Paleomagnetism of the Akiyoshi Limestone: Evidence for Secondary Magnetization

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The Akiyoshi limestone group is an accreted reef complex originated on oceanic basaltic seamounts. The direction value of the natural remanent magnetization (NRM) of the Akiyoshi limestone is not adequate to deduce where the limestone was deposited, because the NRM seems to be secondary (a remagnetized value). The mean in situ direction, namely the remagnetized direction, of the limestone is 49.9° in declination and 61.1° in inclination (Fisher statistic parameters: $k=90.0$ and $\alpha_{95}=4.1^\circ$) for fifteen sites with the precision parameter $k>10.0$. This mean direction is almost the same as the in situ directions of welded tuffs from four formations distributed around the Akiyoshi Plateau, which have been already reported by previous study. These welded tuffs have fission track ages between 85 and 94 Ma. The remagnetized direction is also rather similar to the well-known paleomagnetic direction for Southwest Japan before about 15 Ma. These correspondences suggest that the Akiyoshi limestone and the welded tuffs were remagnetized by some event after about 90 Ma and before 15 Ma. Results of thermal demagnetization and observation in thin sections of the limestone suggest that dominant magnetic particle is magnetite, and that the limestone may not have suffered high temperature ($>500^\circ\text{C}$) alteration. This implies the presence of a low temperature chemical event.

1. Introduction

Geotectonic units in Southwest Japan are characterized by a markedly zonal distribution. These tectonic zones generally become younger from north to south, on the basis of paleontologic evidence (OZAWA *et al.*, 1985). It has been suspected that the zonal distribution of the geological structure was caused by collision and accretion processes of terranes and seamounts as the result of plate subduction (TAIRA *et al.*, 1981; OZAWA *et al.*, 1985). Several authors proposed that such accreted terranes had been originally formed at a much lower latitude than their present positions, on the basis of paleomagnetic investigations of sedimentary and volcanic rocks distributed in the terranes (HATTORI and HIROOKA, 1979; TAIRA,

1981; HATTORI, 1982; HIROOKA *et al.*, 1983; SHIBUYA *et al.*, 1983; SHIBUYA and SASAJIMA, 1986).

Because the terranes in Japan have repeatedly suffered severe tectonic movements, rocks in the terranes must have been located under an environment where they probably tended to acquire secondary magnetization. Based on detailed progressive thermal demagnetization treatments, SHIBUYA and SASAJIMA (1986) reported that red cherts and red siliceous mudstones from the Inuyama area in the southern part of the Mino terrane contain very stable secondary components. Radiolarian age determination (YAO *et al.*, 1980) suggests the middle Triassic to the middle Jurassic age for these rocks. The Mino terrane was emplaced through accretion during the Jurassic (TAIRA *et al.*, 1981). SHIBUYA and SASAJIMA (1986) and SHIBUYA (1986) concluded that the stable secondary magnetization of the rocks had been acquired by low temperature chemical alteration caused by intrusion of the Cretaceous granites at the time between the middle Jurassic and the early Cretaceous.

The Akiyoshi limestone group is also an accreted reef complex originated on oceanic basaltic seamounts (KANMERA and NISHI, 1983). The Akiyoshi limestone ranges in age from early Carboniferous to late Permian, determined from the stratigraphic study finding fusuline and other fossils (OTA, 1977), and its accretionary emplacement probably took place in the late Permian to early Triassic times (KANMERA and NISHI, 1983).

No paleomagnetic investigations of the Akiyoshi limestone group have been carried out in the past. The aims of this paper are as follows: (1) to reveal whether remanent magnetization of the Akiyoshi limestone is primary or secondary, (2) if a primary component is present, to deduce where the limestone was deposited, and/or (3) if a secondary component is present, to tentatively assess the timing and cause of remagnetization.

2. Geological Structure of the Akiyoshi Limestone Group

The Akiyoshi limestone group is widely distributed over a range of about 16 km from east to west and about 8 km from north to south, and builds up a low (300 to 400 m high) hummocky karst. The hummocky karst is divided by the Koto river flowing from north to south near the center into two karst plateaus, the East Plateau and the West Plateau (Fig. 1). The Akiyoshi limestone group has a complicated geological structure, which has not yet been clarified well, and contains abundant fossils of the early Carboniferous to late Permian age (OTA, 1977).

OZAWA (1923) first stated the geological structure of the Akiyoshi limestone and interpreted that the limestone was reversed in order with a recumbent fold, on the basis of a distribution of fusuline fossil zones. This interpretation was supported by further biostratigraphic investigations, although some partial modifications were added to it (SUGIYAMA, 1939; KAWANO, 1950); however, it was also denied (HASEGAWA, 1958, 1963; MURATA, 1961).

TORIYAMA (1954a, 1954b) investigated the geological structure of the Akiyoshi

Fig. 1. Distribution map of the Akiyoshi limestone and sampling sites (E1 to E13 and W1 to W7).

limestone group and the non-calcareous rocks surrounding the Akiyoshi Plateau. As a result, he interpreted that only the northern half of the Akiyoshi limestone was reversed in order, it was normal in the southern half. OTA (1977) performed a detailed examination on the differences in the interpretations by several authors and carried out further precise geological and biostratigraphic investigations. As a result, he concluded that the northern half represented an inverse limb of a flatlying overturned anticline which thrust up the southern sequence, while the southern half formed a normal sequence gently dipping north.

After that, it has been interpreted that the southern half had also partly formed an inverse sequence (OKIMURA, 1966; IGO, 1973; MATSUSUE, 1986). MATSUSUE (1986) concluded that the southern half generally formed an inverse sequence dipping south at an angle of 30° to 50° , on the basis of a detailed biostratigraphy of foraminifera, lithofacies and measurement of dips and strikes of laminae in limestone.

Paleomagnetic sampling was carried out from twenty sites in both the East and West Plateaus (Fig. 1). Orientation was performed with a magnetic compass. As bedding planes cannot be so precisely observed due to the limestone having no distinct bedding, they were roughly estimated in twelve of twenty sampling sites, as referring to dips and strikes of bedding planes (OTA *et al.*, 1973) and of laminae in the limestones (MATSUSUE, 1986), which have been reported in the vicinity of the sampling sites.

3. Magnetic Measurements and Results

Several subsamples, 25 mm in diameter and 25 mm long, were prepared in the laboratory from each oriented sample. Natural remanent magnetization (NRM) was measured with a SCT cryogenic magnetometer whose sensitivity is 10^{-11} Am². Pilot progressive alternating-field (AF) and thermal (TH) demagnetization studies were conducted on one representative subsample from each sampling site. Demagnetization treatment was carried out up to the maximum level of 80 mT in AF cleaning or up to 600°C in TH cleaning.

Representative demagnetization vector diagrams from four pilot subsamples are shown in Fig. 2. No tilt correction was performed on the results shown in this figure. All pilot subsamples showed remarkable directional stability during both demagnetization treatments. Viscous components of the subsamples were removed by 10 mT to 20 mT upon AF cleaning and up to about 300°C upon TH cleaning, and then a single characteristic component of each subsample resulted. The original NRM intensity of samples from every sampling site was within the range of 10^{-3} to 10^{-5} A/m with variable magnitudes. Upon progressive TH demagnetization of pilot subsamples, the remanences usually became unstable and their intensities became less than 10^{-4} A/m at the TH level above 500°C, where it was impossible to distinguish a possible high-temperature component, and only random noise was left. Upon progressive AF demagnetization for pilot subsamples, the remanences were rather stable up to 80 mT, and their intensities decreased uniformly with median destructive fields ranging from 20 to 30 mT.

All subsamples were magnetically cleaned by the AF demagnetization at an optimum level determined for every site, because both demagnetization methods carried out for pilot subsamples consequently revealed similar results, and no pilot subsamples showed unique and significant magnetic behavior during both demagnetization treatments. The results are summarized in Table 1. The in situ directions for every sampling site are also shown with their mean values and α_{95} circles in Fig. 3. The tilt-corrected directions were also calculated for twelve sampling sites (E1 to E12). The corrections were performed while regarding the geological structure as inverse. The tilt-corrected values are not necessarily reliable, because estimation of bedding planes was rather rough, mainly due to the limestone having no distinct bedding.

4. Discussion and Conclusions

The mean directions of all the sites show individual precisions proportional to magnitudes of the NRM intensity of every site. This proportion is probably due to the stable signal-to-noise ratio in magnetic measurements. Nevertheless, all twenty sites, which are located in a wide range of the Akiyoshi area, show rather identical mean in situ directions. This fact implies that the Akiyoshi limestone may have been remagnetized. In several sampling sites (E1 to E12), where the bedding plane was

Fig. 2. Representative demagnetization vector diagrams from four pilot subsamples of the Akiyoshi limestone. Closed symbols are for the horizontal projection and open symbols for projection in the EW vertical plane. Upper figures are alternating-field demagnetizations (values in mT) and lower figures are thermal demagnetizations (values in °C).

roughly estimated, the mean in situ direction is 51.9° in declination and 59.7° in inclination (Fisher statistic parameters; $K=95.8$ and $\alpha_{95}=4.5^\circ$) (Fig. 4 upper). On the other hand, the tilt-corrected direction is 15.2° in declination and -44.7° in inclination ($k=27.4$ and $\alpha_{95}=8.4^\circ$) (Fig. 4 lower). The former mean value shows higher reliability than the latter one, showing the possibility that these rocks were remagnetized after various tectonic movements. The rest of the sites (E13, W1 to W7), where the bedding plane was not estimated, show mean in situ directions of 30° to 100° in declination and of 30° to 70° in inclination (Fig. 3). The mean direction for these eight sites is 50.2° in declination and 62.8° in inclination ($k=17.0$ and $\alpha_{95}=13.8^\circ$) and is almost the same as the mean in situ values for the sites E1 to

Table 1. Paleomagnetic results for the Akiyoshi limestone. *N*: the number of subsamples in site mean computation. INT.: the site mean NRM intensity. DEC. and INC.: the mean in-situ or tilt corrected declination and inclination, respectively. *k*: Fisher precision parameter. α_{95} : the radius of the 95% confidence interval around the mean direction. STR. and DIP: the estimated strike and dip of bedding plane. AGE: the biostratigraphic age (OTA, 1977; MATSUSUE, 1986). The ages are older in order from E1 to E13.

Site	<i>N</i>	AF Level	Int. ($\times 10^{-3}$) (mT) (A/m)	Tilt				Precision		Bedding		AGE
				In-situ		corrected		<i>k</i>	α_{95}	STR.	DIP	
				DEC. (°)	INC. (°)	DEC. (°)	INC. (°)					
East Plateau												
E1	22	20	1.430	72.6	57.6	12.0	-52.5	55.6	4.2	NE55	190	Middle Permian
E2	18	20	0.300	49.3	56.6	33.0	-55.2	31.0	6.3	NE55	190	Middle Permian
E3	9	25	0.620	52.2	62.2	27.0	-60.0	184.4	3.8	NE55	190	Middle Permian
E4	10	20	0.140	43.6	67.5	-0.2	-54.7	88.2	5.2	NE55	210	Lower Permian
E5	19	20	0.660	47.9	45.0	22.4	-38.0	65.6	4.2	NE55	210	Lower Permian
E6	12	20	0.150	55.8	53.6	10.0	-41.3	27.5	8.4	NE55	210	Lower Permian
E7	15	20	0.580	50.1	61.0	15.7	-54.8	72.0	4.5	NE55	200	Lower Permian
E8	8	10	0.073	52.4	60.1	18.5	-36.0	32.4	9.9	NE80	240	Lower Permian
E9	8	10	0.088	52.8	54.3	21.7	-28.1	8.3	20.5	NE80	250	Upper Carboniferous
E10	6	10	0.142	49.6	57.1	14.0	-12.6	42.2	10.4	NE80	270	Middle Carboniferous
E11	7	10	0.046	34.5	70.8	14.5	-52.8	3.3	39.0	NE90	230	Middle Carboniferous
E12	6	10	0.027	55.5	67.8	-4.6	-44.4	11.1	21.1	NE60	220	Lower Carboniferous
E13	17	10	0.015	29.2	27.5	—	—	5.0	17.8	unknown	—	Lower Carboniferous
Mean (E1-E12, <i>N</i> =12)			51.9	59.7	—	—	—	95.8	4.5	—	—	—
			—	—	—	15.2	-44.7	27.4	8.4	—	—	—
West Plateau												
W1	12	10	0.129	66.5	67.9	—	—	30.0	8.1	unknown	—	unknown
W2	8	10	0.196	50.3	67.0	—	—	51.5	7.8	unknown	—	unknown
W3	6	10	0.098	38.8	66.3	—	—	70.9	8.0	unknown	—	unknown
W4	6	10	0.009	103.0	56.7	—	—	3.1	45.2	unknown	—	unknown
W5	7	10	0.052	27.4	54.7	—	—	13.0	17.4	unknown	—	unknown
W6	10	10	0.055	38.1	65.9	—	—	81.2	5.4	unknown	—	unknown
W7	8	10	0.035	85.2	73.6	—	—	5.9	25.0	unknown	—	unknown
Mean (all, <i>N</i> =20)			51.3	60.9	—	—	—	35.6	5.5	—	—	—
Mean (<i>k</i> >10, <i>N</i> =15)			49.9	61.1	—	—	—	90.0	4.1	—	—	—

Fig. 3. Equal-area projections of characteristic in situ directions of magnetization for all demagnetized subsamples of the Akiyoshi limestone. The mean for each site is given as a star with its 95% confidence interval.

Fig. 4. The mean directions of twelve sites (E1 to E12), where bedding planes were roughly estimated. Upper and lower figures show in situ directions and tilt corrected directions, respectively. The means for all the sites are respectively given as a star with its 95% confidence interval.

E12. The coincidence of these two mean in situ direction values indicates that all rocks collected from the Akiyoshi limestone group were remagnetized after various severe tectonic movements which have caused a recumbent fold. The remagnetization seems to have completely overprinted primary magnetizations.

The mean in situ direction for all twenty sites is 51.3° in declination and 60.9° in inclination ($k=35.6$ and $\alpha_{95}=5.5^\circ$) (Fig. 5). The mean in situ direction for fifteen sites with a precision parameter $k>10.0$ is 49.9° in declination and 61.1° in

Fig. 5. The mean in situ direction of all twenty sites. The mean for all the sites is given as a star with its 95% confidence interval.

inclination ($k=90.0$ and $\alpha_{95}=4.1^\circ$). OTOFUJI and MATSUDA (1987) obtained paleomagnetic directions of welded tuffs in four formations distributed around the Akiyoshi Plateau: the Ebune, Oumi, Maitani and Monomidake formations. The mean direction for the four formations is calculated at 53.7° in declination and 63.8° in inclination ($k=505.1$ and $\alpha_{95}=4.1^\circ$) in situ, or at 66.5° in declination and 61.7° in inclination ($k=108.9$ and $\alpha_{95}=8.8^\circ$) after tilt correction. Although this interpretation is different from the conclusion by OTOFUJI and MATSUDA (1987), we interpret that the NRM of these welded tuffs are probably secondary, because the former mean direction obviously shows higher reliability than the latter one (that is, the tilt-corrected one). The mean in situ direction value for these welded tuffs is almost the same as the in situ one for the Akiyoshi limestone.

As the Akiyoshi limestone must have suffered some tectonic movements identical with the surrounding formations, the coincidence of mean in situ direction values between the Akiyoshi limestone and the surrounding welded tuffs suggests that both rocks were remagnetized at the same time by a certain event. The timing of remagnetization is restricted after about 90 Ma, because the welded tuffs have fission track ages between 85 and 94 Ma (OTOFUJI and MATSUDA, 1987). The coincident directions are also identical with the well-known paleomagnetic direction for Southwest Japan before about 15 Ma rather than after about 15 Ma, when Southwest Japan was abruptly rotated through about 50° (OTOFUJI *et al.*, 1985). This correspondence suggests that the remagnetization occurred before about 15 Ma.

YASKAWA (1975) and ITO and TOKIEDA (1986) compiled many paleomagnetic results in Southwest Japan from several authors. Although both compilations contain the results of rocks distributed in the vicinity of the Akiyoshi Plateau, there are no available data to further define the timing of remagnetization.

It is possible that the Akiyoshi limestone may have been remagnetized by a certain low temperature event, although the possibility is not so strong. The TH demagnetization results of pilot subsamples indicate that the NRM consists of two components, one of which is a viscous component and another a secondary (remagnetized) component with blocking temperatures ranging from 300°C to about 500°C (Fig. 2). The blocking temperatures of the secondary component show that the dominant magnetic carrier is magnetite. Magnetite was also observed in thin sections of the limestone samples, with a grain size of several microns (H. Maekawa, personal communication). No evidence of high temperature (about 500°C) alteration for the limestone was observed in the thin sections, and if such an alteration occurred, it must have occurred at a temperature below 300°C , because no evidence of recrystallization was observed (H. Maekawa, personal communication). This observation indicates the possibility that the secondary component of the limestone is chemical remanent magnetization. This possible interpretation agrees well with interpretations by SCOTSE *et al.* (1982), SHIBUYA and SASAJIMA (1986), SHIBUYA (1986) and MOREAU *et al.* (1987). SCOTSE *et al.* (1982) reported secondary magnetizations residing in magnetite for Upper Silurian and Lower Devonian limestones. The results of thermal demagnetization for the limestones are

very similar to our results for the Akiyoshi limestone. They argued that the remagnetization was caused by a chemical or thermochemical event, involving diagenetic growth of new (authigenic) magnetic minerals. MOREAU *et al.* (1987) demonstrated, on the basis of paleomagnetism of pre-Oligocene rocks from Northeast Japan, that the remagnetization was caused by a widespread low temperature chemical event prior to the opening of the Sea of Japan. If such an event really has occurred, the remagnetization of the Akiyoshi limestone could be accounted for by the identical scenario. However, we will not interpret the possible low temperature chemical event as a widespread event influencing all of Japan because of the scarcity of available data. It is very important to find some further independent evidence of such events.

The interpretation that the Akiyoshi limestone was remagnetized prevents us from solving where the limestone was originally deposited. Detection of secondary magnetizations in the limestone, as well as in cherts and siliceous mudstones from the Mino terrane (SHIBUYA and SASAJIMA, 1986) and in Miyako Cretaceous sediments (MOREAU *et al.*, 1987) caution us about the application of paleomagnetic results to evidence related to accretion tectonics. The remagnetization, however, may suggest some unusual tectonic, volcanic or thermal alteration events. Therefore, the timing and scale of the remagnetization have to be estimated from further paleomagnetic and rock magnetic studies.

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