface of the lid in Period IV. The bottom of the pot becomes flat. This period runs from 690 A.D. to 790 A.D.

In Period V, potters begin to use thread instead of a pallet for cutting the turned and shaped clay off from their potter's wheel. This period is the time of decline of the Sue ceramic industry. Period V ranges from the beginning of the 9th century to the middle of the 10th century.

These five periods were divided into 19 stages from A to S by the archaeologists of the Osaka Prefectural Board of Education (TASHIRO, NAKANISHI, NAKAMURA and NAKAI, 1970) who have been excavating steadfastly. The corresponding period and the estimated age of each stage are shown in Fig. 9.

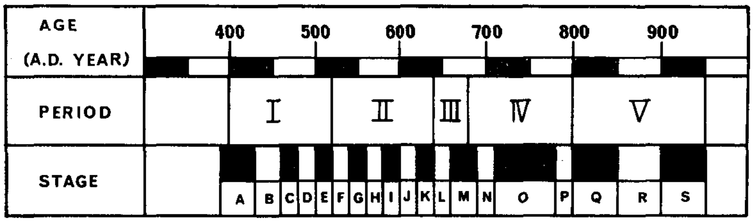

Fig. 9. A chronological chart of the classification of Sue ceramics. (TANABE, 1966; TASHIRO *et al.*, 1970)

After the decay of the ceramic industry in Sue Village, the Tokai District became the center. Glazing came into use at that time. It is very characteristic that the glaze called Kaiyu which was made from plant ash was used only in this district (NARASAKI, 1970). From the end of 12th century mass production of ceramics were notable at six places; Seto, Tokoname, Echizen, Shigaraki, Tamba and Bizen. These places are known by the name of Rokkoyo that means six old kiln sites. In 14th or 15th century many local kilns were built in the Tokai District and in the western part of the country. Both the techniques of firing and stylization of pottery were developed differently from place to place in those days. The results are an extraordinary variety in ceramic fashion produced from 14th century up to the present. A chronological study of kilns and ceramics, therefore, should be carried out precisely according to the particular place. Kilns in the Tokai District were investigated by NARASAKI (1961, 1966 and 1970) and those in the Chugoku District by MAKABE and MAKABE (1965, 1966).

Magnetic Measurements

Remanent magnetism of samples was measured on an astatic magnetometer which is sensitive enough to measure the samples whose intensity is on the order of 10^{-7} e.m.u./gr. The magnetometer has the two-magnets system suspended with a very thin quartz fiber. The magnets have the size of 1 mm $\times$ 2 mm $\times$ 4 mm and are connected with a slender quartz tube of 56 mm long.

Samples are rotated around the vertical axis right beneath the magnets system. The reproducibility of the measurements may be shown by the statistical parameters using Fisher's cone angle of confidence of 95%, α_{95}, or the precision constant k which is given by the repeated measurements on the same sample. Three runs of six repeated measurements of a sample were carried out for this purpose. The mean value of α_{95} and k are given 1°45′ and 1,824 respectively by this experiment.

The stability of natural remanent magnetization (N.R.M.) of samples was tested by the progressive alternating-field demagnetization in the field of 300, 600, 1,200 and

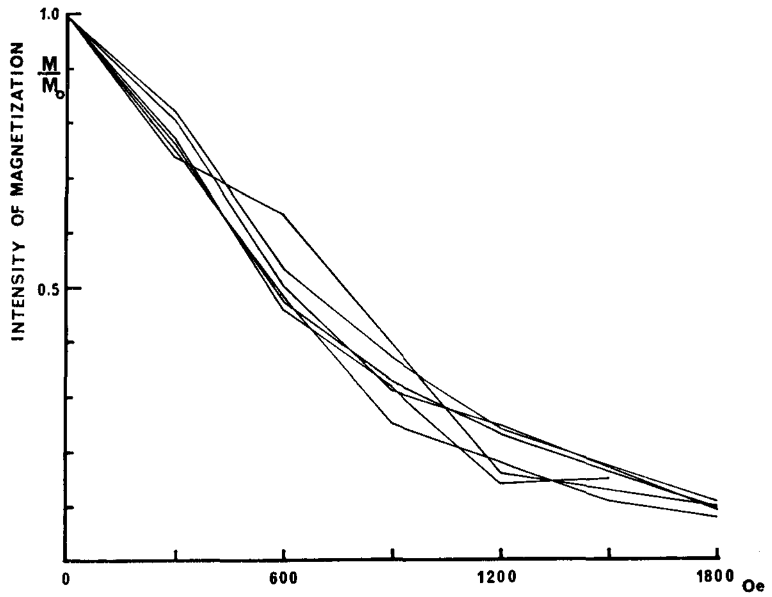

Fig. 10. An example of alternating field demagnetization curves of samples. (Kiln TK-43-B2)

1,800 Oe. (Occasionaly the fields of 300, 600, 900, 1,200 and 1,800 Oe were used). Fig. 10 shows an example of intensity decay of samples by the demagnetization. From the results of the experiments, the direction of remanent magnetization shows no obvious change in the field up to 600 Oe and the scattering of the directions increases very much instead of decreasing in the field higher than 1,200 Oe as is shown in Fig. 11.

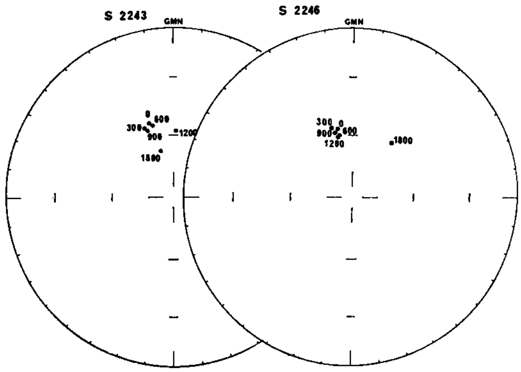

Fig. 11a. Examples of direction changes of two samples (S•2243 and S•2246) by alternating field demagnetization.

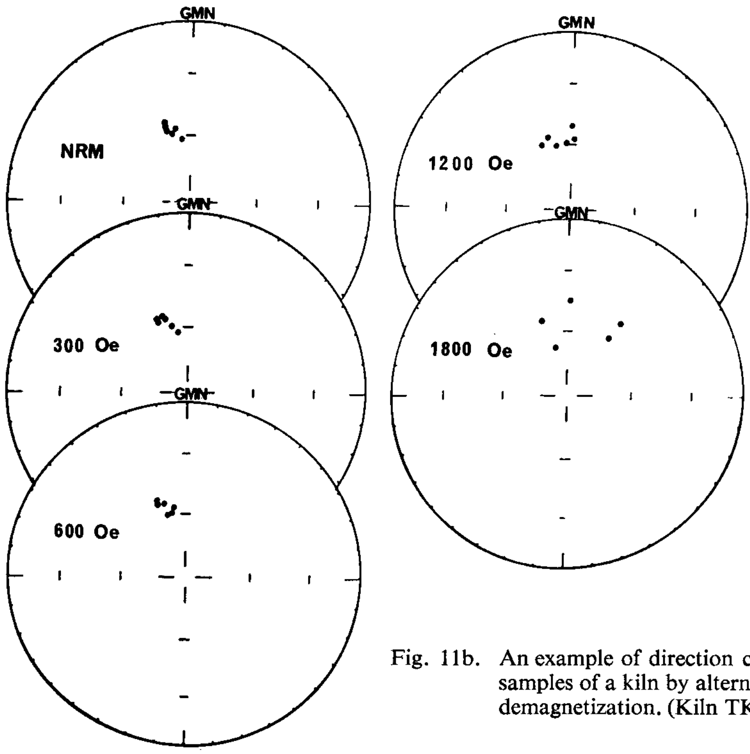

Fig. 11b. An example of direction changes of samples of a kiln by alternating field demagnetization. (Kiln TK-43-B2)

The present author, therefore, assumed that the N.R.M. of samples was stable enough for the study and used the mean values of N.R.M direction for the archaeomagnetic data in this paper.

The accuracy of mean directions of N.R.M. can be given by employing Fisher's cone angle of confidence. The histogram of the angles is represented in Fig. 12. The mode of the angle falls between 2.0° and 3.0°. This value is considerably small in comparison with that of ordinary paleomagnetic data.

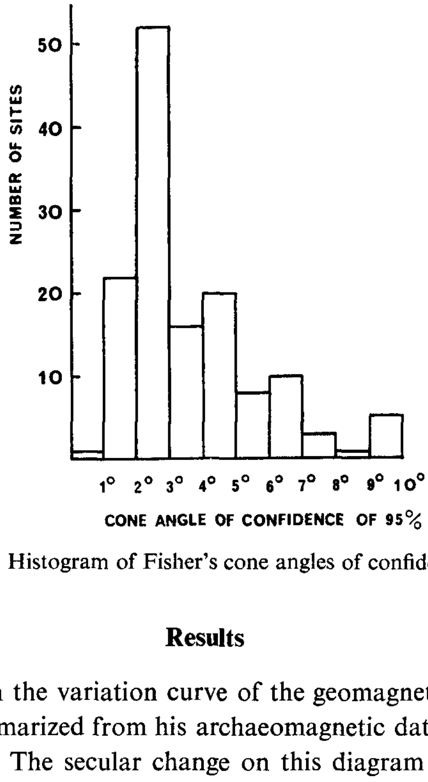

Fig. 12. Histogram of Fisher's cone angles of confidence (α_{95}).

Results

In Fig. 13 is shown the variation curve of the geomagnetic declination which the present author has summarized from his archaeomagnetic data obtained in the south-western part of Japan. The secular change on this diagram covers the time ranging from 100 A.D. to the present. The vertical line drawn across each point on the diagram represents the experimental error of the magnetic measurement, and the length of each line shows the actual error angle, hence corresponding to the radius of Fisher's 95% circle of confidence. Horizontal line is also drawn on the same diagram across each point. The length of this horizontal line is in inverse proportion to the chronological accuracy or proportional to the degree of uncertainty, that is, the longer the length of this line, the larger the uncertainty. As can be seen in the diagram the change of the declination is so smooth and continuous that a plot on the diagram can be followed by the next plot almost successively one after another.

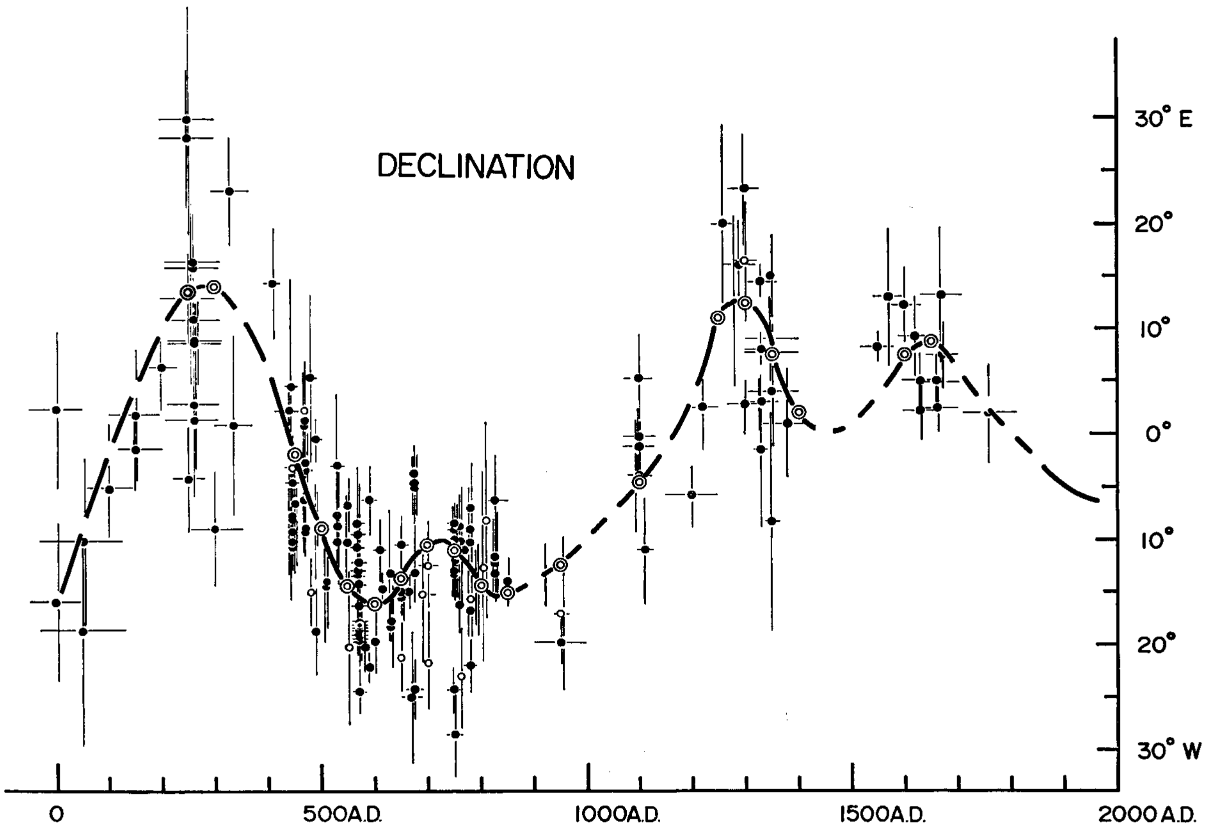

Fig. 13. Secular variation of the geomagnetic declination in southwestern Japan. The data obtained by KAWAI *et al.* (1965b) are also plotted in this diagram (hollow circles). Double circles show the mean value of every 50 years.

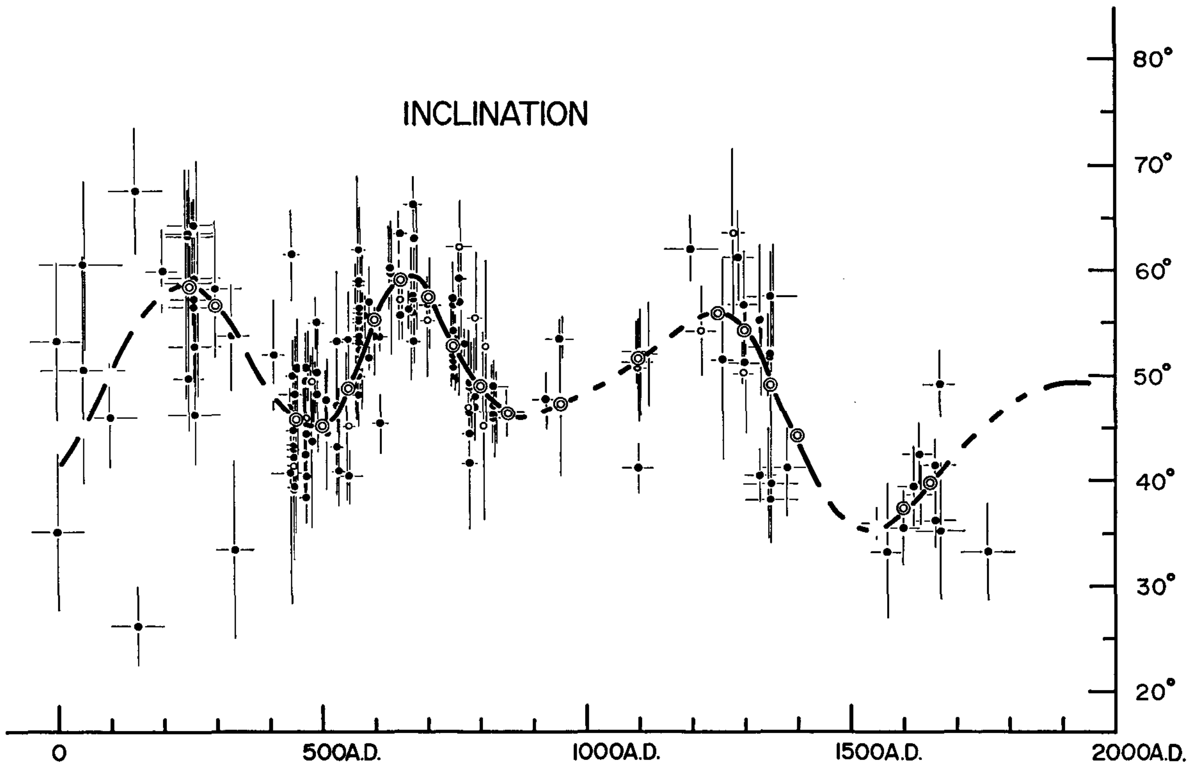

Fig. 14. Secular variation of the geomagnetic inclination in southwestern Japan. Plotting notations are the same in Fig. 13.

Next, for about 700 years, from 450 A.D. to 1150 A.D., the declination was continuously westerly. Then, in the following period, from 1150 A.D. to 1800 A.D., the declination was continuously easterly. And in these periods of either the westerly or the easterly declination, fluctuations took place two times for each, accompanying the maxima and the minima in the declination as shown in Fig. 13. In Fig. 14 it is shown how the inclination of the geomagnetic field has changed since 100 A.D. The mean values of both the declination and the inclination were calculated for every 50 years. The above mean values are plotted with concentric circles on these two diagrams. Two smooth curves, one being of the declination and the other being of the inclination, were drawn on the respective diagram. The data obtained from the magnetic measurements are tabulated in Tables 1, 2, 3 and 4.

Since a magnetic compass was used in the procedure of the orientation of the author's samples, the past geomagnetic declination obtained directly from the magnetic measurements of the samples is the one taken from the present geomagnetic north at his sampling site. To convert this angle into that taken from the present geographic north, the present geomagnetic declination at every sampling site was determined by means of the empirical formula between the geomagnetic declination in Japan in 1960 and the geographic coordinates (Geographical Survey Institute of Japan, 1961), and was added to the past geomagnetic declination obtained from the experiments. The values of declination (D) in the Tables are of the corrected declination.

In order to trace the secular variation of the past geomagnetic field, it is necessary to use samples from various, different ages which come from the same place, because the declination, the inclination and the total intensity of the geomagnetic field are the functions of geographic coordinates as well as of time. It is almost impossible, however, to obtain a sequence of baked earths or lava flows covering many years, say a thousand years or more, at one given place. Therefore, one must find some method by which the values obtained experimentally from samples which were collected at different localities and have various ages can be reduced to what these samples ought to have acquired if they were magnetized at the same place. Or at least, they must be collected in a region within which the difference of the geomagnetic field was small enough to be disregarded.

To compare the results obtained on the sites distant from each other, WATANABE (1959) reduced the obtained values of the past declination at various districts to those at Tokyo by using the empirical formula in 1950 such as that in 1960 mentioned already (TSUBOKAWA, 1952). When we make such a reduction of an experimental value of a past declination at some place to that at a certain reference place, the error due to the uncertainty of the formula must always be much smaller than the value of the reduction itself, but actually it seems impossible. Furthermore, there is no assurance that the formula itself has been effective for several thousand years, in other words, that the isogonic lines in Japan have been unchanged for such a long period. However, there is an isogonic map of ancient Japan (Fig. 15) suggesting that we cannot use the same formula for such a long duration because of the considerable difference from today's. This interesting ancient isogonic map was made by HOYANAGI (1967) from a precise study of an old map of the Japan islands made by Tadataka INŌ. Comparing INŌ's map with the present one, HOYANAGI found systematic discrepancies between them, that is, the north-eastern part and the southwestern part of Japan islands in INŌ's map are situated a little to the east of the true position, when the central part is placed at the correct position. He explained these discrepancies as follows: In 1802, on the basis of his astronomical observation at a central place of Yedo (the old name of Tokyo), INO concluded that the declination of geomagnetic field was small enough (0°19′E) to regard geomagnetic north as true north. Since then, INŌ determined the direction angle on his survey by measuring the deflection angle from the geomagnetic north, without knowing the fact that the declination could differ from place to place. The difference of the declination of the geomagnetic field due to the regional difference was, however, too big to be disregarded, and as the result, the position of the measuring stations on INŌ's map deviated to the east or to the west in a certain extent proportional to their declination. Therefore, Hoyanagi concluded that this discrepancy between the old map and the present one had to show the relative geomagnetic declination of every station at the time of INŌ's survey, and he drew paleo-isogonic lines in Japan as shown in Fig. 15, which were considerably different from the present isogonic lines.

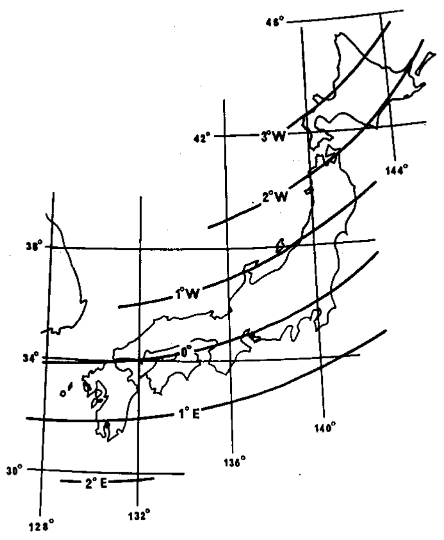

Fig. 15. Approximate isogonic lines around the Japanese Islands at the time of INŌ's survey, presumed by HOYANAGI (1967).

These are the reasons why the present author did not make any reductions as WATANABE did, but adopted the value of the declination on which only a correction of the present geomagnetic declination was made at every sampling locality as already mentioned.

Discussion

Virtual pole position

The virtual pole position corresponding to each set of mean declination and mean inclination for every 50 years was calculated by the following formulae and shown in an equal area polar projection (Fig. 16):

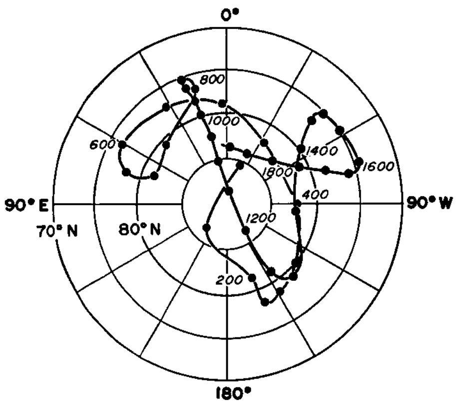

Fig. 16. Virtual pole positions calculated from each set of the mean inclination and the mean declination for every 50 years.

$$\cot p = 1/2 \cdot \tan I$$
$$\sin \varphi = \sin \varphi_o \cdot \cos p + \cos \varphi_o \cdot \sin p \cdot \cos D$$
$$\sin (\lambda - \lambda_o) = \sin p \cdot \sin D/\cos \varphi ,$$

where p and (φ_o, λ_o) are the paleomagnetic colatitude and geographical coordinates of the sampling site respectively, I and D represent the past geomagnetic inclination and declination obtained from the experiments and (φ, λ) is the position of the virtual geomagnetic pole.

As can be seen in the diagram, the virtual pole has continuous, significant movement, drawing a long path around the geographic north pole, and it seems to complete a cycle in a comparatively short period, say about 1,500 years. It is interesting to point out that the virtual pole movement thus obtained consists basically of a counterclockwise rotation about a point on the vicinity of the geographic north pole with a period of about 1,500 years. Besides this basic counterclockwise motion, there exist at least three small clockwise looping or "back and forth" motions superimposing upon the basic counterclockwise motion. This minor clockwise motion has a period of approximately 500 years.

Hypothetic motion of the geomagnetic dipole axis

1) Counterclockwise rotation

In 1965 KAWAI, HIROOKA, and SASAJIMA proposed that the geomagnetic dipole axis has been continuing an anticlockwise rotation around the axis of the earth's rotation. The period of one complete rotation was assumed to be 1,500 years. The radius of the circle on which the north seeking pole has moved was supposed to be 1,100km. These authors came to this conclusion when they compared several archaeomagnetic data obtained from various parts of the world carefully with each other. In the virtual pole movements thus obtained at many points on the earth's surface, they could find such a conspicuous resemblance that a pole motion common to all places could be extracted.

What have been proposed by these authors on the basis of this simple model, however, implies the fact that the geomagnetic dipole field, when averaged out over only two thousand years, possesses the axis coincident with the earth's rotation. Furthermore it indicates that pole is moving conspicuously rapidly at a mean rate of about 0.2°/year.

This idea sounded quite unusual to many geophysicists who have learned that the geomagnetic secular variation is a phenomenon entirely local and independent, therefore, being different from place to place on the surface of the earth. It also sounded even stranger to many theoreticians who have been accustomed to consider the secular variation as having been caused by a so-called westward drift of the non-dipole fields of geomagnetism. For example, COX (1962), CREER (1962), NAGATA (1962), YUKUTAKE (1962, 1967) and CHAMALAUN (1968) have calculated each possible secular variation from the world geomagnetic chart showing the non-dipole field anomalies, or from the paleomagnetic data.

This anticlockwise rotation of the main dipole field also appeared as an unlikely phenomenon since the dipole field seems to have such a large momentum that it might not vibrate so rapidly as KAWAI *et al.* (KAWAI, HIROOKA and SASAJIMA, 1965) have reported in their original paper.

Further the above-mentioned westward drift or the large momentum of the geomagnetic field is lying on a following firm background of argument that, according to the spherical harmonic analyses on the world geomagnetic charts repeatedly carried out by many authors (VESTINE *et al.*, 1947; BULLARD *et al.*, 1959; LEATON *et al.*, 1965; YUKUTAKE, 1968), the present main field is believed to have been moving not only slow but also in a direction clockwise and opposite to the predicted movement. For example, NAGATA and RIKITAKE (1963) have estimated the dipole motion for the recent 5 years to be clockwise with a mean rate of rotation of about 0.02°/year, the value being only one tenth of the rate assumed by KAWAI, SASAJIMA and the present author. Next, VESTINE *et al.* (1963) in summarizing world magnetic observations have concluded that there exists no evidence supporting any movement of the axis since 1835 to 1955 A.D.

Therefore KAWAI and the present author (1967) came to a conclusion that an urgent modification of their original counter-clockwise rotation conception was required in order that the rotation might be reconciled with the clockwise and very sluggish motion today.

2) Hypothetic motion of the dipole field

We have now archaeomagnetic data available from various localities on the earth's surface for various periods. However, the data for the last two hundred years is highly sporadic, scarce or non existent. On the other hand in the records obtained at the geomagnetic observatories, no data are available regarding secular variations in the remote historic past. Spherical harmonic analysis was undertaken on the data of rather recent variation, while the counter-clockwise hypothetic rotation was postulated on the data representing the geomagnetic aspect of rather remote past. The combination of both records ancient and recent, and comprehensive consideration on the basis of the actual secular field seemed important, especially in the stage of this investigation shortly after the original proposal of the simple rotation.

The first step made in constructing the new hypothesis was to review the data from the world geomagnetic observatories in a procedure quite similar to what Kawai and the present author (1967) used in the archaeomagnetic investigation.

The geomagnetic observatories used in this review was those at London, Hongkong, Rio de Janeiro, Ascention Island, Cape Town, etc. Virtual pole position was obtained from observations in both the declination and the inclination at each observatory. Next, the time change of the virtual pole position estimated at each station is given by a curve in Fig. 17. In order to make wider collection of data from the earth's surface, some archaeomagnetic results such as those obtained from Iceland, Japan, and Italy were used. In the diagram a number of virtual pole traveling routes were drawn together.

It is interesting to point out in the diagram that the virtual pole positions in the past from 1700 A.D. to the present can be found from the first quadrant of the diagram almost without exception, regardless of the localities of the geomagnetic observatories

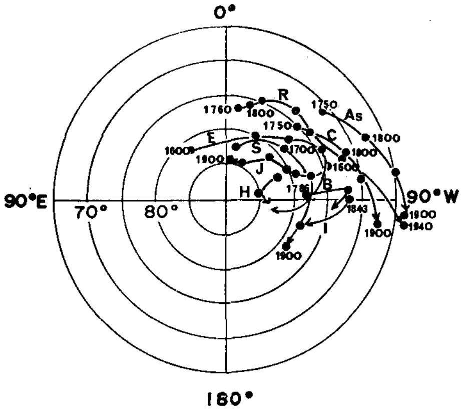

Fig. 17. Time changes of the virtual pole position of various localities after 1600 A.D. up to the present.

As : Ascention Island
B : Boston
E : England (London)
C : Cape Town
H : Hongkong
I : Iceland
J : Japan
R : Rio de Janeiro
S : Sicily

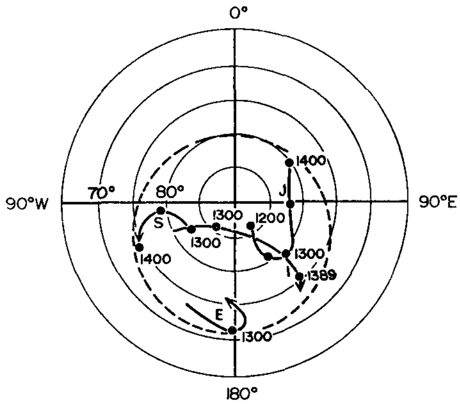

Fig. 18. Time changes of the virtual pole position of England (E), Iceland (I), Japan (J), and Sicily(S) in the period ranging from 1200 to 1400 A.D.

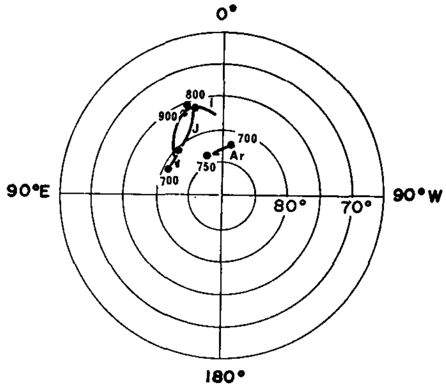

Fig. 19. Time changes of the virtual pole position of Arizona (Ar), Iceland (I), and Japan (J) in the period ranging from 700 to 900 A.D.

or of the sampling sites of the archaeomagnetic studies.

Next, in the period ranging from 1200 A.D. to 1400 A.D. the virtual pole positions can be found within a rather limited area enclosed by a dotted circle as shown in Fig. 18. Furthermore, in the period ranging from 700 A.D. to 900 A.D. the poles can be found also within a narrow area in the second quadrant of the diagram as shown in Fig. 19.

COX and DOELL (1960) have assumed that it is possible to substitute a virtual pole for the true dipole field when the number of stations is sufficiently large. They, therefore, took the mean virtual pole position of the lava flows in some geologic age, assuming it as the place at which the geomagnetic north seeking pole existed at that time in the geologic past. Although the number in the present analysis is still too small for accurate analysis, these data seem too important to be neglected. When the mean of these virtual pole positions in the respective time range was calculated in the respective diagram, the geomagnetic dipole axis was found to have been still continuing a similar anticlockwise rotation as KAWAI *et al.* (KAWAI, HIROOKA and SASAJIMA, 1965) have predicted.

An important characteristic of the pole movement to be emphasized is that the pole is moving in a clockwise direction instead of a counter-clockwise direction when it is looked at carefully over a very short interval of time. For example, in Fig. 17 pole path obtained in Japan shows a clockwise loop. Although the loops were all incomplete in other places, the movement of the pole is always in a direction definitely clockwise. In order, therfore, to compile the two different rotations, one having a longer period and the other a shorter period of rotation, KAWAI and the present author (1967) proposed a simple combination of the rotations. The combined rotation made the axis wobble in the fashion shown in Fig. 20. The most important significance of this motion is that with this combination it is possible to provide the pole movement with such a slow rate that the sluggish characteristic of the dipole motion today can be explained.

The counteracting two rotations, when they were combined, can accelerate the motion when the two rotations are in the same phase and decelerate it when they are mutually out of phase.

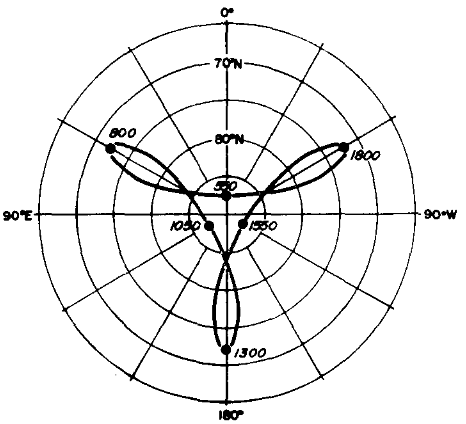

Fig. 20. The model of a hypothetic wobbling motion of the geomagnetic dipole axis. (After KAWAI and HIROOKA, 1967)

Consequently a slow pole movement is sandwitched in between two rapid motions and a rapid one can be found in between two slow motions. In other words, a quick pole movement is followed by a slow motion and so forth. The recent period since 1800 A.D. up to 1900 A.D. is indeed a special period when the phase of the counter-clockwise rotation was accidentally opposite that of the clockwise rotation. Accordingly, the rate was so extremely decelerated that even such analysis as that by Vestine showed no positive evidence for the pole movement that could have been derived (VESTINE *et al.*, 1963).

The most sluggish pole movement in the entire path appears when the axis is lying furthermost from the geographic north pole. At least three times in the past; i.e. in 800 A.D., 1300 A.D. and 1800 A.D. the pole was confirmed to have reached the farthest points at which the pole looked as though it stood still. On the other hand, the most rapid movement takes place when the axis is approaching the geographic north pole and located nearest to it. Also at least twice in the past; i.e. in 1050 A.D. and 1550 A.D. pole passed nearby the north pole at the quickest rate of motion, about 8km/year.

This combined rotation clearly shows that the separation of the geomagnetic field axis from that of the earth's rotation is not in the least a permanent state.

In 1968, KEIMATSU, FUKUSHIMA and NAGATA reported an interesting paper entitled "Archaeo-Aurora and Geomagnetic Secular Variation in Historic Time". In tracing geomagnetic secular variation they presented a completely different approach from that we used in the archaeomagnetic investigation. They utilized a number of documents regarding ancient aurorae recorded in both the Occident and the Orient. The frequency of the observed aurorae and the geomagnetic latitude are closely related as shown in Fig. 21. Frequency reaches the maximum value at 65–70° north in magnetic latitude and decreases to the value of once every ten years at 35° north, and even to that of once every thirty years at 31° north.

Consequently change of magnetic latitude can quite sensitively be traced at the places whose localities are close to the southernmost limit of the auroral observation. The change of the magnetic latitude is nothing but the change of the geomagnetic inclination. So, the archaeo-aurora can be related reasonably to the geomagnetic secular variation.

In their paper, KEIMATSU *et al.* (1968) pointed out an important appearance of an aurora which occurred on the Oct. 6th, 1138 A.D. On that very evening and on the following evening the aurora was seen in Prague. The event was found from the list compiled by FRITS (1873) and also from that compiled by LINK (1962). On the other hand, in the Orient the same aurora was observed at Hangchow in China, as reported by KEIMATSU (1965). Although the magnetic latitude is higher enough for the aurora to appear at Prague, the latitude in Hangchow was considered by them to

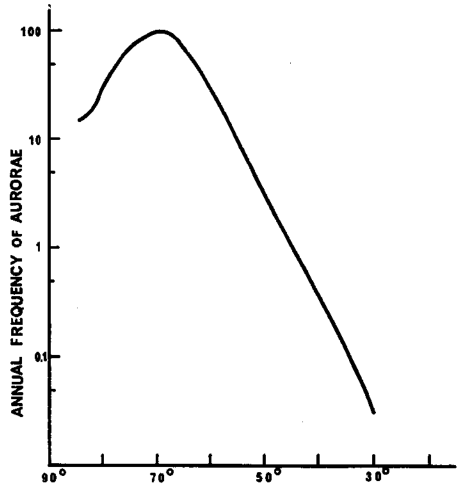

Fig. 21. The latitude dependence of the annual frequency of observed aurorae. (After VESTINE, 1944)

be so low that the aurora may not appear in that particular place. They, therefore, came to a conclusion that there should exist some reasoning, for example, that the dipole axis might have been inclined towards China in such a way that the city was within a visible region of the aurora in that period.

In 1965 when the above-mentioned authors were preparing their report, KAWAI, SASAJIMA, and the present author proposed a counter-clockwise rotation of the dipole axis around the geographic north pole. This rotation demonstrates that Hangchow was about 18° closer to the geomagnetic north pole in 1138 A.D. as compared to the present time. Hangchow, therefore, had a higher magnetic latitude of more than 40 degrees north, on which one can observe the aurora with a reasonable frequency about once every several years.

Although the original, simple, counterclockwise rotation of the dipole axis was abandoned by KAWAI and the present author (1967) soon after its proposal, the high magnetic latitude of China in the period around 1138 A.D. was explained even in their revised concept of motion containing two mutually counteracting rotations (Fig. 22).

Recent theoretical studies on the stability of the geomagnetic field show that the motions in the earth's core could not be symmetrical as BULLARD proposed but asymmetric to maintain the geomagnetic dynamo regenerative (NAGATA, 1969; LILLEY, 1970; JACOBS, 1971). LILLEY suggested that this asymmetry brings out the deviation and the wandering of the geomagnetic dipole axis from the rotational axis. As NAGATA pointed out, the collapse of the geomagnetic field will take place when the flow pattern

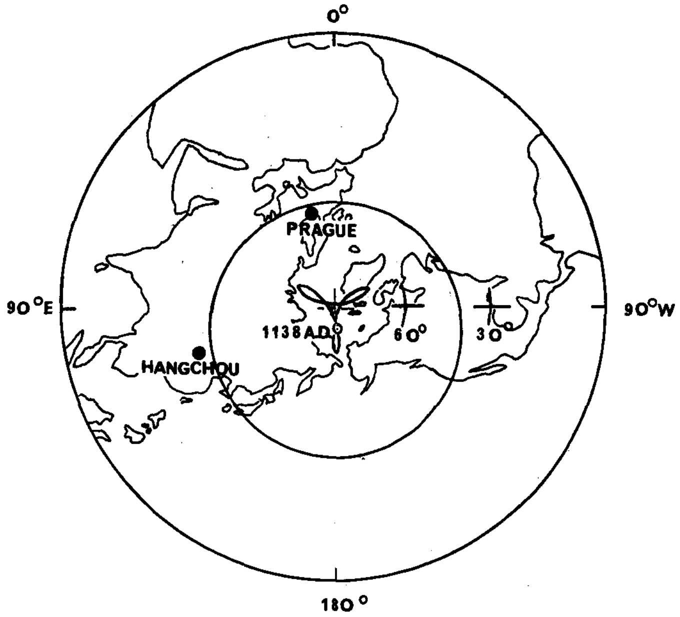

Fig. 22. Two localities from which the same aurora was observed on Oct. 6th, 1138 A.D. The circle shows the region where aurora was observed more than once every ten years.

in the core becomes symmetric. NAGATA and JACOBS considered this is the mechanism of the geomagnetic field reversals.

Thus mentioned above, the hypothesis of the wobbling motion of the dipole axis is supposed to be very reasonable from the theoretical study of the earth's dynamo.

Change in the intensity of the geomagnetic field

E. THELLIER and O. THELLIER (1959) proposed that the intensity of the geomagnetic field at the beginning of the Christian Era was 50% greater than that of the present field and also suggested that the geomagnetic field has been decreasing its intensity steadily during these 2,000 years. Recently many authors published their results of investigations on this subject at various places of the world such as Caucasus, USSR (BURLATSKAYA, 1961), Japan (NAGATA *et al.*, 1963; SASAJIMA and MEANAKA, 1967; KITAZAWA, 1970), Arizona, U.S.A. (DUBOIS and WATANABE, 1965; BUCHA *et al.*, 1970), Czechoslovakia (BUCHA, 1965, 1967a and 1967b), Mexico (NAGATA *et al.*, 1965; BUCHA *et al.*, 1970), Peru and Bolibia (NAGATA *et al.*, 1965; KITAZAWA and KOBAYASHI, 1968), India (ATHAVALE, 1966) and Egypt (ATHAVALE, 1969).

The results of these studies demonstrated that the geomagnetic field of about 2,000 years ago was higher than that of the present as THELLIER and THELLIER have pointed out.

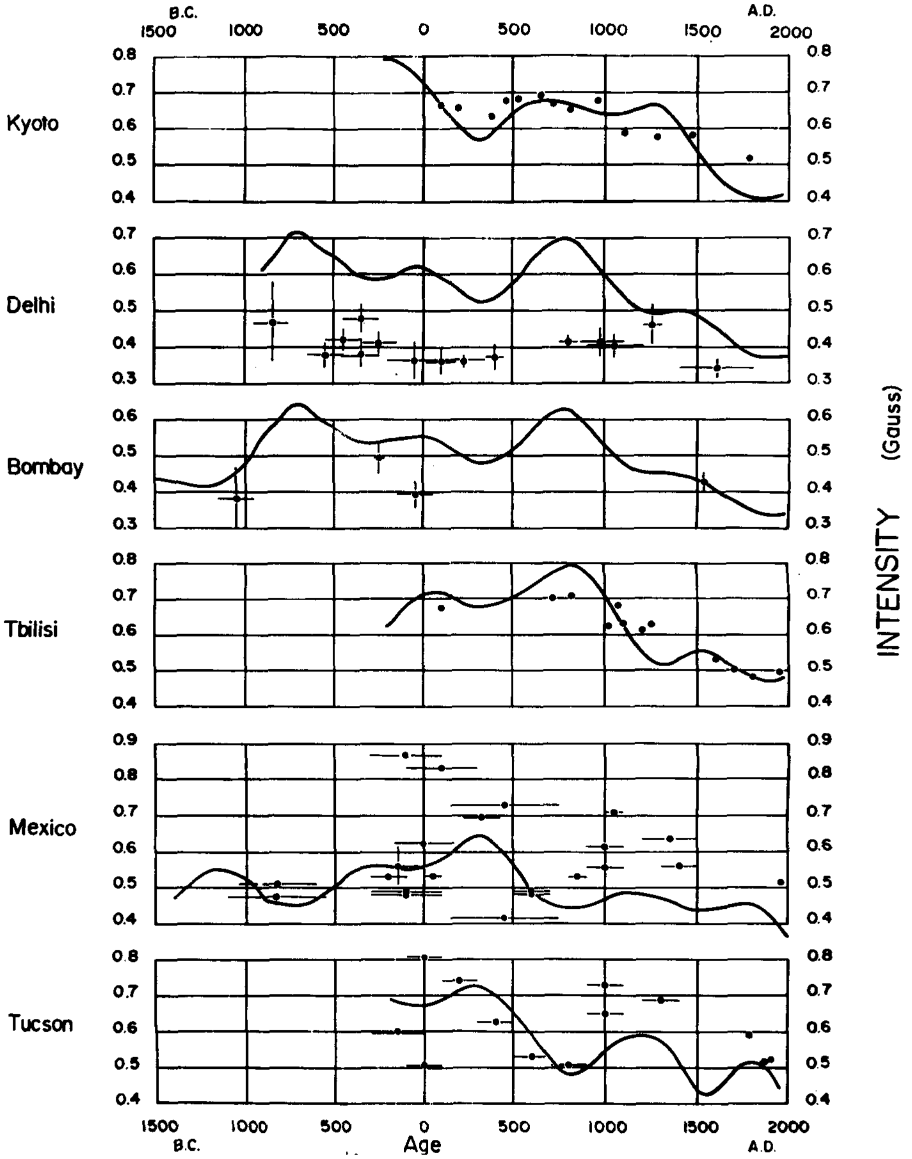

Fig. 23. Changes of the total intensity in various localities. Curves show the expected changes calculated on the basis of the dipole moment fluctuation and hypothetic wobbling of dipole axis and dots are the experimental data.

(Kyoto : after SASAJIMA and MAENAKA, 1966; Delhi and Bombay : after ATHAVALE, 1966; Tbilisi : after BURLATSUKAYA, 1961; Mexico : after NAGATA *et al.*, 1965 and BUCHA, 1970; Tucson : after BUCHA, 1970)

However, the field intensity seems to have been decreasing not steadily as they suggested but with small increasing and decreasing fluctuations during these 2,000 years.

Supposing that the geomagnetic field is caused only by the geomagnetic dipole, the total intensity of the geomagnetic field intensity F at some point A on the surface of the earth is expressed by the following equation,

$$F = 2M/R^3 \cdot (1 + 3\cos^2 I)^{\frac{1}{2}}$$

where M,R and I are the geomagnetic dipole moment, the radius of the earth and the inclination at point A respectively. At the geomagnetic poles where $\cos^2 I$ is equal to 1.0, the value of total intensity F becomes maximum and it is twice the value at equator where the total intensity becomes minimum.

When the geomagnetic dipole axis inclines towards a fixed point A, the geomagnetic inclination of that point increases so that the intensity of the field at the point becomes larger.

So the apparent total intensity change is expected at every point on the earth's surface if the geomagnetic dipole axis wobbled as mentioned in the previous chapters. Since the period of the hypothetical wobbling motion of the geomagnetic dipole axis is about 1,500 years, the intensity change should have the same period of variation. KAWAI and the present author (1967) presumed that both the change of dipole magnetic moment and the apparent intensity change originated from the wobbling of the dipole axis are the main cause of the secular variation of the geomagnetic field intensity. The effect of movements and vicissitudes of non-dipole components is superimposed on this main secular variation.

According to the analysis of the world-wide data of intensity measurements made by BUCHA (1967b) and KITAZAWA (1969), the geomagnetic dipole moment has been fluctuating with the period of about 8,000 years and it was 2,000 years ago when the dipole moment achieved a maximum value.

In Fig. 23 the curves are showing the expected intensity change which is calculated on the bases of this dipole moment fluctuation and hypothetical wobbling of dipole axis at Kyoto, Delhi, Bombay, Tbilisi, Mexico, and Arizona where the results of investigations on intensity covering more than one thousand years are available. In this figure, the mode of increase and decrease of these curves shows good agreement with that of dots which show the experimental data only with the exception of Delhi.

Conclusions

The archaeomagnetic study in the Tokai, Kinki, Chugoku and Kyushu districts clarified the secular changes of both the declination and the inclination of the past from 100 A.D. until the present in southwestern Japan. The inclination varies from

35° to 60° showing three maxima (at 240 A.D., 660 A.D. and 1250 A.D.) and three minima (at 480 A.D., 870 A.D. and 1520 A.D.) during these 1,900 years. The declination change is classified into two types of periods, one is represented by a continuous westerly declination and the other by an easterly one.

Virtual pole positions obtained from the above-mentioned secular variation show that the pole has been moving around in an area of higher latitude than 70° north. The center of the motion does not agree with the present geomagnetic pole but is in the vicinity of the geographic pole. This virtual pole motion seems to support the hypothetic wobbling of the geomagnetic dipole axis which KAWAI and the present author had proposed in 1967 (KAWAI and HIROOKA, 1967; KAWAI *et al.*, 1967).

Recently, precise studies on the intensity change in historic times were carried out in many places of the world. Except in a few cases, the results of these studies show that the intensity change is concordant with the expected change calculated from the hypothetic dipole wobbling.

Archaeo-aurora, a study of the past geomagnetic field on a quite different approach from archaeomagnetism, revealed the fact that the dipole axis was inclined towards China in the time of 12th century. This fact gives strong support to the dipole wobbling proposition.

On the evidence mentioned above, the present author comes back to the same opinion which KAWAI and the present author had earlier proposed; that is, that the secular variation of the geomagnetic field is caused mainly by the wobbling motion of the geomagnetic dipole axis though the movements and the vicissitude of the non-dipole components also have some effects on it.

Although this study is not intended as a procedure of using secular variation for the dating of baked clay in archaeological remains, the characteristic changes of both the declination and the inclination are useful for that purpose, especially in the event that no archaeological evidence which can tell the age of the artifact is found.

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Appendix

Description of sampling sites

Tano Remains

Locality: Tano, Amagasaki City, Hyogo Prefecture.

This site had been a dwelling and burial place throughout the Yayoi period. Seventeen graves and three dwelling pits were excavated in 1965 and 1966 by the Amagasaki City Tano Remains Excavation Survey Commitee (Amagasaki City Tano Remains Excavation Survey Commitee, 1967).

A large area (4,410 m^2) of excavation, nevertheless, very little hearth evidence or other fired clay artifacts were found in this site. Only two places were feasible to be submitted to archaeomagnetic measurement.

i) Tano-TN-5-L60

Samples were obtained from baked earth in a pit which seemed to be a hearth. A potsherd was found on the surface of the baked wall of the pit. The pattern of scratches on its surface shows its date to be around the middle part of the Middle Yayoi Period (1 A.D. $\pm$100).

ii) Tano-4-3-6

Although 34 samples were taken from the excavated baked floor, the baking was so weak that the samples did not get enough thermoremanent magnetization for measurements except in 12 samples. 10 samples were used for the calculation of mean direction of N.R.M. because the other two had a very deviated direction. The time of baking was dated as the later half of the Middle Yayoi Period from archaeological evidence.

Miyanomae Remains

Locality: Miyanomae-Cho, Ikeda City, Osaka Prefecture.

This site has been known by archaeologists as a remains where many potsherds were found dating from various ages after the beginning of the Middle Yayoi Period. In 1969 the members of Osaka Prefectural Board of Education and Kokushikan University excavated this site. They found 12 dwelling pits and 20 graves with square ditches around them of the Yayoi Period, 4 dwelling pits and 3 graves of the Kofun Period, and 20 dwelling pits of later ages.

Samples collected from hearths in dwelling pits GI-51 and GP-49-I were measured.

i) Miyanomae-GI-51

A hearth in the center of round dwelling pit GI-51 is the source of 14 samples. The age of this pit is considered to be in the later half of the Middle Yayoi Period (50 A.D. $\pm$80). 10 samples are used for the calculation of mean direction among 13 measurable ones.

ii) Miyanomae-GI-49-I

Dwelling pit GP-49-I was constructed right above the older dwelling pit GP-49-II. The hearth was built not in the center but in the southeast quadrant of the round pit. The age of this hearth is estimated 150 A.D. $\pm$50 years on the basis of the shape and the patterns of pots excavated.

Benitakeyama Remains

Locality: Benitake-Cho, Takatsuki City, Osaka Prefecture.

One circular and seven square dwelling pits were found on the eastern slope near the top of a hill called Benitakeyama by an excavation in 1970. The dwelling pits are numbered from one to eight. Their age was determined as that of Type V in the Yayoi period. Baked clay samples from the 6th and 7th dwelling pits were submitted for archaeomagnetic measurement.

i) Benitakeyama-7

The 7th dwelling pit is situated in the northeastern corner of the site and has a circular ditch around the floor on which a heap of charred timbers and ashes were found. The house built on the floor caught fire in ancient times. Pottery relicta excavated from this pit belong to Type V in the Yayoi period (250 A.D. $\pm$ 50). Samples were taken from this burnt floor.

ii) Benitakeyama-6

Samples were obtained from a hearth in the center of the square floor of the 6th dwelling pit. The age of this pit is a little younger than that of the 7th pit and is considered to be the end of Type V (300 A.D. $\pm$ 50).

Habikino Kiln Site

Locality: Hakucho-3, Habikino City, Osaka Prefecture.

Nine kilns were discovered at the time of the land readjustment for a new road construction. The archaeologists of Osaka Prefectural Board of Education excavated these kilns during September and October in 1969. Many dolls, cylinders and shields made of baked clay called Haniwa were found about the kilns. Haniwa were produced for funeral use in Kofuns when the leaders of tribes died. The construction of these excavated kiln dates from the middle of 5th century (NOGAMI, 1970). Eight kilns were found altogether in a small place. These were numbered from one to eight. One additional kiln was discovered at a point 200 m west of the eight kilns. Habikino-Wl is the name of this kiln. The kiln Habikino-6 had been so completely destroyed by the readjustment that only ashes and potsherds which were deposited in front of the kiln remained when the archaeologists began to excavate. Habikino-7 was reburied soon after the excavation finished to preserve it from weathering and artificial destruction. Consequently no samples could be obtained from these kilns. The directions of remanent magnetization of 9 samples from Habikino-2 were so scattered that the result of measurements can not be used for archaeomagnetic study.

All the kilns in this site are Noborigama type but smaller in their size as compared to kilns in other sites.

i) Habikino-1

The floor of this kiln has two layers which come one on the top of the other. The upper layer was newly built when the kiln was repaired in ancient times. So the upper one is difinitely younger than the lower, but the time difference of the magnetization of two layers is considered to be smaller than 15 years. In this paper, the lower and the upper layers are expressed by Habikino-1-1 and Habikino-1-2 respectively.

ii) Habikino-3

The lower half of fireplace of this kiln was cut away and was destroyed by the public works. Three layers were confirmed in the floor of this kiln. That means this kiln had been repaired twice during its use. Samples were taken from each layer and notation 1, 2 and 3 were suffixed to the kiln name, Habikino-3, to express the lowest, the middle and the top layer respectively.

Sue Village Kiln Site

Locality: Sakai City, Izumi City, Kishiwada City and Sayama Cho, Osaka Prefecture.

This site covers a large area of 15 Km from east to west and 9 Km from north to south and stretches over Sakai City, Izumi City, Kishiwada City and Sayama Cho in Osaka Prefecture. For this large kiln site, Tanabe (1966) proposed to use the name "Sue Village" which appears first in the earliest Japanese annals "Nihonshoki". This is the oldest and largest site of the production of Sue type ceramics. More than 1000 kilns were constructed in this area in the five centuries duration after 400 A.D. The main part of the area is divided into four blocks from west to east, namely, Komyoike, Toga, Takakuradera and Tokiyama. The kilns were numbered consecutively within each block. To indicate which block the kiln belongs to, notation KM, TG, TK, and MT were used in front of kiln numbers for Komyoike, Toga, Takakuradera and Tokiyama blocks respectively. Archaeomagnetic samples were collected from 14 kilns in Komyoike block, 8 in Toga block, 27 in Takakuradera block and 7 in Tokiyama block. The kilns were divided into four periods and 19 stages according their age as already stated.

Kilns TK-212, MT-84 and MT-85 were excavated by Tanabe and Yokoyama in 1961, 1962, 1963, 1964 (Yokoyama and Tanabe, 1963; Tanabe and Yokoyama, 1965), and all of other kilns were excavated by the archaeologists of Osaka Prefectural Board of Education during from 1965 to 1970.

Description of several kilns is given in the following.

i) KM-11

The floor of this kiln is doublesoled. 25 samples were gotten from the upper layer (KM-11-U) and 7 from the lower (KM-11-L). This kiln belongs to Period II and Stage K.

ii) KM-28

Two kilns were excavated on the southern slope of a hill which is to the east of the pond Komyoike. The northern kiln is styled KM-28-I and the southern one KM-28-II. KM-28-I has two layers in its floor, but the upper layer had already been removed at the time of excavation. So the samples were obtained only from the lower layer (KM-28-I-L). KM-28-I-L and KM-28-II appertain to Period II, Stage K and Period III, Stage L respectively.

iii) KM-38

Three kilns, KM-38-I, II and III, were excavated on the north-side of a hill lying east of the Komyoike and jutting north to the Yamadaike. They were arranged in order of KM-38-II, I and III towards the east and built in such a way that the axis of their draft was almost perpendicular to contour lines of the hill. KM-38-I was a kiln of the Noborigama type bearing many pieces of various Sue ceramics. KM-38-II (Fig. 6) was a kiln of the Hiragama type. Many pieces of various Sue pottery were also excavated in this kiln. The most unusual and conspicuous characteristic which this kiln had was that this kiln played two roles, that is, as a Hiragama for firing Sue pottery and as a Kawaragama for firing roof-tiles. In the pieces of earthenware excavated in this kiln, a lot of pieces of roof-tile were found as well as pieces of Sue pottery, and it is worthy of special mention that these pieces there are several pieces of roof-tile, on the back surface of which several characters were carved. Some of these characters show that these roof-tiles were specially made for the temple, Oobadera, whose foundation is said to be at 750 A.D. according to Gyokinenpu (an early annals), hence the age of this kiln can be regarded as 700 A.D. ± 10 years. Since the kiln KM-38-III was in a bad state of preservation, it is almost impossible to ascertain what type this kiln was.

iv) TK-43

As the kiln TK-43 had been reconstructed three times, it can be counted four kilns which overlying one on the top of the other. These kilns were named A, B, C and D from the top to the bottom. The uppermost kiln (TK-43-A) is the youngest and TK-43-D is the oldest. These kilns have 11 layers altogether in their floors, that is, TK-43-A has 3 layers, TK-43-B has 4 layers and TK-43-C has 3 layers. Samples were collected from the 3 layers of kiln A (TK-43-AU, AM and AL), from the upper 3 layers of kiln B (TK-43-B1, B2 and B3), from the uppermost layer of kiln C and from kiln D. All of the kilns are considered to be in Period II and Stage H.

Kishibe Kiln Site

Locality: Kishibe, Suita City, Osaka Prefecture.

Nine kilns were excavated side by side on the south slope of Shikinzan Hill. They are considered to have been kilns of Hiragama or Kawaragama, and they were labelled east in order by the designation from H_1 to H_9. Another four kilns of the Noborigama type were also found in a row at a slightly higher place on the same slope, and given the designation N_1 to N_4 east in order.

Almost all the artifacts excavated with these kilns were pieces of roof-tiles. Since it was found that some of these roof-tiles were made with the same mould as that of the Heian palace, Fujisawa (1968) considered that the kilns had been specially built to bake roof-tiles for the Heian palace, and abandoned just after the completion of the palace. Hence these kilns can now be regarded as used in 790 A.D. ± 10 years.