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Abstract

Paleomagnetic studies were carried out on the Late Cenozoic rocks in the Togo area, Hokusatsu district, southern Kyushu. Paleomagnetic data were obtained from twelve sites of the Togo and Kasayama Formations, and Togo Andesites.

These data sets are primary natural remanent magnetizations because of a positive result of the reversal test. The Togo Formation and hornblende andesite lava of Togo Andesites have reversed polarity magnetizations. The basaltic andesite lava of the Togo Andesites which is the uppermost layer of the Late Pliocene succession in the area has a normal one. The K-Ar age of the basaltic andesite lava is 2.9 ± 0.2Ma. Consequently, the normal polarity of the lava corresponds to the C2An.1n normal polarity subchron (2.58-3.04 Ma) and the Togo Formation may be correlated with the C2An.1r reversed polarity subchron (3.04-3.11 Ma) which is just before the C2An.1n. The results from the polarity sequence reveal that the Togo Formation is lower horizon than the Nagano Formation of which age is 1.8-2.6 Ma, although the Togo Formation has been thought to be the same horizon of the Nagano Formation.

The overall mean direction of Pliocene rocks in the Togo area is Dec = 330°, Inc = +45°, α_{95} = 13°, and accords with the paleomagnetic directions of Middle Miocene to Pliocene in southern Kyushu. The deflection in southern Kyushu becomes small until 0° at Early Quaternary time. The Togo Formation having westward deflection seems to be older than the Nagano Formation of no westward deflection from the consideration of a counterclockwise rotation. The estimation of these tectonic aspects is concordant with the results from the polarity sequence.

Key words : paleomagnetism, magnetostratigraphy, Togo Formation, Nagano Formation, Hokusatsu district

Introduction

The Late Cenozoic *lake* deposits are distributed sporadically in the Hokusatsu district, southern Kyushu. All of them have been simply dealt with "the Nagano Formation" or "the formation correlative with the Nagano Formation". Such a treatment was caused by the ambiguous definition of the type locality of the Nagano Formation. The definition of the Nagano Formation had appeared only in unpublished manuscripts. Yamamoto and Otsuka (1995) have firstly shown the detailed stratigraphy of the type section of the Nagano Formation which is Late Pliocene to Early Pleistocene in age. Ueno et al. (1999) have paleomagnetically studied on the age of the Nagano Formation together with the Yamagano gold mineralization age. The Togo Formation crops out 20 km west of the type locality of the Nagano Formation. Based on pollen assemblages, the Togo Formation was assumed to be the same stratigraphic horizon of the Nagano Formation in the same paper of Yamamoto and Otsuka (1995). However, the exact correlation has been still uncertain.

It is possible to determine the accurate age of the stratigraphic section using the polarity sequence of the remanent magnetization. Firstly, the polarity sequence of the Togo Formation is examined to determine the age of the formation.

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On the other hand, pre-Quaternary rocks in southern Kyushu are characterized paleomagnetically by about 30° westward deflection of declination. This deflection is explained by a counterclockwise rotation of southern Kyushu during Late Pliocene time (Kodama et al., 1995). The deflection has decreased gradually (Okuda et al., 1997). It is also possible to estimate the age by using the degree of the westward deflection.

It is the purpose of this study to define the age of the Togo Formation comparing with that of the Nagano Formation at the type locality.

Geology and sampling

The basement in the Togo area is the Middle Cretaceous Shimanto Supergroup composed of dark gray sandstone and black shale, and crops out in the northern part of the investigated area (Fig. 1). The Late Cenozoic sediments and igneous rocks cover this supergroup. Those are Togo and Kasayama Formations, Togo Andesites, and Late Pleistocene pyroclastic rocks in ascending order (Fig. 2).

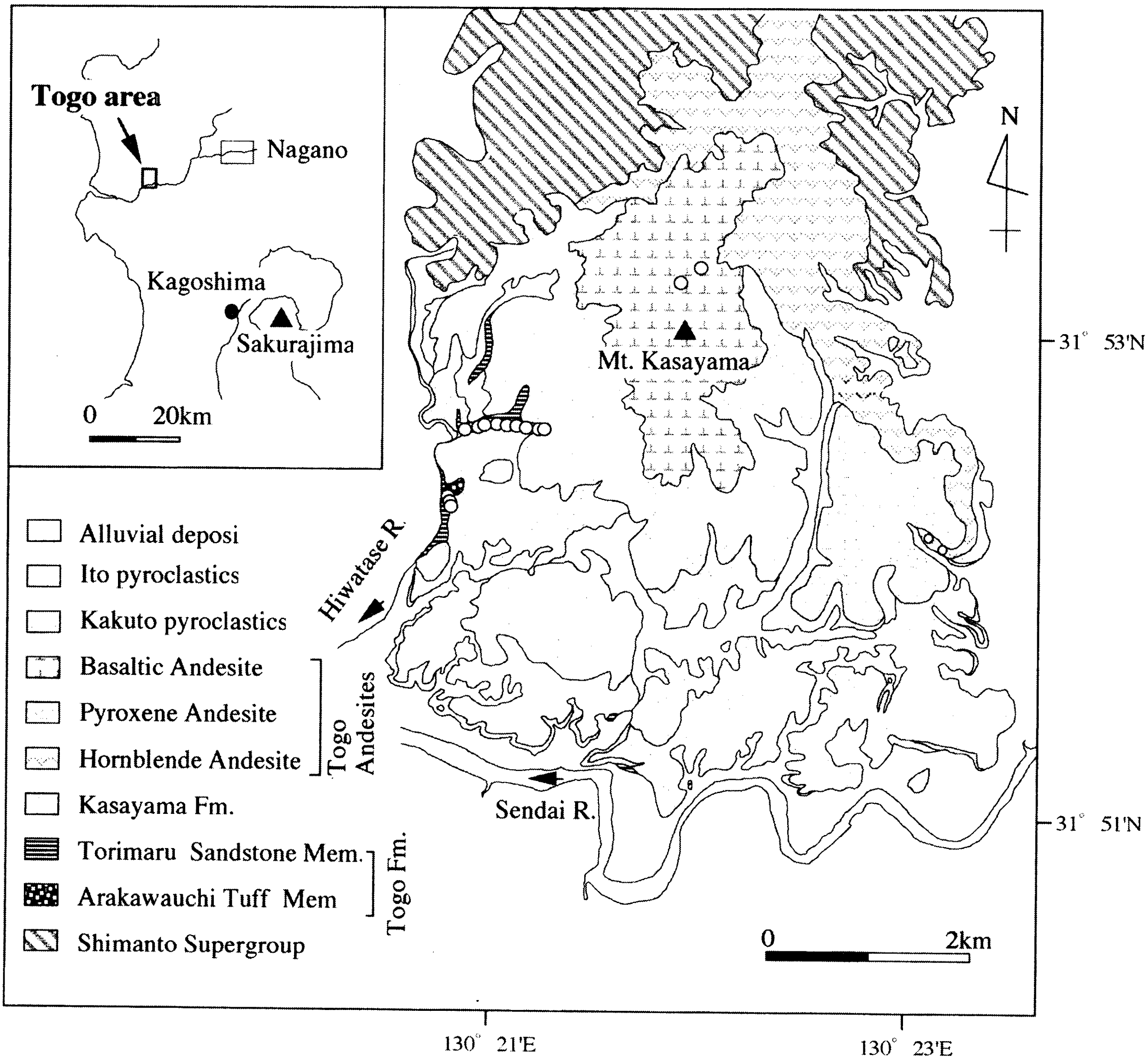

Figure 1. Geological map of the Togo area, Hokusatsu district, southern Kyushu.
Open circles show the paleomagnetic sampling sites. Simplified after Yamamoto and Otsuka (1995).

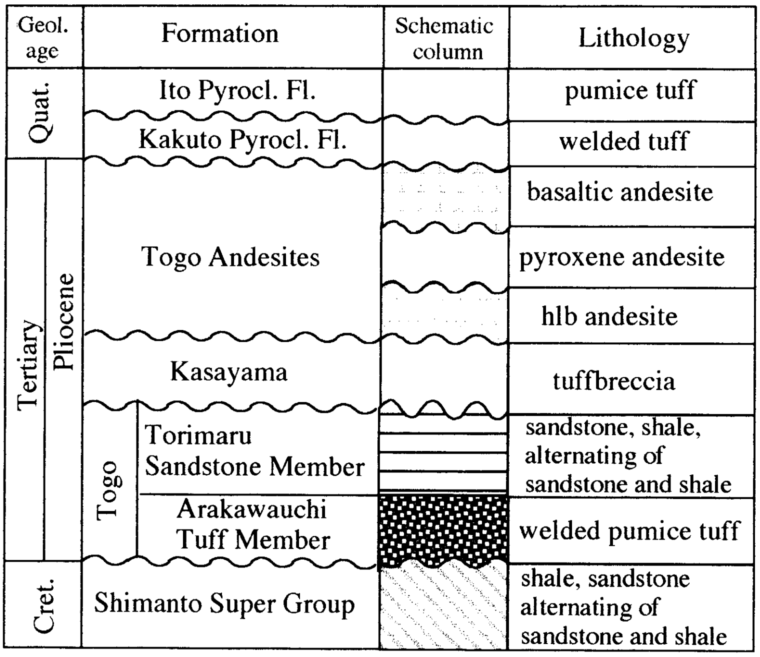

Figure 2. Stratigraphy of the Late Cenozoic formations in the Togo area, Hokusatsu district, southern Kyushu.

The Togo Formation is divided into two members, the Arakawauchi Tuff and Torimaru Sandstone Members (Yamamoto and Otsuka, 1995). The Arakawauchi Tuff Member of 15 meters in thickness is weakly consolidated pumice tuff, and exposes in the eastern side of the Hiwatase River, one of a tributary of the Sendai River (Fig. 1). The Torimaru Sandstone Member of 30 meters in thickness conformably overlies the Arakawauchi Tuff Member, and consists mainly of well-laminated sandstone, mudstone and alternation of them with fragment intercalations of scoria tuff and pumice layers in the upper part of the sequence (Yamamoto and Otsuka, 1955). This member yields abundant ever-green plant fossils indicating temperate climate (Iwao, 1974). The Kasayama Formation having a maximum thickness of more than 150 meters conformably overlies the Torimaru Sandstone Member, and consists of tuff breccia with some intercalations of tuffaceous shale and sandstone. The lower part of this formation, furthermore, contains occasionally large blocks of sandstones derived from the Torimaru Sandstone Member.

The constituents of the Togo Andesites are of hornblende andesite, pyroxene andesite and basaltic andesite lavas. A large part of the basaltic andesite unconformably overlies the Kasayama Formation. The K-Ar age of this lava is dated as 2.9 ± 0.2 Ma (Table 1). The Late Quaternary pyroclastic flow deposits, Kakuto and Ito, cover Pliocene rocks widely.

Paleomagnetic oriented core samples were obtained from the Togo and Kasayama Formations, and Togo Andesites. They were collected with a portable core drill, and oriented by sun and magnetic compasses. The core samples were cut into specimens of 22 mm long in the laboratory, and a total of 127 specimens were prepared.

Paleomagnetic results

Natural remanent magnetizations were measured by a Schonstedt SSM-2A spinner magnetometer. Based on the pilot measurement of stepwise alternating-field (AF) demagnetization up to 70 mT, all specimens were demagnetized in more than 6 steps. AF demagnetization was conducted with a three-axis tumbler demagnetizer (Ueno and Tonouchi, 1987). Measured results of stepwise demagnetization were plotted on a vector component diagram (Zijderveld, 1967). The characteristic remanent magnetization (ChRM) was defined by the minimum three

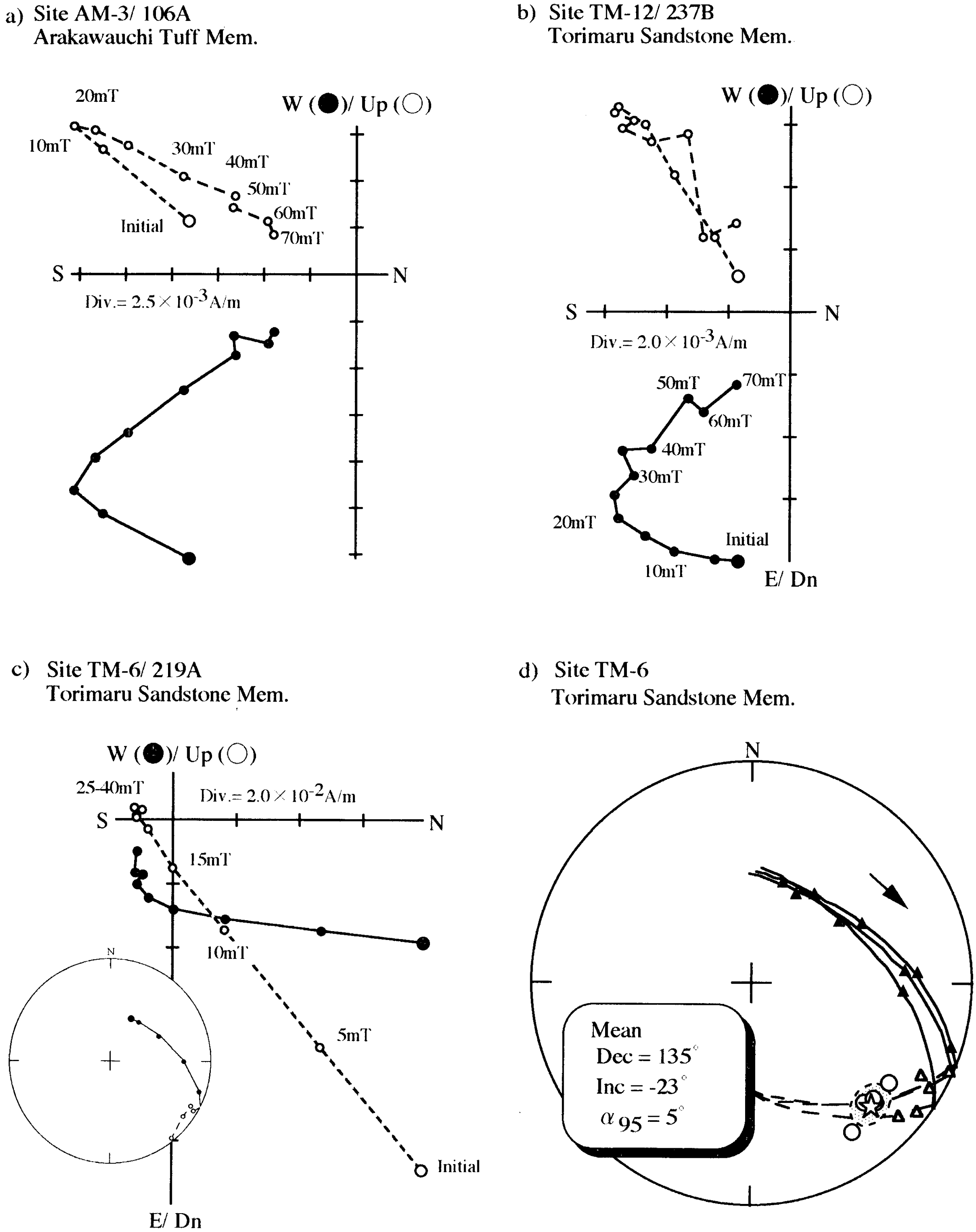

Figure 3. Typical AF demagnetization plots on the vector component diagrams and equal-area projections for the Togo Formation. a) The Arakawauchi Tuff Member. b) Scoria tuff of the Torimaru Sandstone Member. c) Sandy silt from the Torimaru Sandstone Member. d) Site mean direction of Site TM-6 (Torimaru Sandstone Member), which was calculated by the great circle method of McFadden and McElhinny (1988). Open (solid) symbol denotes the upper (lower) hemisphere projection. Triangles represent the directions used for the least squares computation of the great circle. Circles show the direct observations. The star and oval denote the site mean direction and its 95% confidence circle.

data points showing a linear segment toward the origin on the diagram. The ChRM was calculated by a principal component analysis (Kirschvink, 1980). Data whose maximum angular deviation was smaller than 20° were employed. Paleomagnetic data are summarized in Table 2.

Initial natural remanent magnetization intensities of the Togo Formation are 4.2×10^{-2} A/m on average. The specimens possess two component magnetizations of low and high coercivity (Figs. 3a, 3b, 3c). The high coercivity component is directly detected from the Arakawauchi Tuff Member and Torimaru Sandstone Member (Figs. 3a, 3b). These components are reversed ones. The curvature during the demagnetization range above 20 mT in other sedimentary specimens is interpreted as an overlap of low and high coercivity components (Fig. 3c). During the progressive AF demagnetization, the direction moves toward that of a reversed polarity (Figs. 3c, 3d). Although it is difficult to find out the ChRM directly in such a case, the located point of ChRM could be estimated by the great circle method of McFadden and McElhinny (1988). The calculated overall mean direction of the high coercivity components, which is denoted as R1 and obtained from the Arakawauchi Tuff (R1* in Table 2) and Torimaru Sandstone (R1** in Table 2) Members, is Number (N) = 8, Declination (Dec) = 139°, Inclination (Inc) = -39°, the radius of 95% confidence circle (α_{95}) = 9° in stratigraphic coordinates (Fig. 7-R1). This mean direction (R1) is characterized by westward deflection of 41° in declination. The low coercivity component of both members is found below 20 mT, showing a normal magnetization. The mean direction of the low coercivity components is indistinguishable from the expected dipole direction at the investigated area (Fig. 4). This fact indicates that the low coercivity component seems to be a secondary overprinted viscous remanent magnetization (VRM).

Paleomagnetic directions of the Kasayama Formation were obtained from some intercalations of tuffaceous shale. They are characterized by overprinted components which may be the VRM components. During the progressive AF demagnetization up to 70 mT, the paleomagnetic direction moves toward southern upper hemisphere. Although the directions do not reach the final southern upper hemisphere, this gradual migration of the direction may show that the polarity of the Kasayama Formation is reversed (Fig. 5).

The hornblende andesite lava of the Togo Andesites which is distributed in the east of the Mt. Kasayama shows a reversed magnetization (Fig. 6a). The mean direction is N = 2, Dec = 226°, Inc = -63°, α_{95} = 14°(Fig. 7-R2). The basaltic andesite lava which is the uppermost formation of the Togo Andesites also has two component

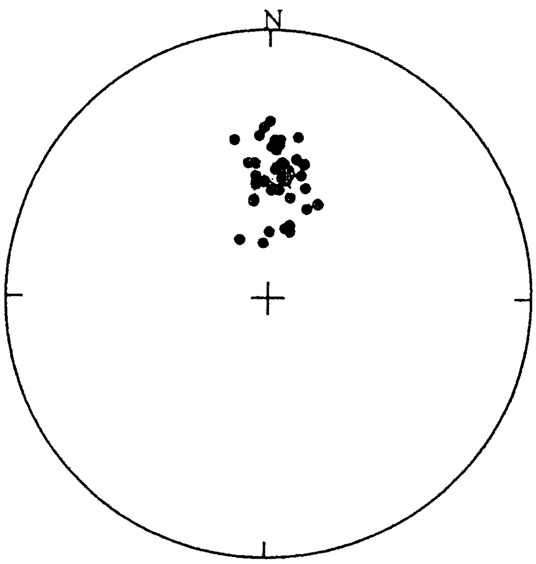

Figure 4. Distribution of the low coercivity magnetization components of the Togo Formation on the equal-area projection.

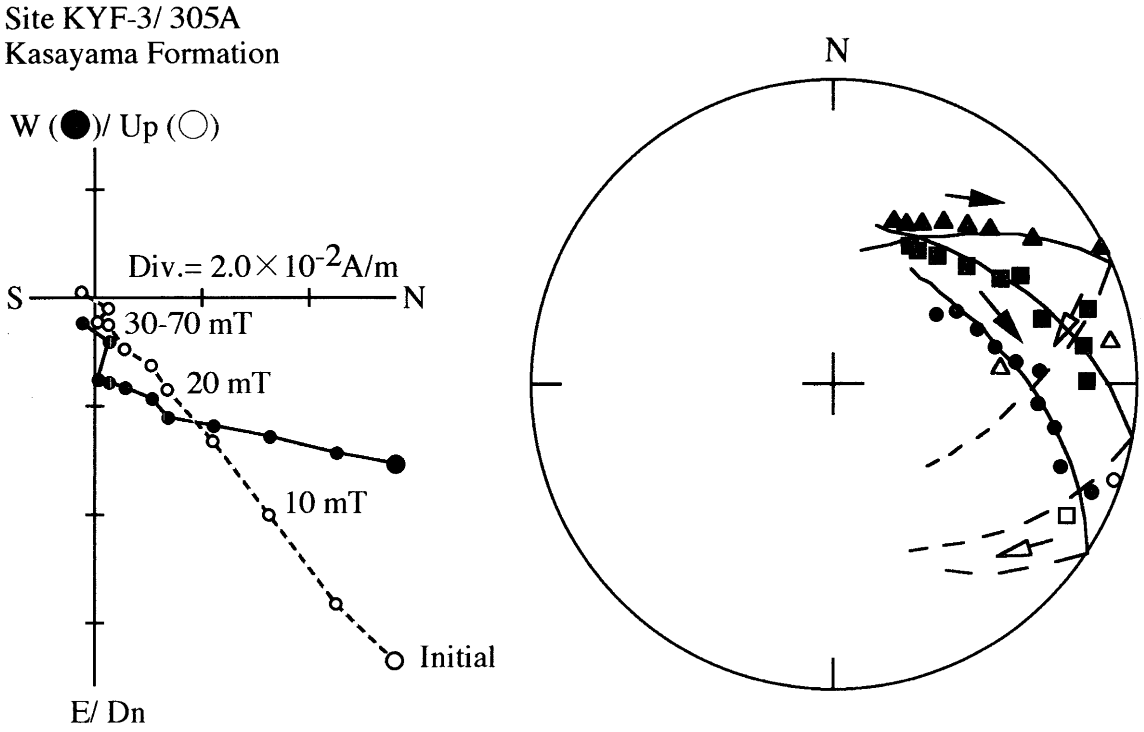

Figure 5. Typical vector component diagram (left) and equal-area projection (right) for the Kasayama Formation. Solid and dashed arcs indicate the best fit great circle of each specimens. Other conventions as in Figure 3.

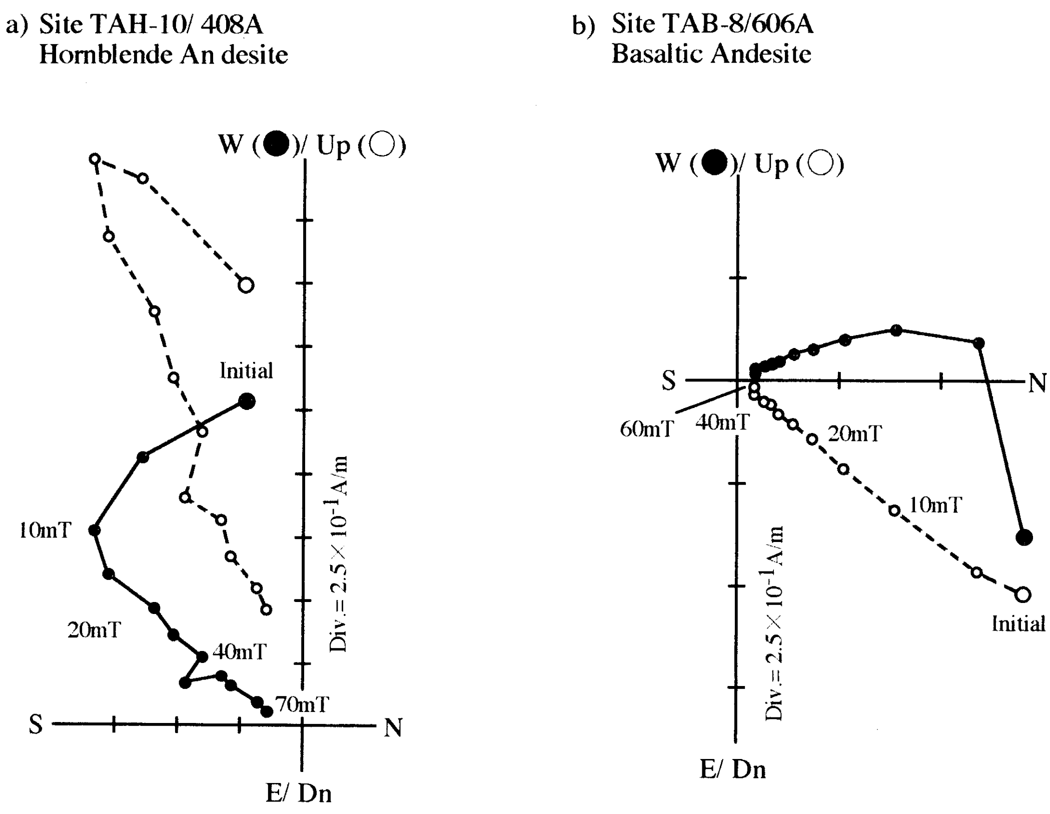

Figure 6. Typical AF demagnetization plots on vector component diagrams for the Togo Andesites.
a) Hornblende andesite. b) Basaltic andesite.

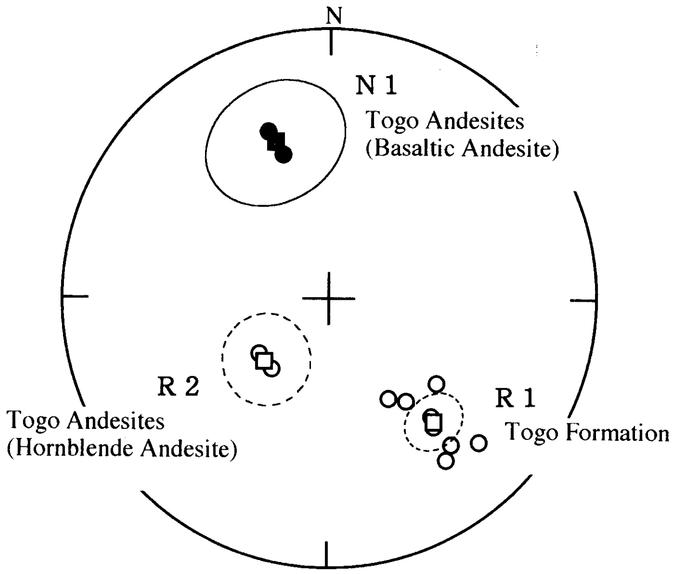

Figure 7. Equal-area projection of the site mean directions and formation mean directions in stratigraphic coordinates.
Squares and ovals show overall mean directions and their 95% confidence circles. Other conventions as in Figure 3.

magnetizations. At early demagnetization steps (<15-20 mT), an unstable component disappears and a stable normal magnetization is detected above 20 mT (Fig. 6b). The mean direction after AF demagnetization of the basaltic andesite lava is N = 2, Dec = 340°, Inc = +38°, α_{95} = 20°, showing the westward deflection in declination (Fig. 7-N1).

Discussion and conclusion

In order to examine the reliability of the paleomagnetic data, the reversal test (McElhinny, 1973) is carried out. The mean direction of the reversed polarity (R1* + R1** + R2 in Table 2) is N = 10, Dec = 147°, Inc = -47°, α_{95} = 16°, and that of normal one (N1 in Table 2) is N = 2, Dec = 340°, Inc = +38°, α_{95} = 20°. These two mean directions have the antipodal relationship at the 95% confidence level. The data sets pass the reversal test, and the detected ChRMs are probably primary NRMs.

The K-Ar age of the basaltic andesite of the Togo Formation is dated as 2.9±0.2 Ma (Table 1). The analyses of Ar and K were performed by Teledyne Isotopes. At the sample preparation step, the phenocrysts were tried to remove and the groundmass rich portions were used for K-Ar dating to avoid the effect of excess argon. The

Table 1. K-Ar age of the basaltic andesite of the Togo Andesites

Sample No.	Material	^{40}Ar (scc/gm 10^{-5})	%^{40}Ar	%K	Age (Ma)
TOG-KAS-01	Basaltic andesite of the Togo Andesites (Two pyroxene andesite)	0.015 0.015	53.6 57.7	1.32 1.33	2.9±0.2

Used constants: Steiger and Jager (1977).
Calculation methods: Dalrymple and Lanphere (1969).

Table 2. Paleomagnetic results from the Togo area

	Site No.	N/n	M	Demag. (mT)	Dec (°)	Inc (°)	α_{95}(°)	κ	Dc(°)	Ic(°)	Pol.
Togo Andesites	[Basaltic andesite lava]			N1							
	TAB-8	8/0	628	L:10-55	339	33	6.0	86	---	---	Nor
	TAB-9	8/0	357	L:10-55	341	42	4.9	127	---	---	Nor
	[Hornblende andesite lava]			R2							
	TAH-10	7/0	158	L: 35-80	233	-63	3.6	283	---	---	Rev
	TAH-11	8/0	234	L: 25-80	219	-63	4.1	182	---	---	Rev
Togo Formation	[Torimaru Sandstone Member]			R1**							
	TM-6	5/3	109	L+G: 0-40	135	-23	4.9	134	133	-23	Rev
	TM-12	7/1	66	L+G: 25-80	139	-42	5.9	90	142	-50	Rev
	TM-7	1/7	29	L+G: 0-40	144	-44	9.0	49	148	-54	Rev
	TM-14	1/6	25	L+G: 0-30	130	-46	10.3	46	128	-47	Rev
	TM-15	1/5	38	L+G: 0-30	146	-24	10.0	64	143	-26	Rev
	TM-16	1/5	20	L+G: 0-30	140	-36	2.7	900	140	-38	Rev
	TM-1	1/8	22	L+G: 0-50	141	-38	6.7	74	138	-41	Rev
	[Arakawauchi Tuff Member]			R1*							
	AM-3	8/0	28	L: 20-70	139	-29	5.0	124	---	---	Rev

N: Number of direct line-fit observations. n: Number of demagnetization great circles. M: Initial NRM intensity ($\times 10^{-3}$A/m). Demag: Demagnetization range of AF demagnetization for least square lines and plane analyses. L and G: analysis method of each site for line fit (L) and great circle (G). Dec and Inc: declination and inclination in geographic coordinates. Dc and Ic: declination and inclination in stratigraphic coordinates. α_{95}: the radius of 95% confidence limit. k: Fisher's precision parameter (Fisher, 1953). Nor (Rev): Normal (Reversed) polarity magnetization.

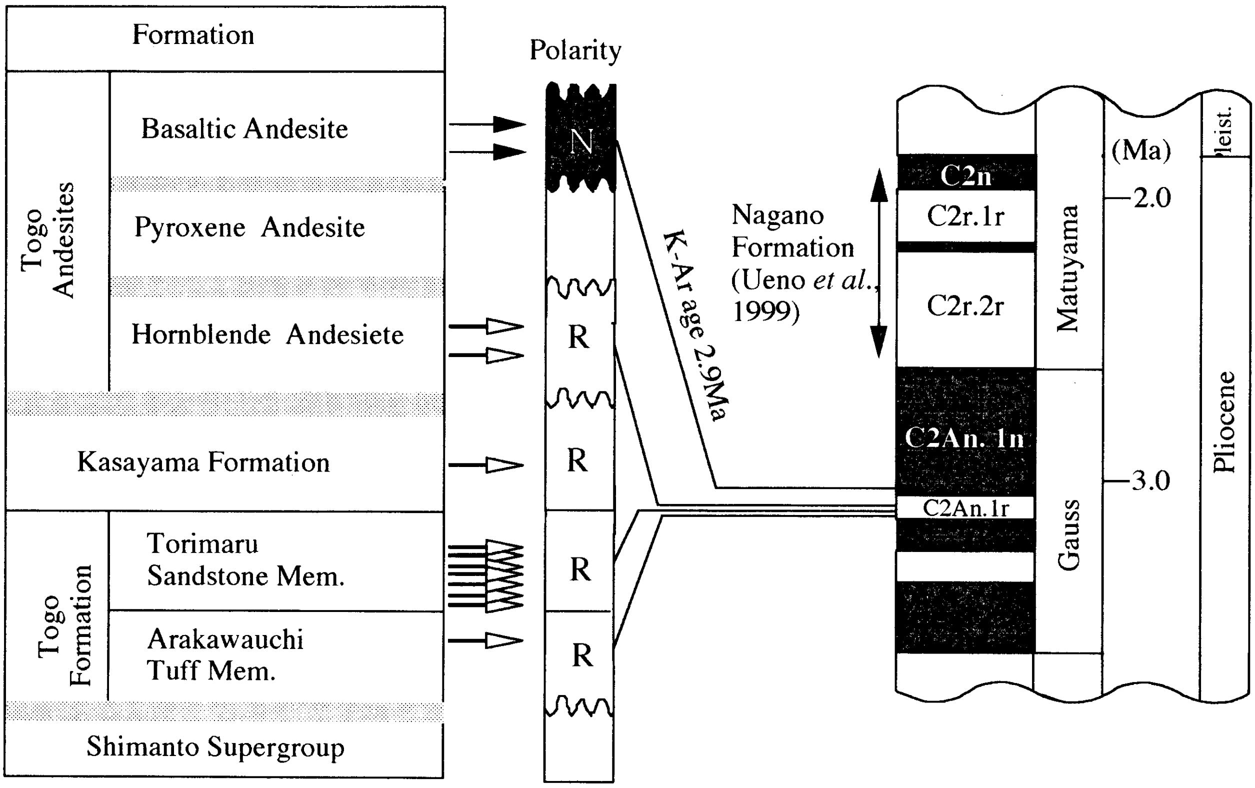

Figure 8. Summary of the paleomagnetic polarity of the Togo area, and correlation with the geomagnetic polarity time scale of Cande and Kent (1995).

freshest rock was used for dating. We believe this age is reliable. Therefore, the basaltic andesite lava of the Togo Andesites of normal polarity is correlated to the C2An.1n normal subchron of 2.58-3.04 Ma in the geomagnetic polarity time scale (Cande and Kent, 1995). The time gap between the Togo Formation and the basaltic andesite lava would not be so long, because the Kasayama Formation conformably overlies the Togo Formation and the Kasayama Formation appears to have a locally interfingering relationship to the Togo Andesites. Judging from these observations, the Togo Formation of reversed polarity is correlated to the C2An.1r reversed polarity subchron of 3.04-3.11 Ma (Fig. 8). The results from the polarity sequence reveal that the Togo Formation is lower horizon than the Lower and Middle Members of the Nagano Formation of which age is within 2.15-2.58 Ma (Ueno et al., 1999).

The declination of the Togo Formation is characterized by the westward deflection, while that of the Nagano Formation has no westward deflection. These different deflections imply the different ages of both formations. This problem is discussed below. The overall mean direction of the 12 site-means of the Togo Formation and Togo Andesites is Dec = 330°, Inc = +45°, α_{95} = 13°. The direction accords with the Middle Miocene to Pliocene paleomagnetic direction of southern Kyushu (Dec = 331°, Inc = +46°) reported by Kodama et al. (1995). Kodama et al. (1995) have explained that a counterclockwise rotation has occurred in southern Kyushu during Late Pliocene time. The deflection has changed gradually from 40° westward at 4.5 Ma to 0° at 2 Ma (Okuda et al., 1997). And furthermore, the westward deflection has not been recognized in Quaternary rocks (Kodama et al., 1995; Okuda et al., 1997). It is assumed the Togo Formation and Togo Andesites having 30° westward deflection are older than the Nagano Formation having no westward deflection.

It is noteworthy both magnetic polarity examination and tectonic consideration have induced the same conclusion.

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