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Paleomagnetic Study in a Folded Zone of Hsuehshan Range, Northeastern Coast of Taiwan

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ABSTRACT

This study uses paleomagnetic methods to analyze the tectonic features in the northeastern coastal area of Taiwan. A total of 14 sites were chosen at the different locations where slightly metamorphosed and multiply deformed sedimentary strata are characterized by gently dipping folds and dense-spaced faults. The results show that the paleo-inclinations of all the sites are negative. This suggests that the characteristic paleomagnetic directions were acquired during magnetic time zones of reversed polarity. The paleo-declinations measured are very scattered. However, after the bedding of each studied site is rotated to the regional structural attitude in northeastern Taiwan, there is a consistent trend at approximately N80°E; most of the corrected paleomagnetic directions point toward the direction of N100°E-N120°E. Micro-tectonic analysis also deciphered the direction of the major compression in the area studied, which occurred in the same period as that of corrected paleomagnetic direction. This suggests that the paleomagnetic directions of the samples in the studied area were acquired before the major folding and faulting which caused great deal of horizontal rotation in both clockwise and counterclockwise senses. In addition, the corrected paleomagnetic directions do not show an expected direction in a normal or reversed polarity epoch. This implies that they may not be the primary component of NRM acquired during the deposition of the formations. Instead, they might result from regional metamorphism/deformation with a certain degree of intensity. Thus, the results reveal that the samples studied have acquired the remanent anisotropy of their magnetizations.

(Key words: Paleomagnetism, Tectonic rotations, Remanent anisotropy)

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1. INTRODUCTION

Paleomagnetic methods have been regarded as a very powerful tool for studying tectonic movements since the 1960s. Since it was applied to the young and important tectonic province in Taiwan, several important paleomagnetic results have been obtained from the eastern Coastal Range and northern Taiwan. Diachronous southward-propagated clockwise rotation has been found in the eastern Coastal Range (Lee, 1989; Lee *et al.*, 1991b), and distinct patterns of horizontal rotation, both clockwise and counterclockwise, have been recognized in two areas divided by the Tanshui River in northern Taiwan (Lee *et al.*, 1991a; Lue *et al.*, 1995). The paleomagnetic analysis has thus been successfully applied to the studies of block rotation in Tertiary sedimentary and volcanic rocks and gives an insight into Tertiary tectonic evolution in Taiwan (Huang *et al.*, 1992; Teng, 1990; Teng *et al.*, 1992).

The area of this study is located along the northeastern coast of Taiwan from Maoao to Tali, where slightly metamorphosed and strongly deformed Oligocene sedimentary rocks of the Chinese continental margin are exposed. Micro-tectonic analysis by Lu *et al.* (1994) has pointed out that the rocks have suffered several phases of strong deformation, which is characterized by numerous complicated structures including contractional, transpressive, block-rotation, and extensional structures. Samples used for all the previous paleomagnetic studies in Taiwan were from either volcanic rocks or sedimentary formations, and such a study has not previously been carried out on metamorphosed rocks. To test whether the paleomagnetic directions acquired in the rocks of the slightly metamorphosed terrain could significantly reflect tectonic features, sampling and analysis on the metamorphosed belt in northeastern Taiwan have been carried out. This paper presents preliminary results and the tectonic significance based on the paleomagnetic analysis along with the field micro-tectonic analysis.

2. GEOLOGICAL SETTINGS

The area studied is at the northern tip of the Hsuehshan Range along the northeastern coast of Taiwan (Figure 1). In general, the Hsuehshan Range mainly consists of thick and monotonous low grade metamorphic argillaceous rocks (Chen *et al.*, 1983). They are intercalated with thin- to thick-bedded sandstones. Based on previous paleontological data, the ages of the sampled rocks are ascribed to the Eocene and the Oligocene (Huang and Huang, 1983). The argillacious rocks have been slightly metamorphosed in a low grade metamorphism of prehnite-pumpellyite to green schist facies (Liou, 1981; Chen *et al.*, 1983).

The Hsuehshan Range generally reveals repeated anticline-syncline folds with fold axes trending NE-SW to ENE-WSW along the coast of northeast Taiwan (Figure 1). However, there exists a zone of concentrated deformation within the Hsuehshan Range extending about several tens kilometers wide from Maoao to Tali (Figure 1). The deformation zone exhibits many gently dipping folds and dense faulting. Generally, the dips in the structures are less than 20° and most of their strikes are close to N80°E direction, except for the areas close to the major faults. The samples for the paleomagnetic analysis in this study were collected in the zone of shear concentration within the Hsuehshan Range. According to their microtectonic study in this region, Lu *et al.* (1994) pointed out that several different types of transpressive

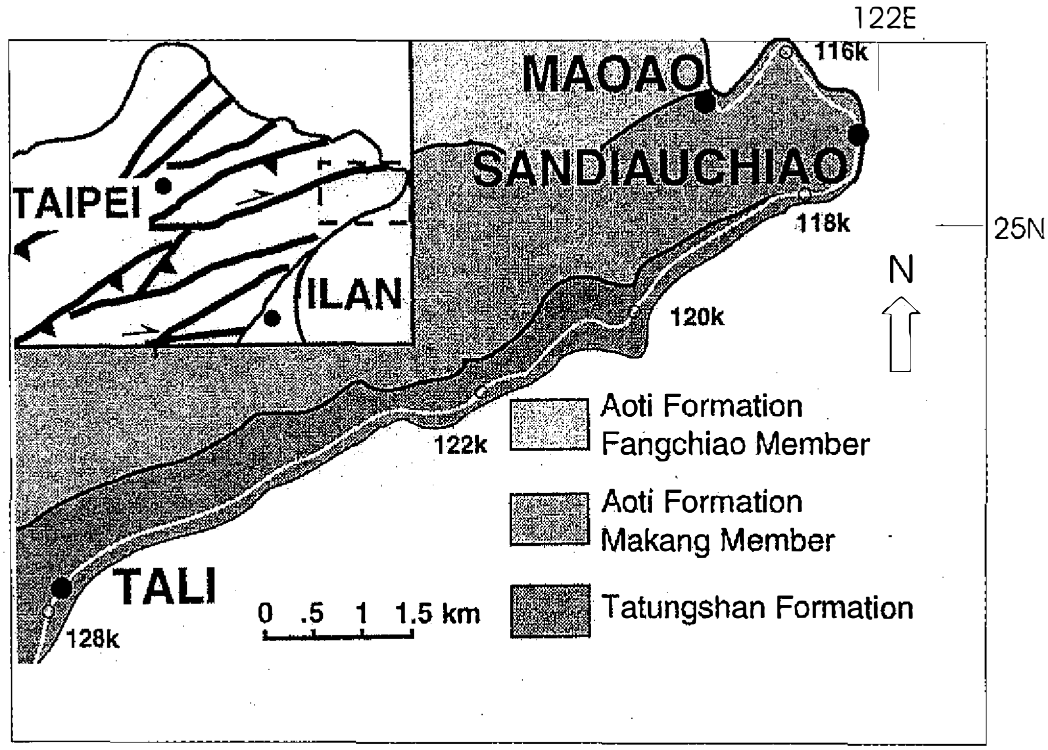

Fig. 1. The sketch geological map of the study area showing sampling area at 118 km, 120 km, 122 km and 128 km along the northeastern cross highway. (after Lu *et al.*, 1994)

structures could be identified and the mechanism to form these structures is complicated. Based on these field observations and also on the experimental modeling, Lu *et al.* (1995) further interpreted the curved belt of northern Taiwan in terms of indental tectonics (with compression, thrust sheet stacking, folding and transcurrent faulting) combined with increasing block rotation, bookshelf-type strike-slip faulting and extension. However, the relationship between block rotation and major structures seems still to be ambiguous.

3. SAMPLING AND ANALYSIS

To investigate the spatial-temporal relationship of the tectonic features, 14 sites were chosen for paleomagnetic studies in the areas distributed between Maoao and Tali. The site localities are shown in Figures 2 to 5. At each site, eight to twenty cylindrical cores of 1 inch diameter were sampled. Standard paleomagnetic techniques were used to mark the orientation of the cores in the field. The bedding attitudes were also carefully measured because of the complexity of the structures. Finally, the cores were cut into several 22 mm long specimens for paleomagnetic measurement.

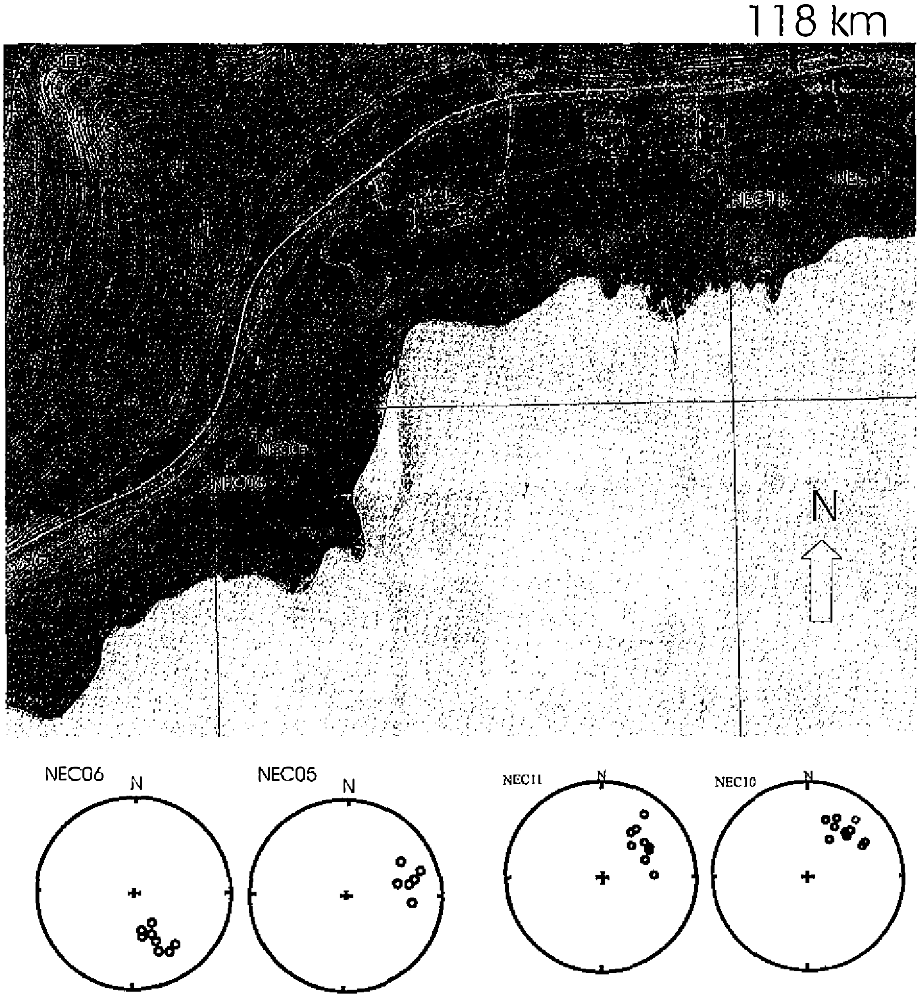

Fig. 2. The air-photograph at the 118 km area of the northeastern cross highway showing sampling site localities and stereo-net plot showing the tilt-corrected paleomagnetic results of the studied sites. Open circle in the stereo-net plot represents the negative inclination.

At least eight specimens for each site were selected for measuring their natural remanent magnetization (NRM) on a 2G Enterprise cryogenic magnetometer (model 755 SRM) in a magnetic shielding room. The specimens were stepwisely thermal demagnetized from room temperature up to about 510°C. Such thermal demagnetization treatments were done with a Schonstedt TSD-1 thermal demagnetizer. The ambient magnetic field in the cooling chamber of the TSD-1 was below 2 nT. In addition, low field magnetic susceptibilities of the specimens were measured repeatedly after each heating step to monitor the compositional change of the magnetic minerals.

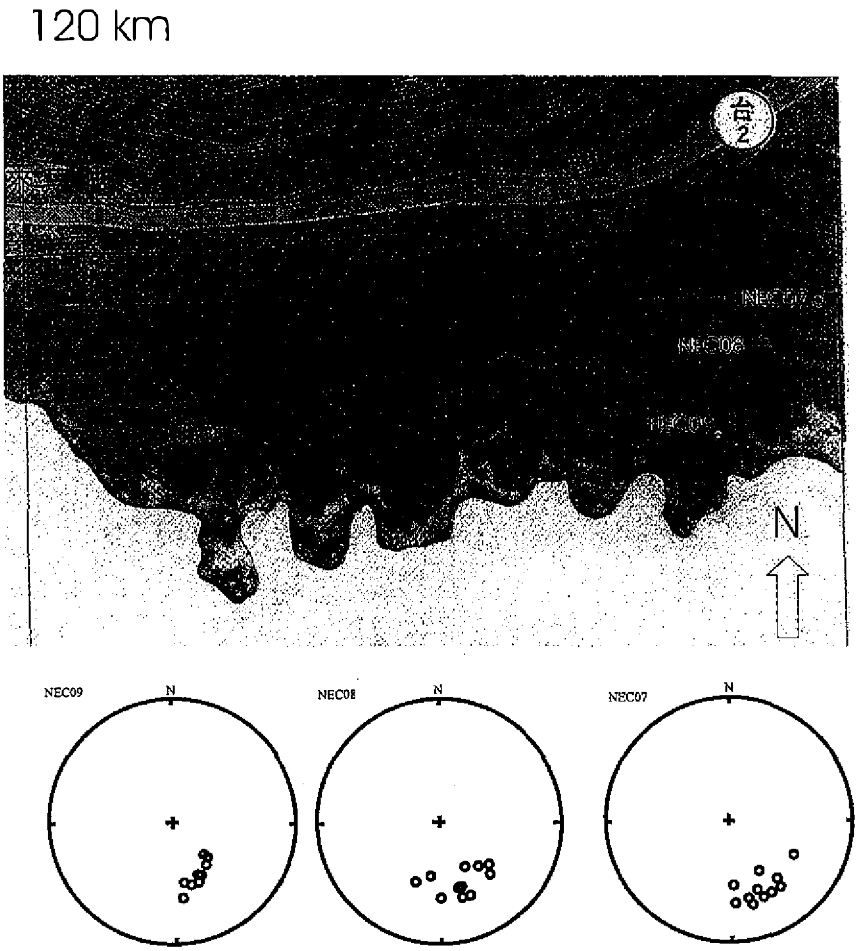

Fig. 3. The air-photograph at the 120 km area of the northeastern cross highway showing sampling site localities and stereo-net plot showing the tilt-corrected paleomagnetic results of the studied sites. Open circle in the stereo-net plot represents the negative inclination.

To obtain the characteristic directions of NRM of the studied specimens, the stability of their remanent magnetizations were first tested and then a linear regression method was employed to analyze the directions of several final demagnetization steps shown on the Zijderveld plot (Zijderveld, 1967). For each site, the Fisher statistical method (Fisher, 1953) was applied to calculate the mean directions before and after back-tilting of bedding correction. Finally, to unravel the tectonic significance of the site mean paleomagnetic directions, the regional bedding attitudes were taken into consideration in association with the investigations from microtectonic analysis.

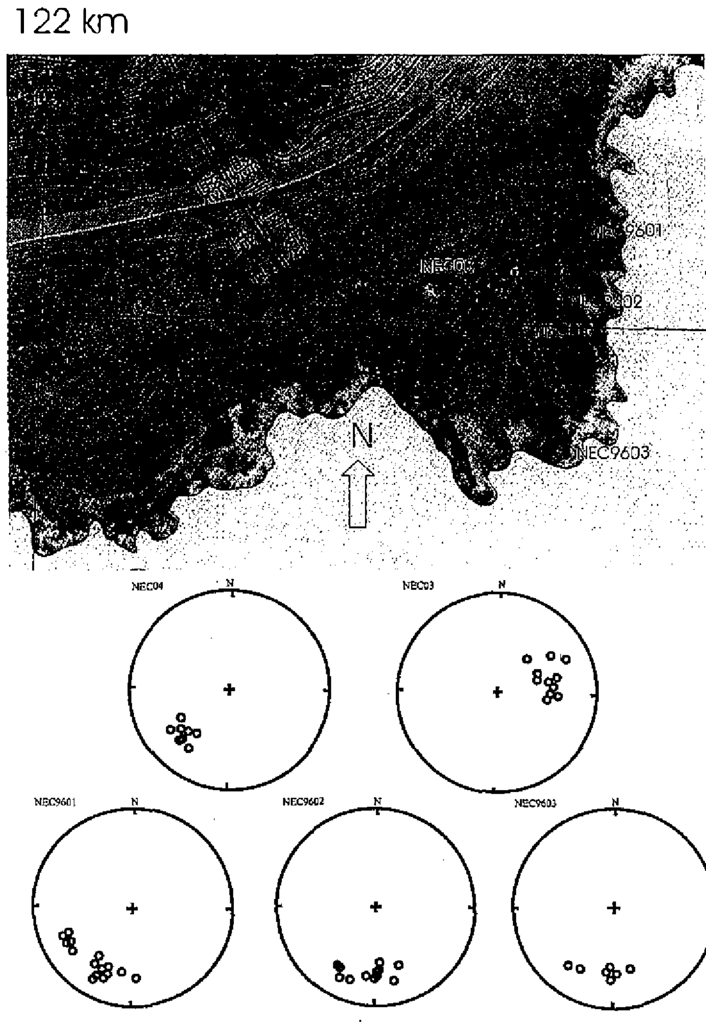

Fig. 4. The air-photograph at the 122 km area of the northeastern cross highway showing sampling site localities and stereo-net plot showing the tilt-corrected paleomagnetic results of the studied sites. Open circle in the stereo-net plot represents the negative inclination.

4. RESULTS

After testing the stability of samples and tilt correction of beddings, the paleomagnetic results of samples for the 14 studied sites are plotted in stereo-net diagrams and are shown in Figures 2 to 5. The site mean directions after and before tilt correction in association with the Fisher statistical parameters, k (precision parameter) and α_{95} (95% confident interval), and the bedding attitudes are listed in Table 1. In order to easily discuss the geological meaning of the paleomagnetic directions, the differences between paleo-declinations and bedding strikes

128 km

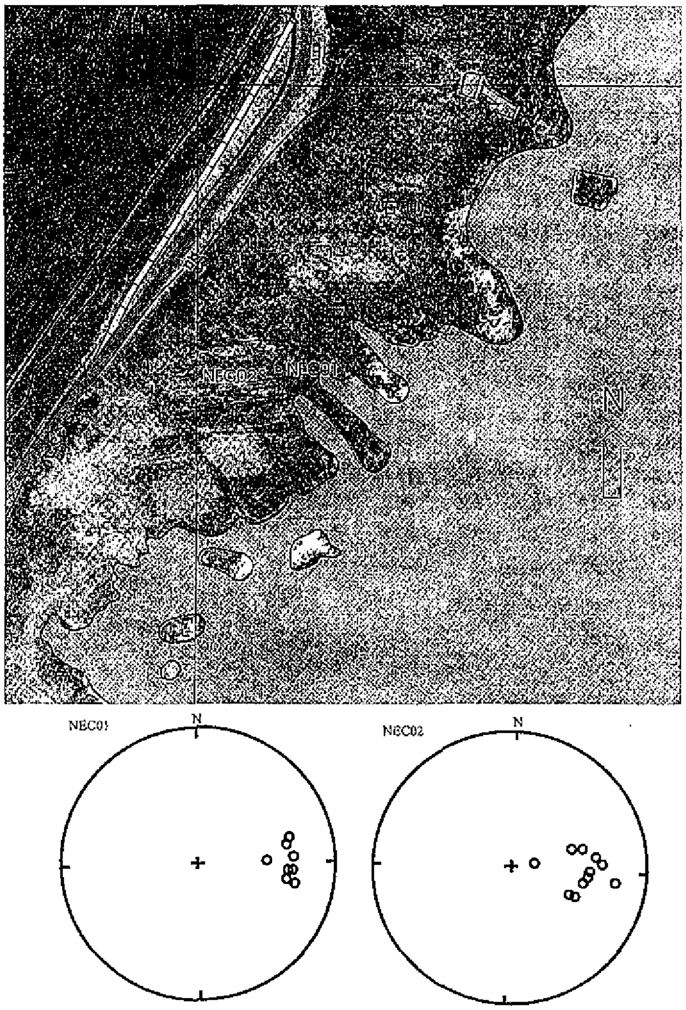

Fig. 5. The air-photograph at the 128 km area of the northeastern cross highway showing sampling site localities and stereo-net plot showing the tilt-corrected paleomagnetic results of the studied sites. Open circle in the stereo-net plot represents the negative inclination.

of the sites were calculated and presented in the columns Φ_s and Φ_g in Table 1 for after and before tilt correction, respectively. In addition, new declinations (column Dec* in Table 1) were obtained by rotating the original tilt-corrected declinations through an angle between the strike of the folded bedding and the bedding strike of the regional trend N80°E at each site. The rotation angles of the structures at the studied sites are also shown in the Table 1 as the column θ.

Table 1. Paleomagnetic results of the shear zone of Hsuehshan Range at north-eastern coast of Taiwan

Site name	N	Ds	Is	κs	α_{95s}	Dg	Ig	κg	α_{95g}	Bedding	Φs	Φg	Dec*	θ
NEC10	9	46.4	-35.3	31.4	8.8	40.7	-36.5	31.5	8.8	030/08°N	16.4	10.7	96.4	-50°
NEC11	8	60.8	-34.4	19.9	11.9	50.7	-42.8	19.9	11.9	022/15°N	38.8	28.7	118.8	-58°
NEC05	5	86.4	-32.8	25.0	13.9	75.0	-31.4	25.0	13.9	030/15°N	56.4	45.0	136.4	-50°
NEC06	7	156.7	-27.2	25.0	11.4	154.5	-45.0	24.9	11.4	075/15°N	81.7	79.5	161.7	-5°
NEC07	10	176.8	-18.3	24.3	9.5	155.6	-7.9	24.4	9.5	140/42°E	36.8	15.6	116.8	60°
NEC08	10	189.2	-22.5	18.8	10.8	160.5	-46.5	18.7	10.8	145/45°E	34.2	15.5	114.2	65°
NEC09	8	171.3	-41.3	43.5	7.9	157.6	-50.4	43.5	7.9	130/16°E	41.3	27.6	121.3	50°
NEC03	10	98.4	-36.5	23.7	9.6	72.7	-44.9	23.7	9.6	070/20°N	28.4	2.7	108.4	-10°
NEC04	7	229.8	-18.8	57.4	7.4	224.2	-35.6	57.6	7.4	170/20°E	59.8	54.2	139.8	90°
NEC9601	11	207.8	-20.4	46.1	6.5	215.3	-31.9	18.4	8.8	165/10°E	42.8	50.3	122.8	85°
NEC9602	13	194.3	-26.6	26.3	7.9	186.4	-31.9	26.3	7.9	170/10°E	24.3	16.4	104.3	90°
NEC9603	6	193.4	-27.3	17.6	14.9	189.2	-34.6	17.6	14.9	160/10°E	33.4	29.2	113.4	80°
NEC01	7	99.5	-30.4	46.9	8.2	90.2	-34.2	46.9	8.2	080/15°N	19.5	10.2	99.5	0°
NEC02	10	93.0	-34.2	22.2	9.9	89.8	-45.5	22.2	9.9	070/12°N	23.0	19.8	103.0	-10°
										Mean*	32.51	25.07		
										stdev.*	13.17	16.15		

N : number of samples for Fisher statistics

Ds & Is : site mean declination and inclination after tilting correction

Dg & Ig : site mean declination and inclination before tilting correction

κs & κg : precision parameter for Fisher statistics after and before tilting correction respectively

α_{95s} & α_{95g} : 95% confidence interval for Fisher statistics after and before tilting correction respectively

Φs : Ds − (strike of bedding)

Φg : Dg − (strike of bedding)

Dec* : new Dec. (Φs +80; when the strike of bedding rotated to N80°E)

θ : rotation angle of the structures relative to the bedding N80°E (+: clockwise; -: counterclockwise)

* : site NEC06 not included

It can be found in Table 1 and Figures 2 to 5 that the corrected inclinations of all the sites studied are negative and most of the values are in an interval of 20°-40°. This implies that the obtained paleomagnetic directions were probably acquired during a reversed epoch. In addition, the expected inclination of the area studied is presently about 40°. The studied samples are argillites, which were mostly indurated from shaly sediments. Magnetizations of sedimentary rocks usually show the phenomenon of a slightly shallower than expected inclination. Therefore, it is speculated that there might not have been any latitudinal drifting in the area studied since the magnetizations were acquired.

The results show that the paleo-declinations distributed dispersed. However, Most of the Φ_s and Φ_g values in Table 1, which represent the angles between the paleo-declinations and bedding strikes in the sampling localities, are in a quite narrow interval, generally between 20°-40° and 10°-30°, for after and before the tilting correction, respectively. Comparing the Φ_s

and Φ_g values, it can be found that the standard deviation for the data set is smaller after the tilting correction than that before. Therefore, it is considered that the characteristic paleomagnetic directions might have formed before the horizontal folding of rock formation. Furthermore, if we put the bedding trend of each site in the same direction, we can find that the induced paleo-declinations will be quite consistent in a direction of about 20°-40° clockwise to the bedding strike. This may imply that before the horizontal folding (rotation), there existed a deformation stage in which the magnetic declinations were made at a moderate angle of 20°-40° to the stratigraphic bedding. The tectonic significance of these results will be discussed later.

In addition, results from sites NEC04, NEC05 and NEC06 show that they have relatively higher values of Φ_s and Φ_g than the other sites. This might indicate the existence of very local tectonic movement in addition to the general event. This needs to be further studied.

5. DISCUSSIONS

Paleomagnetic results have demonstrated that the tilt-corrected paleo-declinations were located with reasonable consistence in a direction of about 20°-40° clockwise to the bedding strike of the sites studied. If we put the same direction of bedding strike for the sites, we will obtain a very consistent paleomagnetic direction. In this case, it could be concluded that the characteristic remanent magnetization directions of the samples studied were acquired during the same time period. A large number of horizontal rotations (in both clockwise and counterclockwise senses; shown in column θ in Table 1) could also be resolved under this mechanism. Existence of different senses of rotation in different parts of the area studied certainly indicates the occurrence of a local block rotation phenomenon in the past. The major folding and faulting processes undoubtedly play the main role for such complex tectonics. In addition, the acquisition of the characteristic remanent magnetization of samples should be considered to be prior to the occurrence of the horizontal rotation.

For the negative inclinations, the declinations generally should point to the south since the characteristic directions of samples were acquired during a reversed magnetic time interval. Thus, the Dec* values (Table 1), which are deduced declination by rotating the bedding strikes for each site to be parallel to the regional trend, should point to the south. From the field study and the aerial photographs of the sampling area, it is found that strike of the regional trend of the lithological bedding in the area adjacent to the sampling sites is around the direction N80°E. Also, it is thought that the regional bedding strike did not change during the gentle tilting of the structure. Then, by correcting the declinations by rotating the strikes of stratigraphic bedding to regional trend of N80°E, the paleo-declinations will point in a direction between N100°E to N120°E. This means that to acquire the coincident inclination, a 60° to 80° counterclockwise rotation (N100°E/N120°E related to N180°E) of the general structural trend of the area studied must have occurred prior to the horizontal folding process. In this case, the bedding strike of the whole area studied will be approximately perpendicular to that of the neighboring area after the structures have been rotated clockwise back to their original orientations. To know whether the area studied underwent a relatively large counterclockwise rotation, to form the orthogonal structure, requires more geological and geophysical evidences. If this is not the case, what is the significance of the consistency of the corrected paleo-declination directions?

Based on field observation and tectonic analysis (Lu *et al.*, 1994; Lee *et al.*, in preparation), the strata of the area studied were principally deformed by a major compression in the direction of N100°E to N120°E (Chu, 1990; Lu *et al.*, 1994). The direction of maximum principal axis is consistent with that of the corrected paleomagnetic declinations. Are they related to each other? Most of our samples are shaly sediments (or argillites) which have suffered regional low grade metamorphism and strong brittle to semi-brittle deformation. It is also known that fine-grained shaly argillite is relatively susceptible to re-crystallization or rearrangement of minerals during regional metamorphism. Thus, it is quite possible that the characteristic paleomagnetic directions were acquired during the major metamorphism/deformation instead of during their deposition. In other words, the NRMs of our samples might have been reset to acquire a remanent anisotropy because of strong horizontal compression. Of course, more evidence is needed to support this argument. Observations and analyses of the magnetic minerals and petrological fabrics on the thin sections should be very helpful.

If the corrected paleo-declinations actually reflect the anisotropy of remanent magnetization resulting from the strong regional tectonic deformation, what does the negative paleo-inclinations suggest? The most probable interpretation is that the characteristic directions after correction with local rotations were acquired during a reversed polarity epoch when the strong horizontal compression occurred. Accordingly, the magnetic minerals contained in our samples might have been reoriented and deformed, or some of them may even have been newly born, and all acquired the remanent magnetization during that time. If this is the case, it is believed that strong horizontal compression must have forced the direction of magnetic declinations along that of the principal compression stress axis, but not for the inclinations. If this is not the case, the inclinations would be expected to re-orient, and they might have shallower inclinations, or even show positive values. However, our observations have shown that the inclinations are negative and half of them are larger than 30° after the back-tilting correction. In addition, if the strong horizontal compression had not completely reset the primary NRM directions, the characteristic directions might still tell us that the rock formations at the studied area were deposited during a reversed magnetic epoch.

A previous paleomagnetic study in the northeastern Taiwan by Lue *et al.* (1995) did not mention the phenomenon of the remanent magnetization of rock samples. Thus, whether the remanent anisotropy of magnetization only exists in the narrow belt within the Hsuehshan Range is worthy of further investigation. If it does, the factors that would cause such a difference between the formations in different parts of the northeastern Hsuehshan Range are of interest. If it does not, searching for the other areas where rocks have acquired remanent anisotropy of magnetization will be another interesting topic for future investigation.

6. CONCLUSIONS

This is the first paleomagnetic analysis of the sub-metamorphic belt in Taiwan. Some important information about the tectonic history in the studied area could be obtained and summarized as follows.

The preliminary results pointed out that the paleo-inclinations of all the sites are negative, which may indicate that the characteristic paleomagnetic directions were acquired during a magnetic time interval of reversed polarity. However, the directions of the paleo-declination were scattered widely. After careful analysis, there seems to be a tendency for paleo-declinations point in directions of about 20°-40° clockwise to the bedding strikes. This indicates that the trend of the magnetic declinations is closely related to that of the stratigraphic bedding, which shows a great variation due to strongly horizontal folding. The characteristic remanent magnetization directions obtained, N100°E - N120°E, by rotating the strikes of bedding for each site back to the regional trend of about N80°E, are not considered as the primary component of the NRM. Instead, it probably represents the direction induced by the regional major compression in the direction of about N110°E-N120°E. This suggests that the NRMs of the samples studied have remanent anisotropy.

In addition to the remanent anisotropy recorded in the samples, a large amount of rotation, both clockwise and counterclockwise, might have occurred in association with major folding and faulting processes. The occurrence of rotations is considered as appearing later than the acquisition of the remanent anisotropy. However, the sequence for the development of the tectonic features in the area studied, including acquiring the remanent anisotropy and block rotations, needs to be further studied.

Furthermore, the mechanism for the relatively large clockwise rotation at three sites, NEC04, NEC05 and NEC06, is worth further analysis. Finally, it is important to determine whether the remanent anisotropy of magnetization exists in the areas surrounding that studied. If it does not, the factors causing such a difference are worthy of further investigation.

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