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PALEOMAGNETIC STUDY OF THE KUANYINSHAN AND TANAWAN FORMATIONS, NORTHERN TAIWAN

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ABSTRACT

Samples collected from the Kuanyinshan Formation at the Chikeng section and the Tananwan Formation at the Zuaisukengchi section in the Linkou-Kuanyinshan area were subjected to remanent magnetization and calcareous nannofossil analyses to find the stratigraphical relationships between and more precise age intervals of these two formations.

Almost all the samples collected from the former were normally magnetized, while most of those samples from the latter were reversely magnetized. Very abundant *Reticulofenestra pseudoumbilica* and *Pseudoemiliania lacunosa* were found within the former and a lot of *Gephyrocapsa oceanica* were obtained in the latter. Considering both paleomagnetic and nannofossil data, the former can be assigned to the Gauss normal epoch and the latter to the Matuyama reversed epoch. Compared to the formations in the Foothills, the Kuanyinshan Formation could be correlated to the upper part of the Pliocene Kueichulin Formation and the Chinsuei Shale, and the Tananwan Formation probably to the Pleistocene Choulan Formation and Tokoushan Formation.

In addition, mean paleomagnetic direction of the Kuanyinshan Formation seems to indicate a counterclockwise rotation phenomenon as proposed by Lue *et al.* (1995). However, such a kind of motion was not found at the Tananwan Formation, supporting that the counterclockwise rotation of northern Taiwan might have stopped before the beginning of the Matuyama reversed epoch, i.e. before 2.6 Ma.

INTRODUCTION

Taiwan, as an island located in an arc-continent collision zone, comprises rock strata that have been highly deformed and fractured. Previous paleomagnetic analyses demonstrated that some of the rocks in northern Taiwan had been subjected to clockwise rotation as a result of the collision (Angelier *et al.*, 1990; Lee *et al.*, 1991; Lue *et al.*, 1991). In spite of some arguments against the presence of tectonic rotation in northern Taiwan (Miki *et al.*, 1993), recent more intense investigations found that both clockwise and counterclockwise rotations were quite common in the rock formations older than 3 Ma. Lue *et al.* (1995) suggested that such rotations even occurred after 3 Ma. Nevertheless, the precise age and implication of the tectonic rotations remain still unknown.

In order to provide better time constraints on tectonic rotations in northern Taiwan, we chose the Kuanyinshan and Tananwan Formations exposed in the Linkou-Kuanyinshan area for more magnetostratigraphic analysis. It is well known that paleomagnetic reversals, supplemented by biostratigraphic data, offer a powerful tool for precise age determinations and stratigraphic correlation. Despite of the difficulties associated with discontinuous outcrops and poor magnetic signals, we successfully extracted important and sufficient paleomagnetic as well as nannofossil data out of the said Formations and thereby try to establish a magnetostratigraphic scheme in this paper.

GEOLOGICAL SETTING

The Linkou-Kuanyinshan area is situated to the west of the Taipei basin. It is seperated from the basin by the Hsinchuang Fault (Fig. 1). Basically, it is a flat terrace up to 250 m in altitude (Ho, 1969). In its north, a Quaternary volcanic cone up to 700 m high covers the terrace. Except some minor deformed strata exposed along the Hsinchuang Fault, the Linkou terrace is floored with flat-lying sedimentary strata that can be divided into two coeval stratigraphic units. In the east, the Linkou Formation consists mainly of conglomerates and intercalated sandstones. In the west, the Tananwan Formation is composed of interlayering sandstones, mudstones, and conglomerates. Facies changes between the Linkou and Tananwan rocks are gradational and believed to be indicative of a fan-delta system (Chen and Teng, 1990).

The Linkou-Tananwan Formations extend north into the Kuanyinshan area where they are tilted by the protruding Quaternary volcanics (Chen, 1989; Hwang and Lo, 1986). Besides the conglomeratic strata comparable to the Linkou-Tananwan deposits, mudstones of more than 200 m are exposed near the center of the volcanic cones. All these tilted mudstones, sandstones, and conglomerates are lumped together as the Kuanyinshan Formation by Makiyama (1934) to be seperated by the flat-lying Linkou-Tananwan strata. Hence the relationship between the Kuanyinshan Formation and the Linkou and Tananwan Formations is still in dispute. Unconformably overlying the Kuanyinshan Formation is the Kuanyinshan volcanics which have been dated by K-Ar radiometry and fission track as 0.6 to 0.2 Ma (Juang, 1988).

SAMPLING AND LABORATORY ANALYSIS

For the purpose of investigating the magnetic time zonations, sampling was carried out in the middle to lower parts of the Kuanyinshan Formation of the Chikeng section and the Tananwan Formation of the Zuaisukengchi section. The relative stratigraphical heights of the samples were carefully measured during the work in the field. A total of 154 levels were drilled from the Kuanyinshan Formation and 113 levels from the Zuaisukengchi section. The site localities are shown in Figure 1. Standard paleomagnetic orientation techniques were applied to orient these cores. Each core is 2.5 cm in diameter and has been cut into several specimens of 2.2 cm in length.

From analyzing the pilot samples, thermal demagnetization method was employed for investigating the characteristic directions of samples. After each demagnetization step, bulk susceptibilities of each specimens were measured. This is for preventing the samples to cause the changes of magnetic mineral due to over heating during thermal treatments. To test the stability of samples and to find the stable components of natural remanent magnetization (NRM) of specimens, the linear regression method was applied on analyzing the direction variations during demagnetization. Having a good age control, several specimens from different levels of sections and different sites were chosen for nannofossil analysis. Then, stratigraphical distribution of paleomagnetic polarities and biostratigraphical data were analyzed for age intervals of the studied sequences.

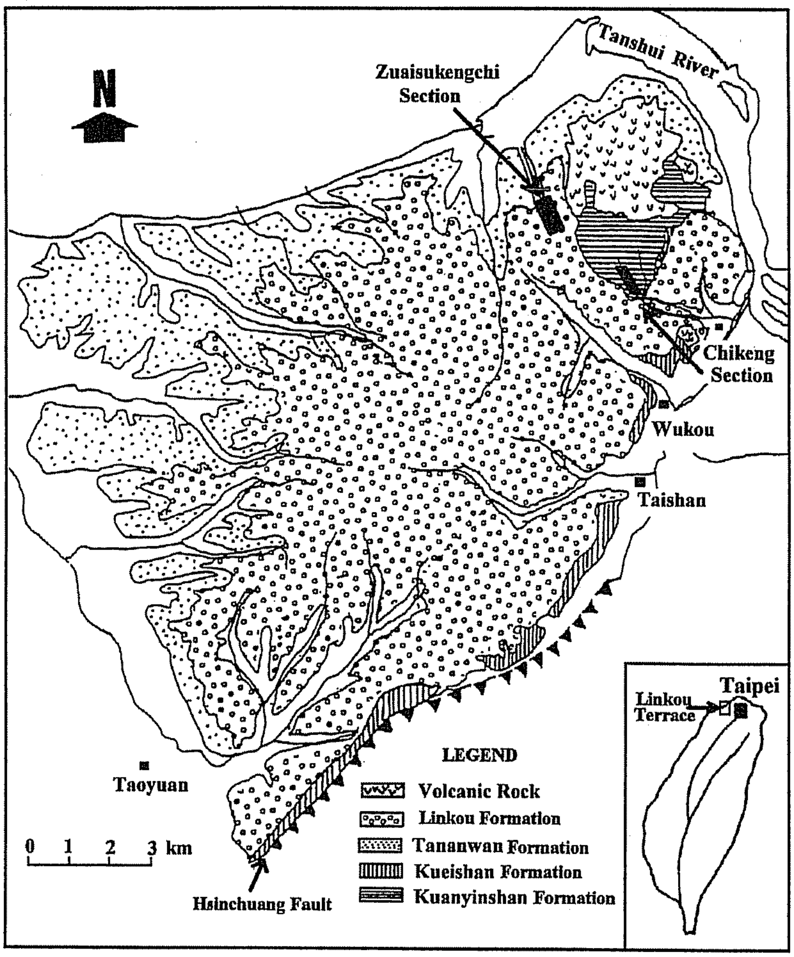

Figure 1. Sketched geological map of Linkou-Kuanyinshan area and the sampling site localities.

RESULTS

Typical orthogonal component plots shown in Figure 2 present the changes of NRM of samples during progressive stepwise thermal demagnetization treatments from room temperature to 550°C. The secondary component of NRM seemed to be cleaned at very low temperature of about 240°C, and the characteristic direction of NRM could be obtained at higher temperature. These characteristic directions of NRM after bedding correction, and their corresponding virtual geomagnetic pole (VGP) positions varied with the relative stratigraphical heights are shown in Table 1 and Table 2 for the Chikeng and Zuaisukengchi sections, respectively, except some samples didn't pass the stability test which might be due to their relatively coarse grain size.

The stratigraphical distributions of the paleomagnetic declinations and inclinations of these two sequences and their lithologies were shown in Figure 3 and Figure 4, respectively. In general, samples collected from the Kuanyinshan Formation were normally magnetized, while those taken from the Tananwan Formation showed reversed polarities.

Nannofossil analysis indicates that very abundant *Reticulofenestra pseudoumbilica* was found within the Kuanyinshan Formation at the Chikeng section. Another very important species, *Pseudoemiliania lacunosa*, has also been found at the stratigraphical height of about 32 meters. However, a lot of *Gephyrocapsa oceanica* were broadly obtained in the Tananwan Formation at the Zuaisukengchi section.

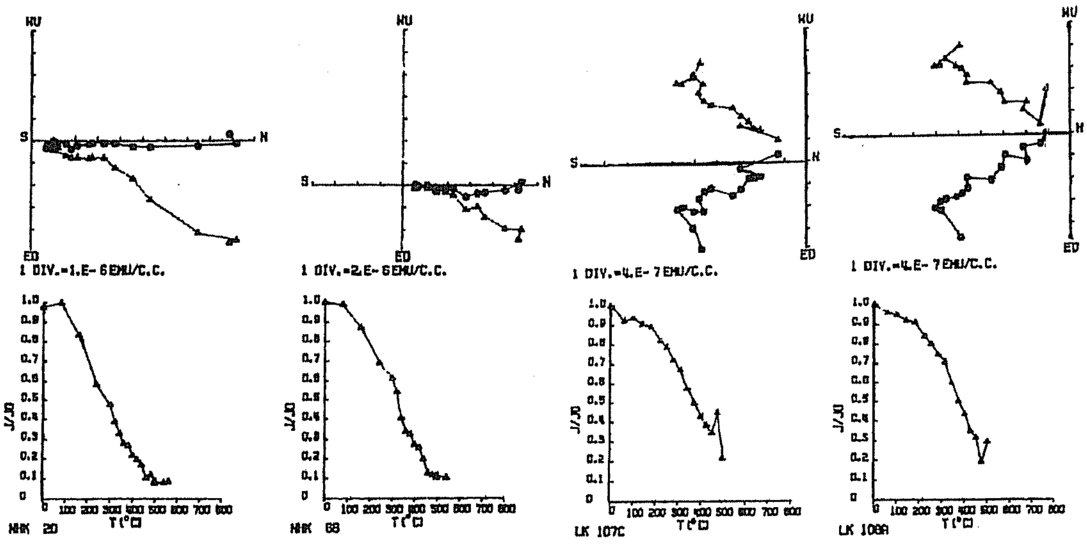

Figure 2. Typical orthogonal component plots of the studied samples.

Table 1. Paleomagnetic results of the samples from Chikeng section (after tilt correction).

Sample	H (cm)	Dec.	Inc.	Plat.	Plon.
NHK105.0C	77.04	349.9	-37.2	43.0	193.0
NHK108.0D	134.81	351.3	14.2	70.2	206.3
NHK116.0B	288.89	330.1	19.8	57.9	247.5
NHK123.0C	423.70	354.6	30.3	79.8	210.6
NHK128.0C	520.00	345.7	20.0	69.9	224.9
NHK129.0D	871.44	346.9	44.7	78.1	278.3
NHK132.0D	910.44	343.7	24.2	70.2	233.8
NHK133.0D	2250.0	344.2	44.8	75.7	278.3
NHK134.0D	2283.35	338.0	71.7	54.9	338.9
NHK137.0A	2383.41	24.0	10.2	59.5	248.6
NHK138.0B	2416.76	358.6	74.0	55.0	358.8
NHK140.0B	2483.47	8.8	55.9	66.2	279.1
NHK142.0D	2250.18	349.3	55.1	76.1	321.1
NHK145.0C	2650.24	39.4	40.4	54.1	206.5
NHK147.0C	2716.94	346.9	22.9	71.8	225.4
NHK150.0D	2817.00	341.2	72.6	54.7	342.8
NHK153.0C	2425.00	11.3	49.0	78.9	183.8
NHK156.0C	2371.50	352.1	54.9	77.7	328.2
NHK158.0C	2335.83	357.2	42.5	87.4	257.7
NHK160.0B	2300.16	358.2	66.5	66.2	357.1
NHK164.0B	2228.83	5.7	35.4	66.8	286.8
NHK166.0A	2193.16	0.6	41.0	65.3	300.0
NHK168.0B	2157.50	4.5	38.5	68.6	289.0
NHK171.0C	2104.00	5.1	43.3	65.9	288.8
NHK173.0B	2068.33	11.3	42.2	79.7	213.6
NHK175.0D	2032.66	15.8	41.8	75.6	212.6
NHK177.0B	1997.00	14.6	42.1	76.7	212.2
NHK179.0C	1961.33	25.1	51.9	66.9	187.2
NHK181.0D	1925.66	11.7	28.2	75.0	252.2
NHK183.0B	3076.10	16.9	29.5	71.6	239.0
NHK185.0C	3106.01	346.1	43.6	77.4	274.2
NHK187.0C	3135.92	16.2	42.3	75.3	210.9
NHK188.0C	3150.88	341.6	39.9	73.0	265.3
NHK191.0D	3195.75	5.7	41.7	65.0	287.8
NHK192.0C	3210.71	345.1	55.0	73.5	312.4
NHK194.0C	3240.62	2.0	49.1	69.3	295.7
NHK196.0A	3270.53	3.2	63.7	66.4	293.3
NHK197.0D	3285.49	331.9	54.4	63.9	298.6
NHK199.0B	3315.40	318.8	67.9	49.4	320.3
NHK202.0B	3360.27	353.2	54.9	78.2	331.8
NHK203.0C	3375.23	335.9	56.6	66.3	306.1
NHK205.0C	3405.14	320.0	53.1	54.4	293.3
NHK208.0C	3454.16	340.1	56.0	69.6	308.4
NHK209.0A	3470.50	311.3	53.5	47.1	293.7
NHK211.0B	3503.18	0.4	67.4	68.5	300.2
NHK214.0A	3552.19	344.9	46.3	76.3	283.5
NHK216.0C	3584.87	315.1	59.5	49.8	303.5
NHK217.0A	3601.21	338.2	65.1	62.1	327.3
NHK219.0B	3633.88	21.9	49.7	70.0	191.1
NHK220.0B	3650.22	17.6	57.3	70.4	166.8
NHK222.0B	3682.90	1.3	71.7	65.6	298.2
NHK223.0C	3699.24	349.6	61.8	70.3	337.0
NHK226.0A	3748.26	341.0	53.1	71.4	301.5
NHK227.0B	3764.60	335.1	67.8	58.1	329.8
NHK229.0B	3797.28	45.5	64.3	48.3	169.5
NHK230.0B	3813.62	18.1	65.4	63.5	149.5
NHK232.0C	3846.29	5.2	68.3	68.4	287.1
NHK234.0B	7278.00	106.7	-46.8	-25.4	232.1
NHK237.0A	7313.14	339.9	44.8	71.9	278.2
NHK238.0A	7324.86	338.3	48.1	70.3	286.4
NHK241.0B	7360.00	17.7	56.9	70.6	168.0
NHK244.0D	7466.00	18.4	39.9	73.0	216.2
NHK247.0B	7496.00	16.5	35.7	73.8	227.8
NHK249.0A	7516.00	7.0	18.8	68.2	282.4
NHK252.0A	7546.00	350.1	4.4	65.1	204.1
NHK254.0B	7566.00	351.7	38.7	81.7	247.8

Table 2. Paleomagnetic results of the samples from Zuaisukengchi sections (after tilt corrections).

Sample	H (cm)	Dec.	Inc.	Plat.	Plon.
LK7001.0B	0.0	167.5	-29.9	-75.2	176.0
LK7003.0B	8.0	183.2	-13.2	-71.3	350.0
LK7007.0B	35.0	179.7	-35.5	-84.5	124.4
LK7010.0B	50.0	171.9	-21.4	-74.0	151.6
LK7011.0C	112.0	171.3	-59.5	-73.1	278.0
LK7012.0C	127.0	254.0	-69.3	-29.3	221.6
LK7013.0D	130.0	166.7	-10.0	-66.2	156.1
LK7014.0D	135.0	185.1	-56.6	-77.2	198.6
LK7015.0D	139.0	181.4	-39.9	-87.3	331.9
LK7018.0D	153.0	167.2	-4.6	-64.1	151.8
LK7020.0D	165.0	182.9	-22.5	-76.3	347.9
LK7021.0C	171.0	192.4	-1.9	-63.0	331.7
LK7022.0D	177.0	158.2	-19.3	-64.3	179.0
LK7024.0B	186.0	159.6	-57.7	-68.3	253.8
LK7025.0A	196.0	190.9	-32.6	-77.5	303.9
LK7026.0B	212.0	197.3	-25.2	-69.9	302.9
LK7028.0B	229.0	173.7	-9.5	-68.8	139.0
LK7029.0C	236.0	172.1	-43.7	-82.8	216.6
LK7031.0A	261.0	174.8	-18.1	-73.4	139.7
LK7033.0A	246.0	192.5	-24.2	-72.9	314.2
LK7034.0C	241.0	189.7	-2.8	-64.5	337.0
LK7036.0C	323.0	191.5	-25.9	-74.2	314.5
LK7037.0C	342.0	195.0	-66.7	-63.2	202.0
LK7039.0C	358.0	162.9	-32.8	-72.5	190.3
LK7040.0C	360.0	179.8	-41.6	-88.8	130.5
LK7042.0C	373.0	179.0	-68.8	-62.9	300.0
LK7043.0B	380.0	38.7	5.0	46.4	236.4
LK7045.0A	388.0	160.1	-43.0	-72.0	215.3
LK7046.0B	413.0	197.3	-61.0	-67.8	215.8
LK7047.0C	424.0	100.9	-55.4	-22.8	241.8
LK7048.0	433.0	60.2	20.1	31.3	214.4
LK7049.0C	425.0	36.5	38.5	56.4	209.6
LK7050.0C	441.0	102.2	14.4	-7.8	199.5
LK7051.0A	451.0	132.0	28.9	-28.1	175.7
LK7052.0A	2451.0	282.3	-5.8	9.8	262.1
LK7053.0B	2463.0	203.8	11.6	-51.3	320.0
LK7054.0B	2463.0	210.8	-16.8	-56.4	294.0
LK7055.0A	2479.0	206.5	-21.7	-61.4	294.1
LK7056.0C	2495.0	188.9	-22.5	-74.2	326.3
LK7057.0C	2506.0	220.2	-11.7	-47.0	289.6
LK7058.0A	2518.0	183.0	-37.3	-84.9	326.4
LK7059.0A	2518.0	219.5	-13.3	-48.1	289.1
LK7060.0B	2618.0	170.8	-42.8	-81.7	211.6
LK7061.0B	2630.0	192.4	-51.5	-77.0	234.2
LK7062.0B	2640.0	173.0	-25.4	-76.5	152.0
LK7063.0B	2647.0	172.9	-45.9	-83.3	231.9
LK7064.0B	2672.0	170.3	-44.0	-81.2	217.9
LK7065.0A	2715.0	251.2	-45.9	-27.0	250.8
LK7066.0B	2724.0	191.6	-43.9	-79.5	264.3
LK7067.0B	2734.0	190.3	-46.6	-80.4	251.0
LK7068.0	2762.0	355.2	7.0	67.9	192.9
LK7069.0D	2767.0	268.6	33.8	6.5	287.4
LK7070.0	2775.0	182.3	-55.7	-78.7	189.5
LK7071.0	3225.0	224.8	-41.9	-49.5	261.5
LK7072.0A	3235.0	163.0	-41.3	-74.5	209.9
LK7073.0	3255.0	88.5	10.2	3.5	207.4
LK7074.0B	3285.0	187.5	-35.9	-81.3	305.4
LK7075.0	3302.0	187.0	-20.2	-73.9	334.4
LK7076.0B	3313.0	191.2	-0.1	-62.7	334.9
LK7077.0	3323.0	177.1	6.5	-61.5	127.5
LK7078.0B	3340.0	184.5	-21.6	-75.5	342.2
LK7079.0A	3366.0	197.2	-8.3	-63.3	318.9
LK7080.0A	3392.0	186.9	-28.0	-77.9	326.4
LK7081.0A	3413.0	179.9	-11.5	-70.7	121.7
LK7082.0A	3426.0	133.2	-21.2	-43.6	202.5
LK7083.0B	3478.0	194.4	-58.9	-71.1	216.2
LK7084.0A	3488.0	205.5	-43.0	-66.9	264.8
LK7085.0B	3502.0	154.6	-14.5	-60.0	179.6
LK7086.0B	3510.0	130.4	-36.8	-44.3	216.2
LK7087.0A	3576.0	176.5	-38.7	-85.4	166.6
LK7088.0C	3586.0	186.0	-30.0	-79.4	326.9
LK7089.0B	3598.0	193.0	-39.5	-77.8	280.1
LK7090.0	5198.0	174.8	-39.3	-84.5	181.7
LK7091.0B	5398.0	183.6	-45.9	-86.1	235.0
LK7092.0B	5424.0	181.9	-42.1	-88.1	294.2
LK7093.0A	5428.0	192.6	-42.3	-78.6	270.5
LK7094.0B	5428.0	186.4	-41.3	-84.0	282.1
LK7095.0B	5442.0	192.6	-53.4	-75.9	228.1
LK7096.0B	5460.0	186.7	-48.0	-82.9	235.0
LK7097.0A	5468.0	184.9	-49.4	-83.3	218.9
LK7098.0	5473.0	191.9	-34.7	-77.5	296.2
LK7099.0A	5513.0	200.7	-54.3	-69.7	236.6
LK7100.0	7582.0	245.4	-75.4	-33.4	210.2
LK7101.0C	7597.0	19.4	68.4	59.6	145.5
LK7102.0	7607.0	97.6	67.0	14.2	162.8
LK7103.0B	7623.0	319.5	-49.6	22.3	217.2
LK7104.0D	7630.0	110.6	-83.9	-28.8	288.5
LK7105.0C	7640.0	116.5	-76.7	-33.8	274.0
LK7106.0B	7655.0	152.0	-69.0	-55.4	271.1
LK7107.0C	7695.0	242.3	-68.0	-36.5	223.8
LK7108.0A	7705.0	275.8	-56.9	-10.7	233.5
LK7109.0A	7713.0	251.0	-52.2	-28.5	244.8
LK7110.0C	7726.0	196.8	-51.0	-73.8	242.1
LK7111.0C	7736.0	176.1	-35.5	-83.4	155.6
LK7112.0B	7792.0	177.7	-39.0	-86.3	156.5
LK7113.0B	7800.0	184.0	-47.6	-84.9	223.8

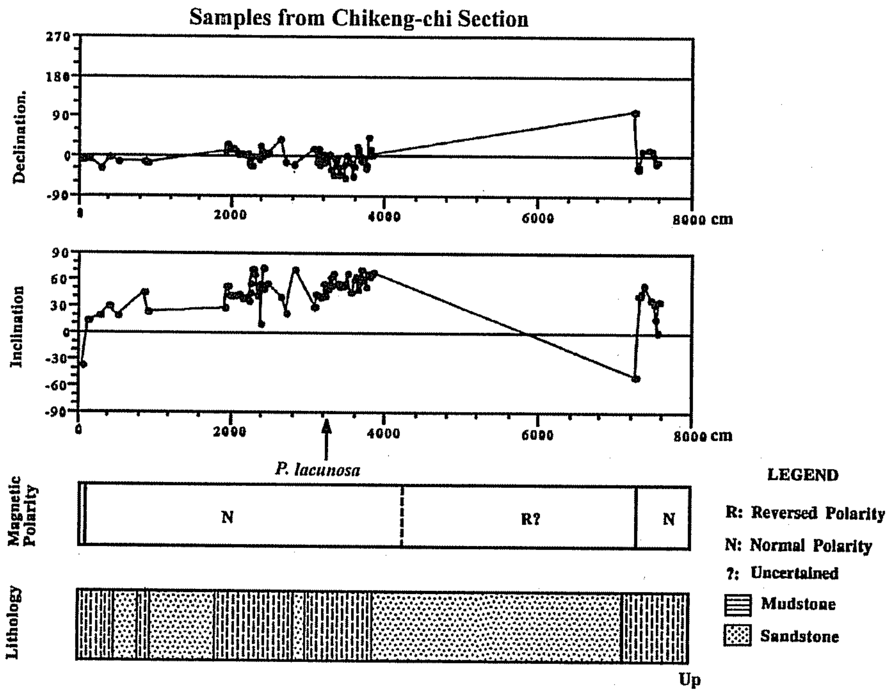

Figure 3. The stratigraphical distribution of paleomagnetic directions and the lithology of the Kuanyinshan Formation at Chikeng section.

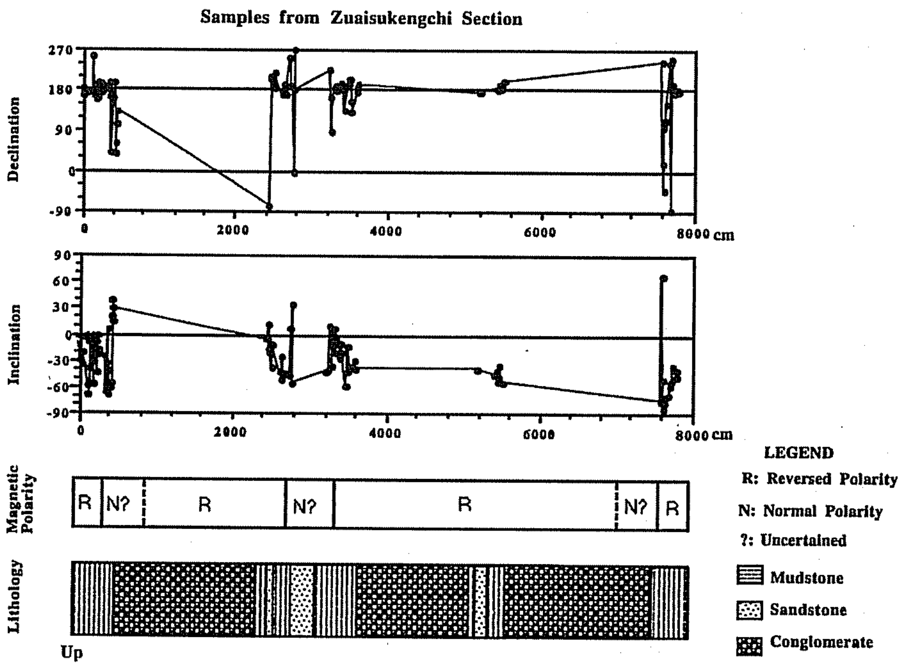

Figure 4. The stratigraphical distribution of paleomagnetic directions and the lithology of the Tananwan Formation at Zuaisukengchi section.

MAGNETIC TIME ZONATIONS

The last appearance datum (LAD) of *Reticulofenestra pseudoumbilica* is dated at the upper limit of the NN15 zone and *Pseudoemiliania lacunosa* appeared during mid-Pliocene to Pleistocene. Both these two species were found near the central part (around 32 meters) of the Kuanyinshan Formation at the Chikeng section. From field study, the Chikeng section takes a dome-like structure. The center of the dome seems to be the oldest part of this section. The co-existence of these two species might suggest that this sequence first appeared in the latest Gilbert epoch of magnetic time zonation. However, our paleomagnetic results did not support this point. They show that the whole studied sequence is of normal polarity, except two samples might show an abnormal direction during polarity reversal transition. To reasonably interpret both nannofossil and paleomagnetic results, we believe that the species, *Reticulofenestra pseudoumbilica*, found in this sequence might be reworked. Thus, we proposed that the Kuanyinshan Formation probably deposited during the Gauss normal epoch, which has the age interval of 3.55-2.6 Ma (Cande and Kent, 1992). Under this consideration, the Kuanyinshan Formation of the Chikeng section may be correlated to the upper part of the Pliocene Kueichulin Formation and the Chinshui Shale at western Foothills of northern Taiwan.

For the Tananwan Formation of the Zuaisukengchi section, the dominating nannofossil is *Gephyrocapsa oceanica*. It is well known to appear during the Plio-Pleistocene. It is obvious that the age of this stuied sequence is younger than that of the Kuanyinshan Formation. In addition, paleomagnetic results indicate that its polarity is generally reversed. Based on both of paleomagnetic and nannofossil data, the Tanawan Formation could be assigned to appear within the Matuyama reversed epoch, which has the time interval between 2.6 and 0.78 Ma (Cande and Kent, 1992). Compared to the other formations in the Western Foothills, the Tananwan Formation in the Linkou area might be correlated to the Pleistocene Choulan Formation and Tokoushan Formation.

For both studied sections, some samples did show abnormal directions or even opposite polarity in comparing to most of the others. Whether they will provide any significance about short polarity events, which could help to determine more precise magnetic time interval, will be discussed.

DISCUSSIONS

In Figure 3, only two samples were found to show abnormal directions. It is mentioned that the Chikeng section looks like a "dome" structure. The most inner part is proposed to be near the relative stratigraphical height of about 28-32 meters calculated from the northern end of the studied section. If we flip the northern part to the southern part, the magnetic zonations of the Chikeng section will be N(normal)-T(transition)-N. Whether the two abnormal samples suggest the existence of a polarity reversal event? From Table 2 and Figure 4, it could be found that samples from the Zuaisukengchi section generally show reversed polarity, but several of them did show abnormal directions and even some show normal polarity. The transition or normal polarity zones seem to appear within the intervals of the relative stratigraphical heights between 3.8 to 24.5 meters, 27.5 to 32.5 meters and 75 to 77 meters. Do these three zones represent the normal events in the Matuyama reversed epoch?

From Figures 3 and 4, it is found that most of the samples shown the abnormal paleomagnetic directions were located very close to the boundary of lithology changes, while the other samples showing very regular magnetic polarities were all collected within the fine-grained mudstone layers. Two possibilities could be drawn to interpret these abnormal results: (1) they do represent short reversal events and (2) they were affected by deposition processes. If it is the second case, it is a very good advise for paleomagnetic workers to avoid sampling at sites of relative coarser grain area. However, if it is the first case, the one within 75-77 meters of the Zuaisukengchi Formation might be considered as the Olduvai event and that between 3.8-24.5 meters might be the Jaramillo events. Of course, these points merit further study.

In addition to magnetostratigraphic analysis, paleomagnetic declinations of the two stuided sequences seem to provide tectonic evidence about northwestern Taiwan. Previous paleomagnetic study by Lue *et al.* (1995) pointed out that two senses of rotations have been occurred in northern Taiwan: clockwise in the eastern part and counterclockwise in the western part. If we look carefully through the paleomagnetic declination data of the two studied sequences in Figures 3 and 4, counterclockwise rotation seems to be found in the Kuanyinshan Formation but not in the Tananwan Formation. This phenomenon not only agrees well with the observation of Lue *et al.* (1995) but further indicates that the counterclockwise rotation might have ended before the Matuyama reversed epoch. However, the spatial distribution of such tectonic features needs to be studied more broadly. In addition, rotation phenomena could be another strong evidence to support the stratigraphic relationship between these two studied sequences that the Tananwan Formation occurred later than the Kuanyinshan Formation.

SUMMARIES

Based on both paleomagnetic polarities and biostragraphical analysis, this study suggests to assign the Kuanyinshan Formation to the Gauss normal epoch and the Tananwan Formation to appear within Matuyama reversed epoch. It is said that the former section appeared during an age interval older than 2.6 Ma and the latter during an age interval between 2.6 Ma to 0.78 Ma. From these assignments, the Kuanyinshan Formation is believed to correlate to the upper part of the Pliocene Kueichulin Formation and/or the Chinshui Shale in the Western Foothills of northern Taiwan. And the Tananwan Formation in the Linkou area may be correlated to the Pleistocene Choulan and Tokoushan Formations. The abnormal paleomagnetic directions of the two studied sections might be indicative of either the existence of short magnetic polarity events or of lithology changes.

In addition, mean paleomagnetic declinations of the two studied sections imply that the counterclockwise rotation in northern Taiwan found by Lue *et al.* (1995) seems to have continuously occurred through Gauss normal epoch and ceased at early stage of the Matuyama reversed epoch.

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