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PALEOMAGNETIC STUDY OF LACUSTRINE SEDIMENTS FROM SUN-MOON LAKE, CENTRAL TAIWAN

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ABSTRACT

This study presents results of magnetic susceptibility and secular variation pattern of paleomagnetic intensity for a piston core (3.69 m long) taken from Sun-Moon Lake in central Taiwan. A total of 145 specimens were analyzed. Four levels of the core, at depths of 48cm, 201cm, 309 cm and 367 cm, have been dated by C-14. The ages of these levels are proposed to be 540±50 yr B.P., 5,150±50 B.P., 10,960±60 B.P. and 19,460±230 B.P., respectively (Lou, 1996).

Paleomagnetic intensity secular variation pattern shows two peaks appeared at core depths of 280-300 cm and 205-235 cm. Comparing this record to previous studies at Taipei Basin, Taiwan (Lee, 1999) and Taihu area, China (Wang, 1998), the ages of the center of these two levels could be assigned to about 10,000 yr. B.P. and about 7,400 yr. B.P., respectively. They are quite consistent to the C-14 age. However, no other high intensities could be found in the time interval prior to 10,000 yr. B.P. This is very different from the record of Taipei Basin where several other peaks have been reported between 20000-10000 yr. B.P. Thus, the results suggest that either there was a sedimentary interruption during the last glacial time or C-14 age dated at depth of 367 cm, about 19,500 yr. B.P., by Lou (1996) could be too old.

Magnetic susceptibility measurements indicate that high values appear at depths of 0-32 cm, 194-205 cm, 256-280 cm and 290-318 cm where the major constitution of sediments is mud. Extremely low magnetic susceptibility values are found at the rest of the portions of the core where sediments are dominately peat layers. Some of these layers even have zero or negative susceptibility values. This implies that peat layers contained fewer magnetic minerals than muddy layers and might contain diamagnetic material.

High magnetic susceptibilities are found to consistently appear at time intervals later than the occurrence of cold and dry events proposed by pollen assemblage analysis (Lou, 1996). This phenomenon is unlike the results from Yuan-Yang Lake where high magnetic susceptibility peaks were formed during cold and dry periods according to the interpretation of Lee *et al.* (1998). The difference of the two records is considered to be due to the sediment transportation system. The sediment source at the studied area is relatively far away from the coring site, and the very few inlet streams at Sun-Moon Lake area probably took more time to transport the muddy sediments into the lake. That is probably the main factor to cause the time delay between the magnetic peaks and the cold and dry events proposed by the pollen assemblage analysis. In addition, the high magnetic susceptibility found at the top part of the core studied could be related to the environment change caused by the construction of the dam.

Key words: magnetic susceptibility, lake sediment, NRM, ARM, paleo-intensity, secular variation, environment change

INTRODUCTION

Paleomagnetic data including polarity reversals, secular variation patterns of the earth magnetic field and magnetic susceptibility records, have been considered to be very useful for paleo-environment change studies. This is because that these results not only provide high-resolution continuous records for stratigraphic correlation and precise age controlled data, but they also supply direct information about paleo-environment changes. In the last two decades, they have been broadly applied to analyze sedimentary sequences, such as sequences for deep-sea cores, lake sediments and Chinese loess, etc. (Barton & McElhinny, 1981; Creer, 1974; 1977; Creer *et al.*, 1976; 1980; 1981; Hyodo *et al.*, 1993; Turner and Thompson, 1981; Thouveny *et al.*, 1994).

However, before the '90s, most secular variations and polarity studies on sedimentary rocks dealt only with the directional pattern of the paleomagnetic field but not their paleo-intensity. This is due to the fact that thermal remanent magnetization (TRM) acquired by volcanic rocks has the 'activity' property of partial TRM, but detrital remanent magnetization (DRM) acquired by sedimentary does not have. In addition, oxidation of magnetic minerals of sediments often occurred during heating processes. These make it very difficult to study paleomagnetic intensity of sediments. Tric *et al.* (1992) used anhysteresis remanent magnetization (ARM) to simulate the acquisition of natural remanent magnetization (NRM) and successfully concluded that the stratigraphic variation patterns of the ratio of NRM to ARM both after 20 mT cleaning could monitor the existing discrete paleo-intensity records analyzed from volcanic rocks. Since then, several similar studies have been made for lacustrine and marine sediments (Meynadier *et al.*, 1992; Valet & Meynadier, 1993; Yamazaki & Ioka, 1994). Such intensity secular variation patterns have been extended to about 4 million years before present (Valet & Meynadier, 1993).

To study paleo-climate changes in central Taiwan, Lou (1996) analyzed pollen assemblages of a lacustrine sediment core taken from Sun-Moon Lake. For age control, he chose four levels to do AMS C-14 dating. Based on these four age data, he constructed a time history for the core studied and indicated that this core covered the information for the last 20,000 years. He reported several periods of paleo-climate change during this time period. In addition, he pointed out that there was a very low sedimentation rate between 10,000 to 20,000 yr.B.P. In order to establish more precise time series, we decided to do a paleomagnetic intensity analysis for the same core and it will be presented in this study. In addition, a magnetic susceptibility analysis for a core taken from Yuan-Yank Lake in northern Taiwan has provided information about paleo-climate changes for the last 4,000 years in that area (Lee *et al.*, 1998). The results indicated that high magnetic susceptibilities were often found in association with cold and dry seasons based on pollen analysis in that area. To see whether magnetic susceptibility could also reflect signals of paleo-climate changes in central Taiwan, the variation pattern of magnetic susceptibility of samples was also analyzed in this study.

To use secular variation pattern for stratigraphic correlation and age control, the best way is to have the regional records for comparison. It is due to that the core studied usually has short time span, the characteristics of dipole and non-dipole effects of the earth magnetic field need to be taken into considertion. In Taiwan and its neighboring area, there were already two paleo-intensity secular variation records available (Lee, 1999; Wang, 1998). These two data sets covered an age interval of the last 21,000 years. They could be used as a base for correlating the results of this study to them.

GEOLOGICAL SETTING AND LITHOLOGY OF THE CORE

In central Taiwan, there are more than 10 lake basins trended in NNE-SSW direction. These basins spread about 30 km along N-S direction. Most of them are dried at present day except the Sun-Moon Lake basin. Sun-Moon Lake is the largest lake in Taiwan now, which covers an area of about 20 km^2 since a dam has been constructed for electricity supply in 1950. Its location is 23°51'N of latitude and 120°54'E of longitude (Fig. 1). Originally, the height of the lake surface is about 726 m above sea level and the water depth is about 4.6 m. However, the lake surface can raise by 18 m during rainy season in summer.

The Sun-Moon Lake basin was developed during Late Pleistocene to Holocene. It has already accumulated more than 30 meters thick lacustrine deposits. The lake could be divided into two parts: the larger one, Sun Lake, in the north and the smaller one, Moon lake, in the southwest (Fig. 1). The source of lake water generally comes from the rainfalls, only very minor of it comes from its three inlets: two small streams in the west and one in the east. The yearly rainfall in the studied area is about 2,340 mm in average.

The core studied was taken from the northern part of the Moon Lake. Site locality is shown in Figure 1 where the water depth is the deepest part of the whole lake. A coring system (made by ETH) was employed to raise cores. The recovered length of the core analyzed in this study is 3.69 m. It is mainly constituted of peat layers, mud layers and organic debris. Generally, the peat layers are dark-brown to dark-gray in colored and the mud layers are yellowish-brown or light gray in color. The detailed lithology of this core is shown in Figure 2.

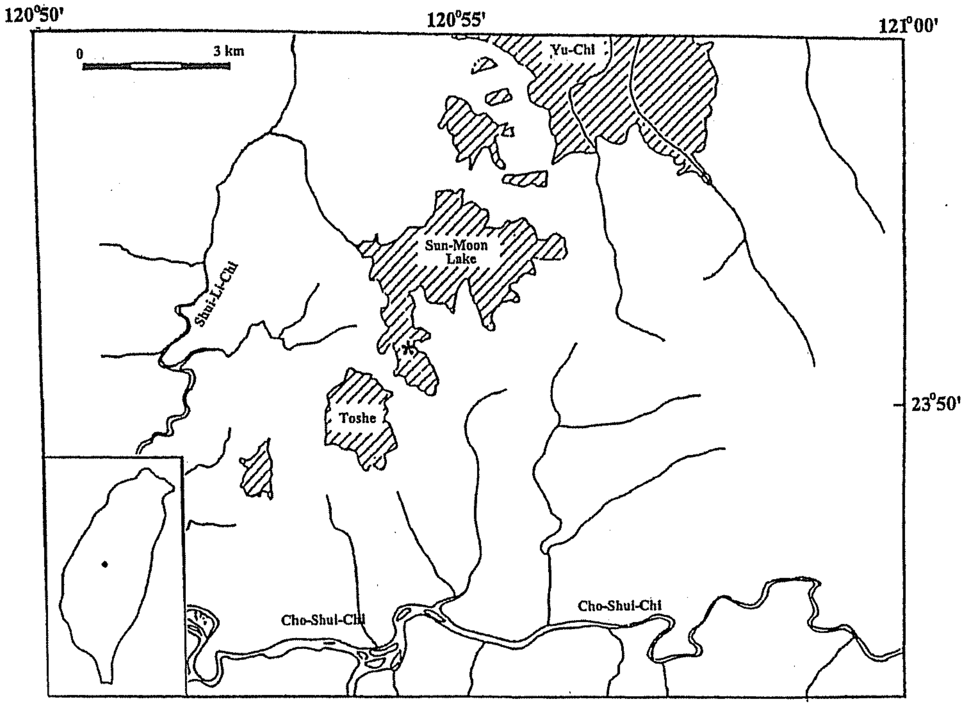

Figure 1. Sketch map of Sun-Moon Lake showing the site locality of the studied core (denoted as *).

SAMPLING AND LABORATORY ANALYSIS

A total of 145 samples were taken from the sedimentary piston core by using plastic boxes with the dimension of 2.0 cm x 2.0 cm x 1.6 cm. The stratigraphical heights of the studied samples were carefully documented.

Low field magnetic susceptibilities (χ) of the samples were measured on a Bartington MS2 susceptibility instrument at its low frequency mode. The natural remanent magnetization (NRM) of the samples and their demagnetization treatments were carried out on a horizontal type of cryogenic magnetometer (model SRM 755 of the 2G Enterprise Company, equipped with a three-axis AF demagnetizer). Demagnetization employed progressive increasing alternating field (AF) and the steps are from 0 mT to 100 mT with an increment of 10 mT. After, anhysteresis remanent magnetization (ARM) of the samples was built up by applying a stable magnetic field of 1 Gauss in associated with an AF demagnetization field of 100 mT (peak value) at the same time. Finally, the samples' ARMs were measured and demagnetized again with the completely same procedures as those treated for NRMs.

Stratigraphical variation patterns of χ/NRM and χ/ARM at different demagnetization steps were first compared. It is for the purpose of choosing the optimum level for paleomagnetic intensity study. To simulate the intensity secular variation pattern, NRM vs. ARM pattern at the chosen demagnetization stage was then analyzed. In order to establish a precise time sequence for the core studied, the NRM/ARM pattern is compared to the other records in Taiwan and in

China (Lee, 1999; Wang, 1998) in consideration of all the dated C-14 ages. Finally, the stratigraphical patterns of NRM and ARM (both before demagnetization treatment) and the magnetic susceptibility were set up, and applied to investigate the events of paleo-environment changes.

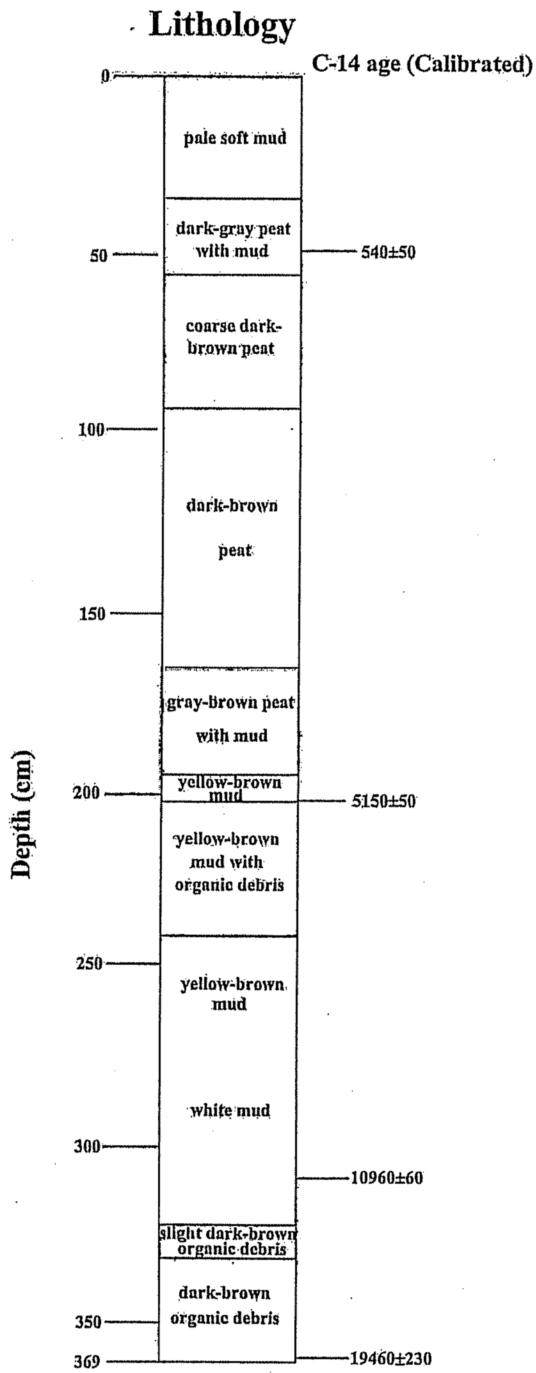

Figure 2. Lithology of the studied core taken from Sun-Moon Lake.

RESULTS

Four levels, at depths of 48 cm, 201 cm, 309 cm and 367 cm below core top, have been subjected to carry out the AMS C-14 dating. The results indicate that the calibrated C-14 ages of these four levels are 540 ± 50 yr.B.P., 5,150 ± 50 yr.B.P., 10,960 ± 60 yr.B.P., and 19,460 ± 230 yr.B.P., respectively (Lou, 1996). They were generally referred for constructing time sequence in this study, but their accuracy will be discussed later.

Figure 3 shows the stratigraphical variation patterns of χ/NRM and χ/ARM at four different demagnetization steps: 0 mT, 10 mT, 20 mT and 40 mT. The results indicated that at both 0 and 10 mT stages, patterns of χ/NRM and χ/ARM are more similar than the others. In consideration of NRM before AF demagnetization may contain some secondary components, thus, the results after 10 mT cleaning stage is considered to be the most representative data set to be used for monitoring paleomagnetic intensity variation. The intensity secular variation pattern simulated by the NRM/ARM at 10 mT demagnetization stage is shown in Figure 4. From this figure, two high peaks appeared at depths of about 290 cm and 250 cm could be recognized.

Stratigraphical distributions of magnetic susceptibilities, NRM and ARM intensities before AF demagnetization treatments are shown in Figure. 5. It could be found that high magnetic susceptibilities appear at the depths of 290-318 cm, 256-280 cm, 194-205 cm and 0-32 cm, especially the first three zones. However, the other parts of the core have extremely low magnetic susceptibility values, some of them even appear to have zero or negative values. It could also be found that the trend of magnetic susceptibility is different from those of NRM and ARM. What the significance of these trends and their implications to environmental changes will be discussed later.

DISCUSSIONS

It is well known that magnetic secular variation pattern could provide age control in addition to the C-14 dating. To do this, the obtained sequence should be correlated to the existed records. In general, local or regional records are better than global events for the correlation. This is due to the characteristics of dipole and non-dipole components of the earth magnetic field. Previous paleo-intensity studies of the sedimentary cores sampled from Taipei Basin, Taiwan and from Taihu area, China have supported this argument (Lee, 1999; Wang, 1998). Several high intensity peak areas have been investigated in these two records.

In the present study, two high intensity peaks could be found at depths of 280-300 cm and 205-235 cm (Fig. 4). In comparison this result to the two previous records by Lee (1999) and Wang (1998) and taken the C-14 data of the three records into account, the center part of the two high peak area could be assigned to have the ages of about 10,000 yr.B.P. and of about 7, 400 yr. B.P, respectively. However, unlike the two previous records to show the existence of some other high peaks happened at the age interval between 10,000 to 21,000 yr. B.P., nothing could be found at the present time sequence. Site localities of the three records are not very far apart. Thus, the three different areas should show the same geomagnetic behavior because they are under the same dipole and non-dipole field control. Why the three records are so different is worthy of further investigation.

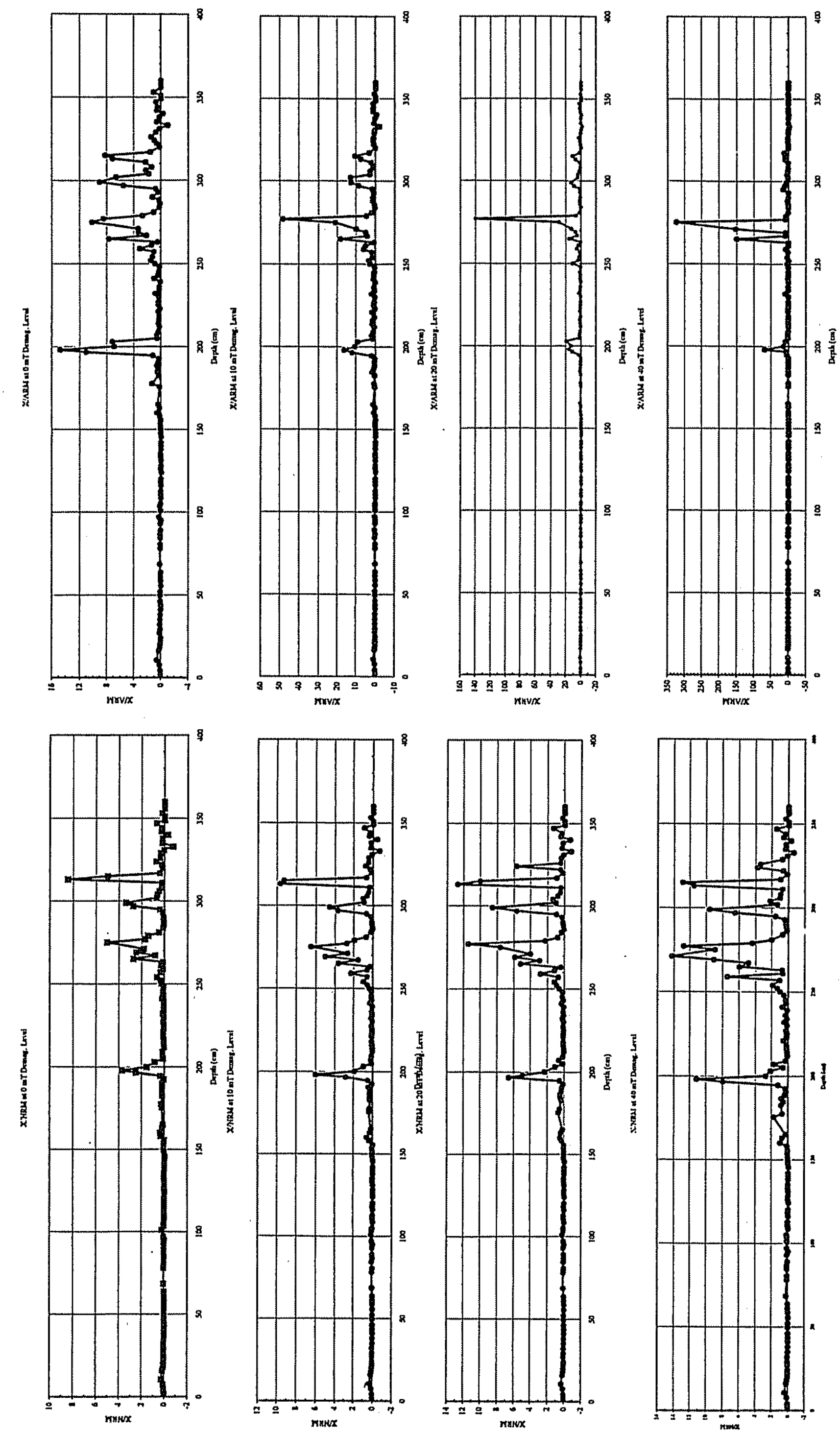

Figure 3. The stratigraphical variation patterns of χ (magnetic susceptibility) v.s. NRM and χ v.s. ARM at different demagnetization steps.

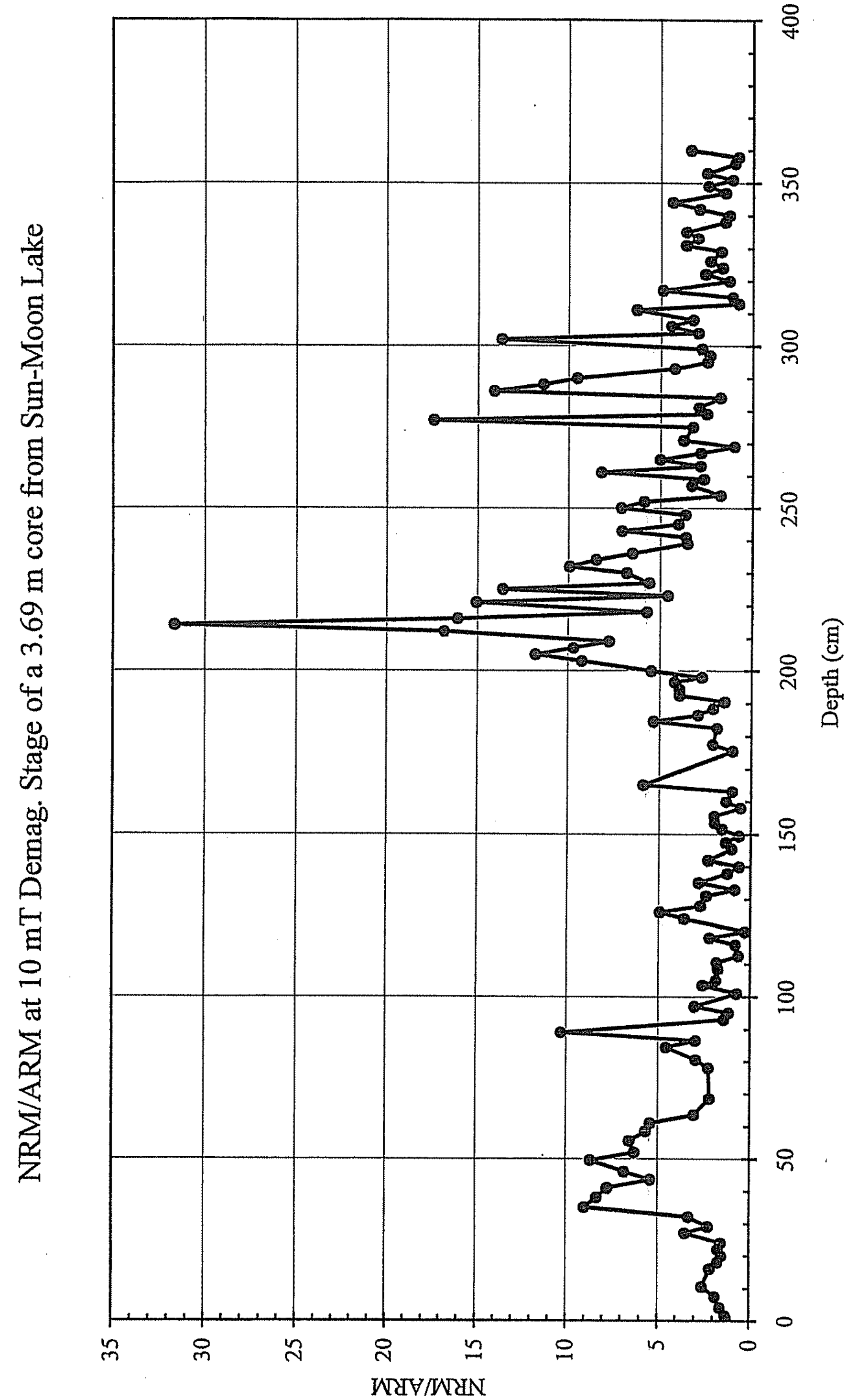

Figure 4. The stratigraphical variation pattern of NRM v.s. ARM at 10 mT demagnetization step monitoring the secular variation of paleomagnetic intensity.

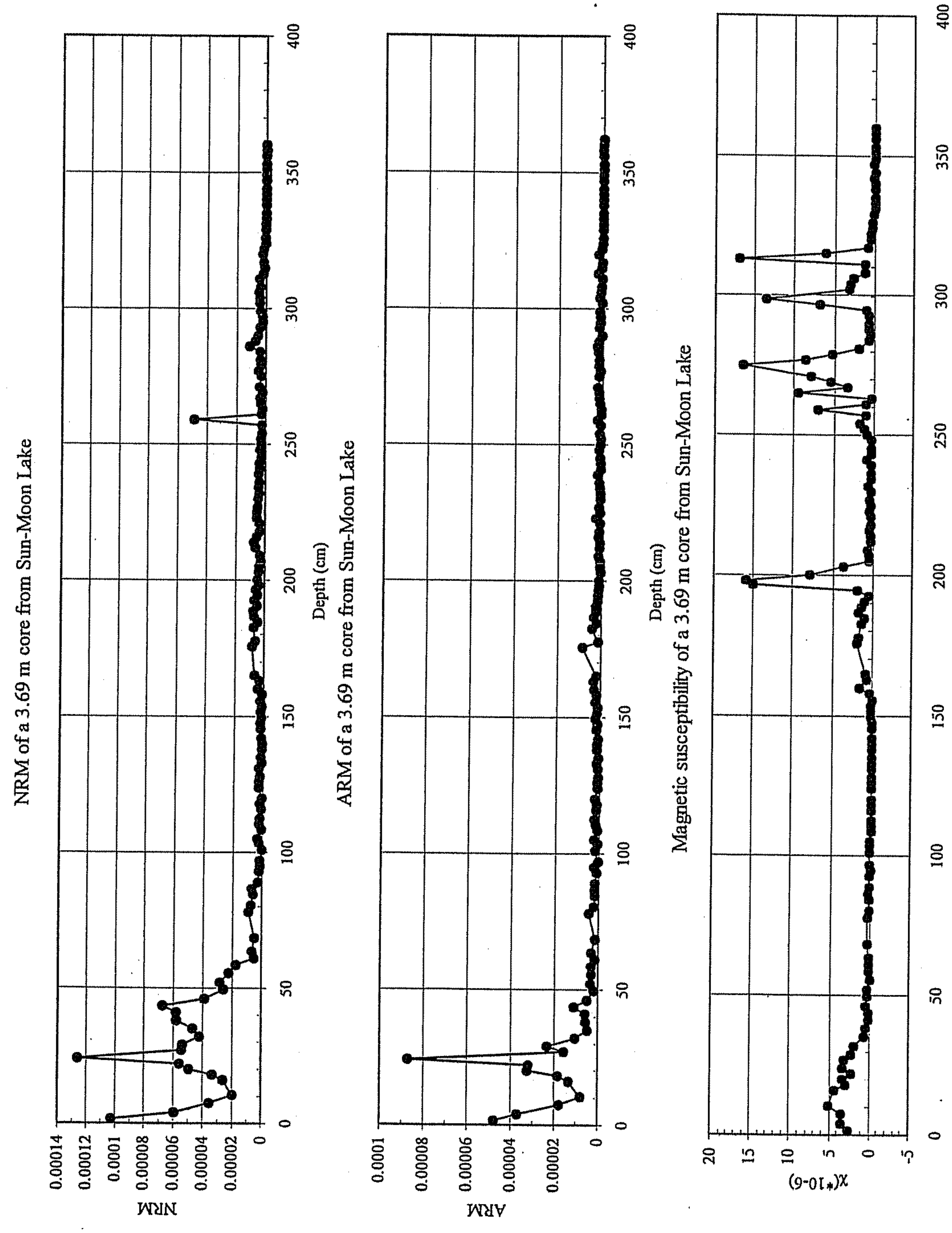

Figure 5. The stratigraphical distribution patterns of magnetic susceptibility, ARM and NRM intensities before demagnetization treatment of the studied core taken from Sun-Moon Lake, Central Taiwan.

A possible interpretation is that sedimentary interruption occurred during the time interval between 19,000 yrB.P. and 13,000 yrB.P. This is due to that two high intensity peaks found at the record from Taipei Basin appeared at about 13,500 and 17,500 yrB.P. (Lee, 1999), but they are not recognized in the present study. The proposed time interval for the occurrence of sedimentation interruption is quite possible, because it is just located within the period of last glacial maximum. Low organic production and low water level probably prevent the sediments from deposition during that time.

Comparing the magnetic susceptibility trend shown in Figure 5 to the lithology of the studied core (Fig. 2), it could be found that the constituents of the samples appeared high magnetic susceptibilities dominate mud sediments, and the others are peat layers. Obviously, mud layers contained much more ferromagnetic minerals than the peat layers. Furthermore, zero and negative magnetic susceptibilities appeared at peat layers may reflect that these layers contained only the paramagnetic and/or diamagnetic materials. The different kinds of magnetic minerals contained in different portions of the core undoubtedly result different magnetic properties. This implies that the amount of magnetic minerals might not be the only factor to reflect magnetic behaviors of the sediments. This is proved by the fact that the NRM and ARM patterns did not show the same trend as that of the magnetic susceptibility.

Lee *et al.* (1998) studied magnetic susceptibility pattern of a sediment core taken from Yuan-Yang Lake and indicated that high magnetic susceptibilities were investigated to occur during cold and dry seasons. They interpreted the phenomenon as relative large amount of detritus sediments were eroded from the neighboring rock formations and were brought into the lake during those time periods. Rock sediments usually contained much more ferrimagnetic minerals than the layers of organic materials. This is the reason for forming high magnetic susceptibilities during cold and dry time. If this is also the mechanism for the Sun-Moon Lake area, the 4 high magnetic susceptibility peak zones shown in Figure 5 should represent 4 different relative cold and dry periods.

However, analyzed pollen assemblages of the same core, Lou (1996) pointed out that the sediments have been disturbed due to the construction of the dam since 1950. So, the high magnetic susceptibility zone found at the top 32 cm of the core probably related to such event of environment change. Furthermore, he also indicated that dry periods appeared at the depth below 320 cm, 290-280 cm and 230-170 cm. The third zone is somehow consistent for both the two data sets. But, for the first two periods, obviously, the appearance of dry season proposed by pollen assemblage is earlier than that by magnetic susceptibilities. It is believed that the difference might be due to different conditions of the deposition environments. Considering that the high peaks of magnetic susceptibility were due to access the rock sediments from the surrounding rock formations, then, it could be found that rock formations are much closer to the deposition area of lacustrine sediments at the Yuan-Yang Lake area than that at the Sun-Moon Lake area. During cold and dry periods, sediments eroded from the rock formations could be transported very fast into the Yuan-Yang Lake, i.e. the time lag is relatively very short. However, it would not happen at Sun-Moon Lake area. It has mentioned before that the Sun-Moon Lake covers an area of about 20 km^2 and very few inlet streams could be found in it surrounding area. It implies that before the dam is constructed, the site locality of this study should be far away from the surrounded mountain relative to the Yuan-Yang Lake area. Very few inlet streams existed might mean that sediments eroded from the rock formations were very difficult to be transported into the deposition area during cold and dry periods. Until wet periods, when the inlet streams have enough energy, then the rock sediments were brought into the lake area.

This might be the reason for the inconsistency of indicating the appearance of cold and dry period by high magnetic susceptibility peaks and pollen analysis at the Sun-Moon Lake area.

In summary, the high magnetic susceptibility zones, found in the Figure 5, should not represent the cold and dry periods as that indicated at the Yuan-Yang Lake area. Instead, it may represent a time lag due to different depositional environment, an environment change etc. This certainly needs to be further studied.

CONCLUSIONS

In this study, paleomagnetic intensity secular variation pattern was not only successfully used for helping C-14 dating to set up a more precise time series of a lake sediment core taken from Sun-Moon Lake at central Taiwan but also corrected the C-14 dating. Two peaks appeared at core depths of about 280-300 cm and 205-235 cm are assigned to be about 10,000 yr.B.P. and 7,400 yr.B.P., respectively. No other high intensities could be found prior to 10,000 yr.B.P., which is very different from the other record from Taipei Basin. This implies that either sedimentary interruption had occurred between 10 to 20 kyrB.P. or the C-14 age data at depth of 367 cm (Lou, 1996) may be dated too old.

Magnetic susceptibility variation pattern indicated that high peaks appear at depths of 0-32 cm, 160-190 cm, 194-205 cm, 256-280 cm and 290-318 cm where sediments are mostly mud in composition. The rest portions of the core are dominately by peat layers where the magnetic susceptibility measurements are extremely low, some of them even have zero or negative values. This implies that peat layers contained much less magnetic minerals than muddy layers. Furthermore, the high magnetic susceptibilities zones are found to appear at the time interval later than the occurrence of cold and dry events proposed by pollen assemblage analysis (Lou, 1996). If the high magnetic susceptibilities reflected the amount of rock sediments eroded during cold and dry periods, the 5 recognized high magnetic susceptibility zones of this study are proposed to appear within the warm and wet periods instead of cold and dry time intervals. This proposition is different from that proposed at the Yuan-Yang Lake area because of the difference of depositional environments of the two lake areas.

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