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Rotations in the northeastern collision belt of Taiwan: preliminary results from paleomagnetism

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ABSTRACT

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We present the results of determinations of the ellipsoids of magnetic susceptibility anisotropy and of the paleomagnetic directions for 17 sedimentary rock sites of the northeastern collision belt of Taiwan.

The results of magnetic fabric determinations indicate that magnetic lineations have developed in most sites. Two major groups of lineations have been reconstructed: the trends are distributed around the NNE–SSW direction for the first one and around the ENE–WSW direction for the second one. Comparing these directions with the results of tectonic analysis of fault-slip data in the same area (Angelier et al., 1990), the first group of magnetic lineation is found to be perpendicular to the maximum compression axis σ_1 of the compressional event number 3 (direction 113). This direction of major compression corresponds to the present-day convergent direction of the Philippine Sea plate relative to the Eurasian plate. The second group of magnetic lineations is perpendicular to another axis σ_1 of a major compressional event number 4 (direction 150). Because no relationship between magnetic lineations and paleocurrent distributions has been found, we consider that the magnetic fabric in our samples principally results from the influence of tectonic paleostress.

Our paleomagnetic results indicated reversed polarities in sampling sites. The declinations range from 190° to 220°, indicating that a clockwise rotation of at least 15° had occurred in the northeastern part of Taiwan. This supports previous results principally based on microtectonic analyses that led Angelier et al. (1986, 1990) to propose that a clockwise rotation of approximately 20° had occurred in the northern Taiwan belt. This clockwise rotation is probably related to the N–S opening of the Okinawa Trough as well as to the SE–NW compression induced by the collision between the northwestern tip of the Philippine Sea plate and the Eurasian plate in northern Taiwan.

Introduction

Taiwan is located at the boundary between the Philippine Sea plate and the Eurasian plate. These two plates have been in collision with each other here in Taiwan since the late Miocene–early Pliocene. The Taiwan collision segment of the convergent boundary connects the south-verging Ryukyu arc and trench system and the west-verging Luzon arc and Manila subduction zones (Fig. 1). In order to interpret the collision process and the fold-and-thrust structures related to this collision, several studies have been carried out (Ho, 1976, 1979, 1982, 1986a, 1986b; Suppe, 1980, 1981; Barrier, 1985; Barrier and Angelier, 1986); Angelier et al., 1986, 1990; Lee, 1989). In particular several studies focussed on the Coastal Range of eastern Taiwan, where the major convergent boundary is located and active and where a widespread diachronic clockwise rotation has been described from paleomagnetic data (Lee, 1989; Lee et al., 1990; 1991).

The area studied in the present paper, northern Taiwan, is the northernmost segment of the collision belt which is characterized by a spectacular bend convex to the northwest, so that all major structural trends rotate clockwise about 55° between 24°N and 25°N (Fig. 1). In this area, a subduction zone has been delimited where the Philippine Sea plate is going down underneath the

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Eurasian plate produced by the collision (Tsai et al., 1977). We aim at constraining the kinematic and geodynamic reconstructions by using paleomagnetic data to calculate the rotation that affected this bent belt of northern Taiwan.

For investigating the major mechanisms, Angelier et al. (1986), based on a microtectonic analysis of fault-slip data collected directly from the field in the Foothills of western Taiwan, drew the extrapolated trajectories of the maximum compressional stress σ_1 in Taiwan and reconstructed two main compressional events (the younger one with an azimuth 300° of compression and the older one with an azimuth 335°). These major compressional events have had a major effect in the development of the present-day structures of the fold-and-thrust belt. Angelier et al. (1986) thus proposed that a counterclockwise change of about 35° in the dominating compressional trends might have occurred. In addition, they mentioned that a clockwise rotation of about 20° might have affected northern and northeastern Taiwan. No paleomagnetic control was available but they based this theory on a reconstruction of the stress trajectories with respect to the recent direction of plate convergence. Recently, Angelier et al. (1990) analyzed the fault-slip data in the Hsuehshan Range in more detail and proposed five stages for interpreting the tectonic evolution of northern Taiwan from the late Miocene to the present.

Since Graham (1966) indicated that a magnetic fabric can result from the progressive deformation of grains under compression, the anisotropy of magnetic susceptibility (AMS) has been used as a strain indicator in many areas. Most of these studies were focussed in metamorphic belts (Hrouda and Janak, 1976; Hrouda et al., 1978), but some of them were made on the sediments (Kligfield et al., 1977, 1982; Kissel et al., 1986; Lee, 1989; Lee et al., 1990). They all indicated that a relationship did exist between the AMS of rock samples and the regional compressional stress. In particular the works of Lee et al. (1990) in the Coastal Range of Taiwan have indicated a clockwise rotation phenomenon by comparing the results of AMS analysis with those of microtectonic analysis. Thus, from that point of view, the AMS analysis would help us to study the compressional

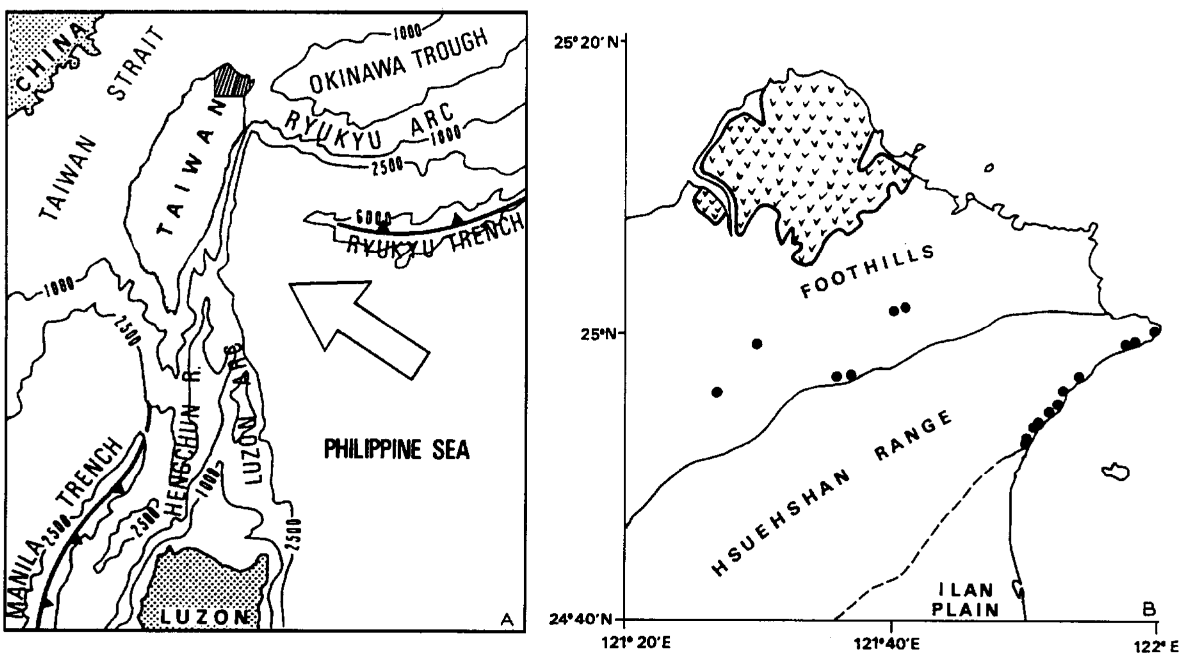

Fig. 1. (A) General map of Taiwan: isobath in meters, large open arrow showing the convergent direction of the Philippine Sea plate relative to the Eurasian plate, hatch area pattern showing the studied area. (B) Main tectonic units of northeastern Taiwan and the localities of sampling sites (black dots). Tatun Volcano Group marked as "v" pattern and the boundary between Foothills and Hsuehshan Range is the Chuchih Fault.

mechanisms by supporting the results obtained independently from quantitative tectonic analysis; in particular, this analysis may help us to recognize the most important events in the studied area, the northeastern collision belt of Taiwan.

Paleomagnetic study is a powerful tool for investigating tectonic features, especially for reconstructing the evolution of plate tectonics. Although the structures of northern Taiwan are complex and the geological formations in the Hsuehshan Range have been metamorphosed below the condition of prehnite–pumpellyite facies metamorphism in the studied area (Chen et al., 1983), we hoped that through this preliminary study of AMS and paleomagnetic directions in rock samples, more information could be provided in order to reconstruct more accurately the tectonic evolution of the collision belt of northern Taiwan. In summary, the two major problems that we addressed were (1) the relationship between AMS and the tectonic mechanisms, and (2) the magnitude of a rotation in the twisted segment of the fold-and-thrust belt.

Geological setting

The major stratigraphic units of the studied area include the Hsuehshan Range and the Foothills of Taiwan (e.g., Ho, 1976). The Hsuehshan Range is one of the major tectonic units of the Central Range in the late Cenozoic orogen of Taiwan. In the studied area, it surrounds the Ilan Plain which is the landward extension of the Okinawa Trough adjacent to the Ryukyu arc-trench system (Fig. 1). Stratigraphically, the Hsuehshan Range is mainly composed of Tertiary slate formations. Most of this belt is made up of a monotonous succession of argillite, slate, phyllite and sandstone where well layered shaly rocks are dominant. Fossil analysis indicated that the age of this unit ranges from Eocene to early Middle Miocene (Ho, 1982).

The Foothills is a non-metamorphic fold-and-thrust belt which is located to the west of the Hsuehshan Range slate belt. These two tectonic units are separated by a major thrust fault, the Chuchih Fault (Fig. 1) which steeply dips to the east at the surface (Biq, 1971) but may have shallower dips at depth so that the Foothills may extend far to the east underneath the upthrust slate belt. Lithologically, the formations of the Foothills are principally constituted of non-metamorphic sandstones and shales; according to paleontological analyses they belong to the late Cenozoic.

In addition, to the west and north of the Foothills, late Pliocene to Pleistocene volcanic groups include the Tatun Volcano Group, the Keelung Volcano and some less important outcrops. Volcanic rocks are andesitic. A previous paleomagnetic study (Lee et al., 1985) indicated that after the eruptions of these volcanoes, that is during the late Pleistocene and the Holocene, no rotation and drifting phenomenon has occurred in northern Taiwan.

Sampling and laboratory analysis

Rock samples were collected from outcrops of fine grained shale, mudstone and sandstone by using an electric powered core drill. The corer is a 25 mm barrel with a sintered diamond cutting head cooled by water. Under the standard paleomagnetic sampling techniques, over 250 orientated cores from 17 sites of the Hseuhshan Range and Foothills were sampled. The site localities are shown in Fig. 1. Each core was cut into several specimens of 22 mm in length. For each site, at least one specimen was chosen to study the magnetic mineralogy.

The bulk and anisotropy of magnetic susceptibility (AMS) of samples were measured on the low-field Molspin Minicep System. Then, three principal axes of the ellipsoid of AMS (K_{max}, K_{int}, K_{min}) were calculated both before and after bedding corrections. Analyzing the characteristics of magnetic fabric, three major anisotropy parameters were first calculated (L—magnetic lineation defined as K_{max}/K_{int}; F—magnetic foliation defined as K_{int}/K_{min} and DA—degree of anisotropy defined as K_{max}/K_{min}). Then, L vs. F plots were employed to study the distribution of the average grain shapes for sampling sites. The directions of the three principal axes of AMS were projected on stereograms to study the origin of the magnetic fabric acquired by samples with the former L–F plots. Finally, the directions of magnetic lineations were compared to the paleostress pattern obtained independently from microtectonic fault slip data analysis, in order to find the relationship between the magnetic fabric and the tectonic mechanisms in the same sites of the studied area.

Studying paleomagnetic directions, samples were treated by progressive stepwise thermal demagnetizations. Remanent magnetizations were measured on the SQUID cryogenic magnetometer. Stereographic projection and the orthogonal component plots were used to test the stability and to determine the stable component of natural remanent magnetizations (NRM). Then, using Fisher statistics (Fisher, 1953), mean directions were computed in each site. It is important to observe that sampling for paleomagnetic analyses (AMS and directions) and fault slip data directions were carried out simultaneously in the same sites, thus allowing direct comparisons of results.

Magnetic mineralogy

It is very important to test the stability and the precocity of the NRM acquired by rock samples. Studying the magnetic mineralogy of rock samples to classify the contained magnetic mineral is consequently essential.

Since Dunlop (1972) indicated that the acquisition curves of the isothermal remanent magnetization (IRM) could provide the information to identify the major magnetic mineral contained by rock samples, several studies have been developed (Lowrie and Heller, 1982; Kissel et al., 1985, 1986; Lee et al., 1986, 1988, 1990). They pointed out

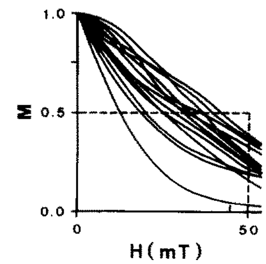

Fig. 3. The typical AF demagnetization curves of SIRM showing that the MDF of samples are less than 50 mT.

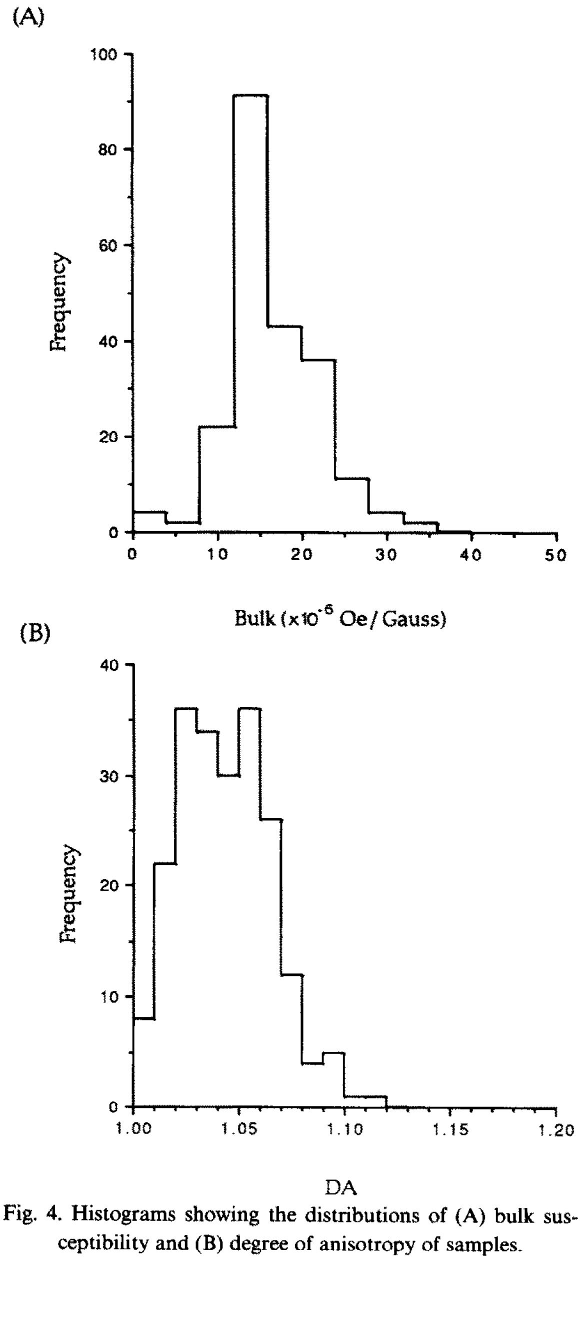

Fig. 4. Histograms showing the distributions of (A) bulk susceptibility and (B) degree of anisotropy of samples.

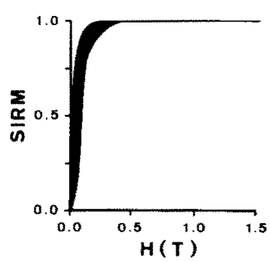

Fig. 2. The typical acquisition curves of IRM of samples showing that samples acquired the saturation IRM under an applied field of less than 0.3 Tesla.

that the IRM acquired by magnetite is saturated with an applied magnetic field less than 0.5 T; however, this limit is much higher (about 2.5 T to 5 T) for minerals such as hematite and goethite. The results of this study in the case of northern Taiwan, indicate that most of the samples have acquired the saturation IRM at an applied magnetic field less than 0.3 T (Fig. 2). This suggests that magnetite is the most important magnetic mineral contained in our samples.

Some other studies have mentioned that the median destructive field (MDF) of the saturation IRM can be also used to do such investigations (Ozdemir and Banerjee, 1982; Kissel et al., 1985,

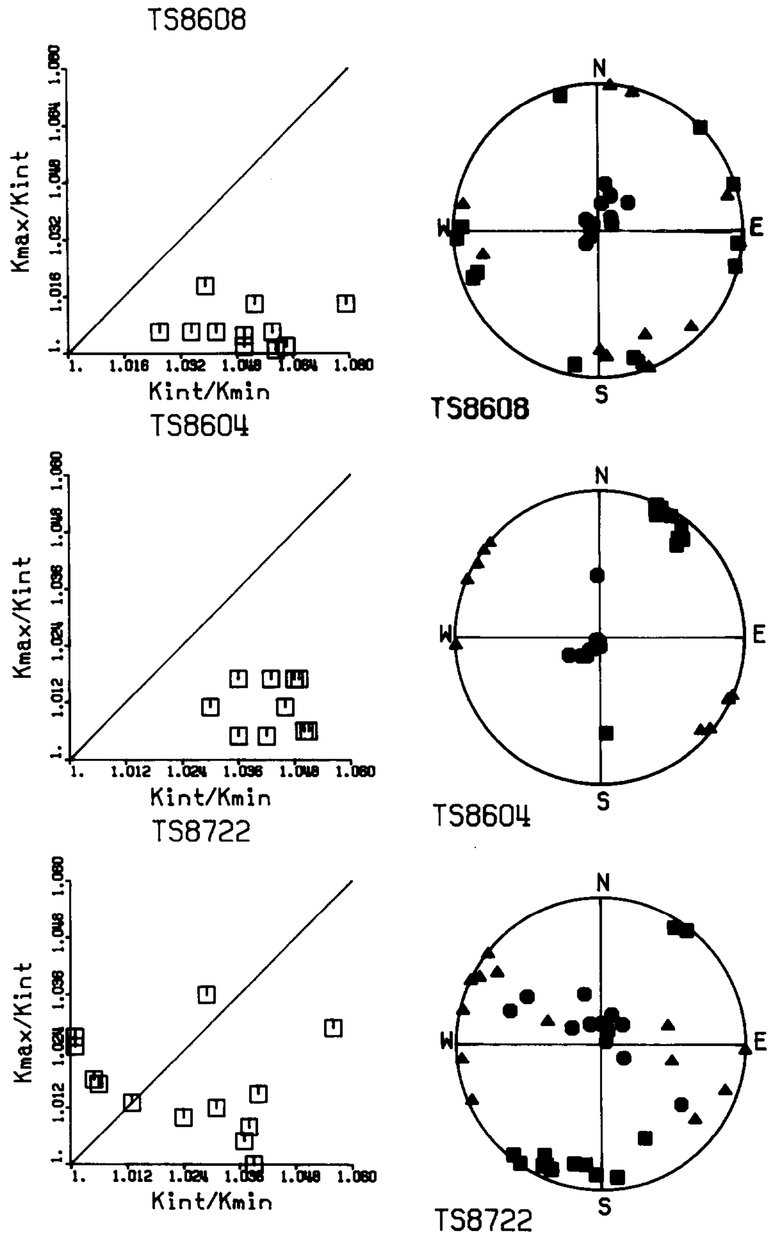

Fig. 5. Three different types of magnetic fabric: Type (A) of sedimentary origin; Type (B) of sedimentary origin but having been under tectonic influence; Type (C) of tectonic origin. Left-hand side showing the K_{max}/K_{int} vs. K_{int}/K_{min} plots and the right-hand side showing the typical stereographic projection diagrams of the three principal axes of AMS (black squares = K_{max}; black triangles = K_{int}; black circles = K_{min}).

1986; Lee et al., 1986, 1988, 1990). Thus, those samples which have obtained the SIRM were subjected to progressive stepwise AF demagnetizations to investigate their MDFs. The results are shown in Fig. 3. It can be found that the MDF of samples' SIRM are all less than 50 mT. This confirmed the preceding proposition that the major magnetic mineral contained in our samples is magnetite.

Anisotropy of magnetic susceptibility

The bulk susceptibilities of samples are distributed from $4-40 \times 10^{-6}$ centered around 16×10^{-6} (Fig. 4A) which are a little lower than that of the common sedimentary rocks. The degree of anisotropy ranges from 1.00 to 1.12 (Fig. 4B) which might indicate that some factors have affected the magnetic fabric of samples during or after the sedimentation. To study this, directional plots of the AMS ellipsoid and the ratio of the three principal magnitudes are analyzed for each site.

Figure 5 illustrates three different types of magnetic fabric that we have identified. The left-hand side of the figure presents the L vs. F plots and the right-hand side presents the directional distribution of three principle axes of the AMS. Type (A) shows that the K_{min} axes are well grouped around the normal direction of the depositional bedding plane and the two other axes are scattered in the bedding plane. The ratios of the magnitude of these three principal axes indicated that the average grain shape in samples is oblate. Six sites have this type of magnetic fabric, which reveals that the origin of their AMS probably results mostly from the post-depositional compaction. Type (B) shows that the three principal axes are clustered equally well. The magnitude ellipsoids of the samples show that the grain shape is also oblate. However, in some sites, we could find evidence for prolate grain shape. These results indicated that apart from the compaction, the magnetic fabric might have been affected by either regional or local compressional stress, or by a paleocurrent during or after the solidification of the sediments. Eight sites displayed such a magnetic fabric. Type (C) shows that the K_{max} axes are well-grouped within the bedding plane, but the other two axes are scattered to form a girdle normal to the K_{max} axes. Undoubtedly, this type of fabric developed under the tectonic inflence. So, the existence of type (C) fabric strongly suggests that the origin of type (B) is probably due to the influence of paleostress rather than to paleo-

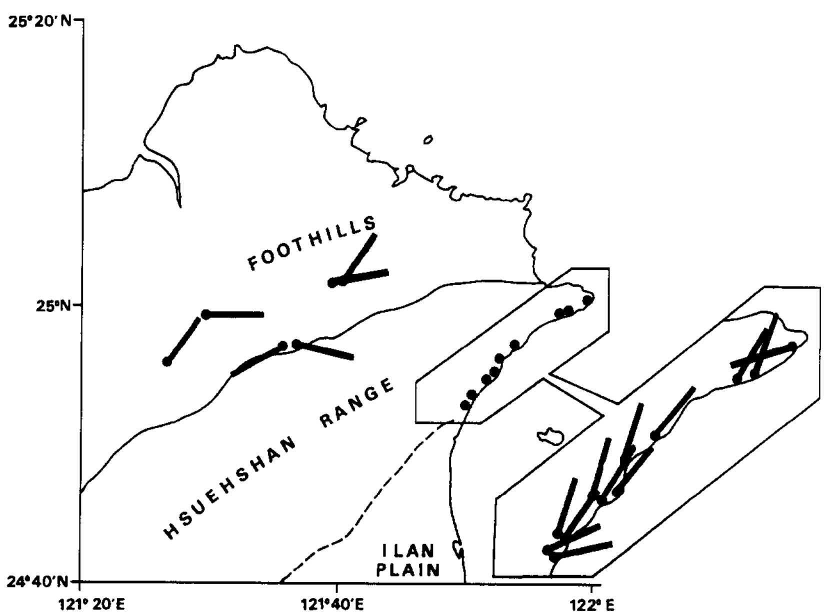

Fig. 6. Distribution of mean site directions of magnetic lineation.

current. Three sites displayed a magnetic fabric of type (C).

Magnetic lineations were found in those sites having magnetic fabric of types (B) and (C). Figure 6 shows the magnetic lineation distribution in these sites. Two different groups can be identified: one is distributed from N15°E–S15°W to N35°E–S35°W, and centered around N25°E–S25°W; another is distributed from N53°E–S53°W to N72°E–S72°W, and centered around N63°E–S63°W. To investigate the relationship between magnetic lineation and the compressional paleostress, directions of the magnetic lineations were compared to the directions obtained inde-

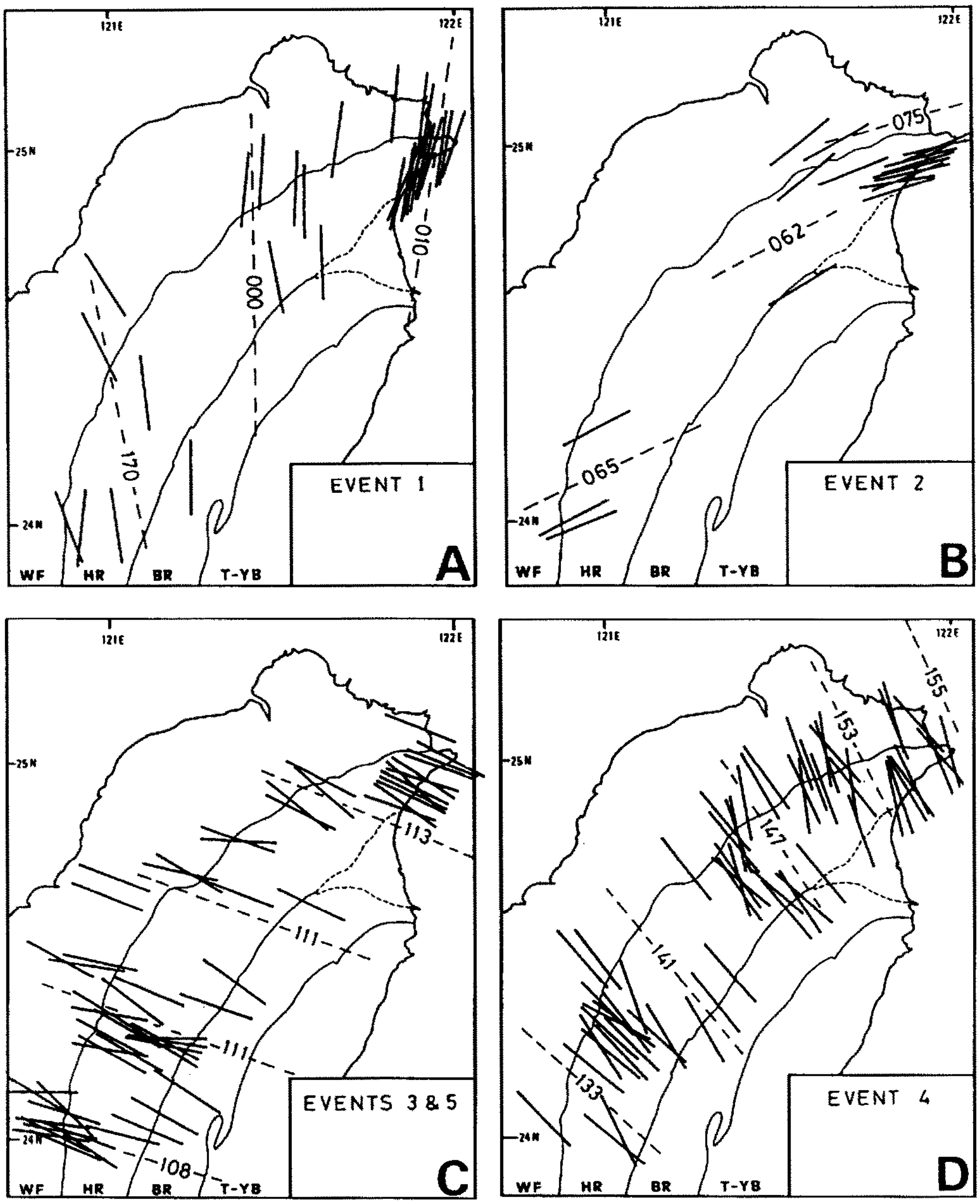

Fig. 7. Directions of compression identified in northern Taiwan by Angelier et al. (1990). (A) Event 1, N–S compression; (B) event 2, WSW–ENE compression; (C) events 3 and 5, WNW–ESE compression and (D) event 4, NW–SE compression. Events 3 and 5 in (C) could be distinguished in some sites by tectonic chronology criteria and respectively predate and postdate event 4 in (D). They are shown in a single map (c) because in some sites they cannot be identified due to the similarity of compressional trends within the range of uncertainties. *WF* = western Foothills; *HR* = Hsuehshan Range; *BR* = Backbone Range; *T–YB* = Tailuko–Yuli belt.

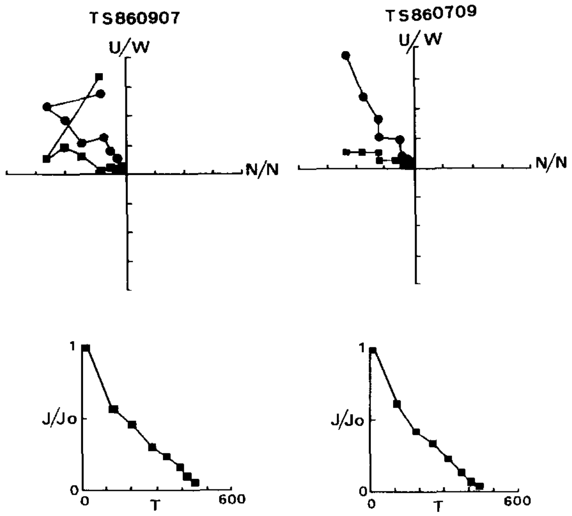

Fig. 8. The typical Zijderveld diagrams (black square = $N-E$ component; dots = N–D component) and the associated normalized intensity curves.

pendently from analyzing the microtectonic features in the field (Fig. 7). It can be shown that the K_{max} axes of the first group are almost perpendicular to the major maximum compression axes, σ_1 of event 3 and 5 of Angelier et al. (1990) and those of the last group are normal to that of event 4. This evidence supports our previous proposition that the magnetic fabric of type (B) and (C) has been influenced by the paleostress in the studied area. Furthermore, this result suggests that at least two events of tectonic paleostress played a major role in the studied region.

Paleomagnetism

Paleomagnetic results indicated that the intensities of the NRM of samples were generally very weak. This is consistent with the low susceptibility, which points out that the amount of magnetic minerals contained in our samples is probably very limited. By analyzing the orthogonal component plots, it can be found that a lot of samples show that their NRM directions varied quickly and unstably during thermal demagnetizations. These samples have been rejected for further analysis.

Finally, for a total of 35 samples from seven sites the stable component of NRM could be traced out from several final demagnetization steps. Two typical Zijderveld diagrams (Zijderveld, 1967) and the associated normalized intensity curves of the samples are presented in Fig. 8.

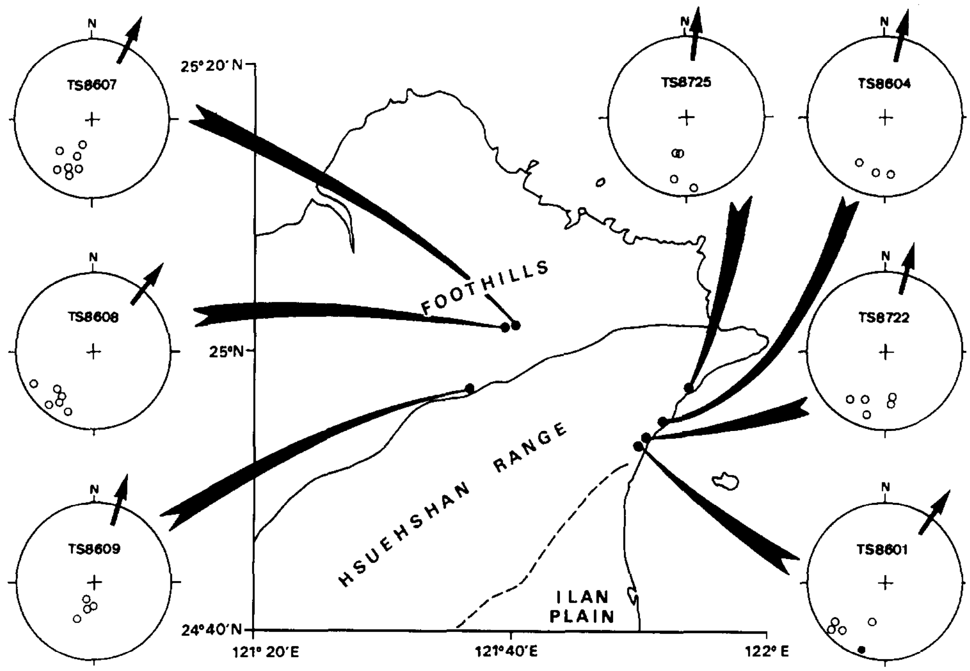

Fig. 9. The equal area projections of stable component paleomagnetic directions. Open symbols = inclination upward, closed symbols = inclination downward; arrows = the correspondent normal polarity site mean declination.

TABLE 1

Fisher statistical results of the paleomagnetism showing the site mean directions, the associated statistical parameters and virtual geomagnetic pole positions *

Site	N	Site mean directions		α_{95}	k	VGP	
		dec.	inc.			plat.	plon.
TS8601	5	217.0	−12.2	21.3	13.9	−50.4	290.3
TS8604	3	192.0	−19.6	28.4	19.9	−72.2	317.9
TS8607	7	208.7	−29.8	13.0	22.4	−62.0	280.7
TS8608	6	219.6	−13.7	12.0	32.0	−48.5	287.3
TS8609	4	196.5	−53.0	18.3	26.2	−72.5	232.0
TS8722	5	193.6	−22.3	20.4	15.0	−72.3	310.8
TS8725	4	187.2	−25.4	23.4	10.3	−77.6	325.4
MEAN	7	202.6	−25.5	13.8	23.5	−65.8	294.4

* dec = declination, inc. = inclination; α_{95} = 95% confidence interval; k = precision parameter; VGP = virtual geomagnetic pole positions; plat. = paleolatitude, plon. = paleolongitude.

The stable component directions of these samples were projected on the stereo-net and are shown in Fig. 9. The mean directions of these sites after bedding correction and the associated Fisher statistical parameters (Fisher, 1953) are shown in Table 1. From this table, It can be seen that the 95% confidence intervals are generally rather large. This certainly reflects the fact that the paleomagnetic directions of these sites are somewhat dispersed, but it is principally due to the limited numbers of samples in the sites, which are insufficient for the full application of the Fisher statistics.

Although the paleomagnetic results are not really satisfactory in terms of statistics in most sites that were sampled, they are consistent from one site to another and still provide valuable information for studying the tectonics in this region. The magnetic polarities of these sites are all reversed. The inclinations are distributed between −12° and −30° except at site TS8609, and the declinations are distributed from about 187° to 220°. To investigate the tectonic movement at the study area, the reversed paleomagnetic directions of our samples were flipped to the corresponding normal polarity directions and we find that the declinations of our samples have deflected about 7°–40° toward east (Fig. 9, the arrows) and inclinations are distributed between 12° and 30°. In addition, we also need to have the stable directions of this area.

The study area is located at the southeastern margin of the Eurasian plate and the sampling sites are of Paleogene age. Because there have been reports about paleomagnetic directions of this age in Taiwan, the stable directions were selected using data from the neighboring south China area. We used the events 269–270 in the Ottawa-based listings of the Geomagnetic Service of Canada, collected in Piper (1988), which indicated that the samples were collected and analyzed from the Hubei and Hunan provinces of China, the paleomagnetic directions were reported to be 357.9°/47.9° and 345°/40° respectively. In addition, the calculated axial geomagnetic dipole field direction at the studied region is about 357.3°/43.3° at the present day. If we take the mean of these directions (352° for declination and 43° for inclination), it appears that the studied area might have rotated 15°–45° clockwise and flattened 10°–20° after the sedimentation of the rock formations under investigation. Because paleomagnetic directions are usually reported to indicate the inclination errors for the sedimentary rock samples, further work needs to be done to determine unether the 10°–20° flattening found in our samples reflects a northward drift in the northeastern collision belt of Taiwan.

Discussions

Based on a microtectonic analysis of fault slip data from the Foothills of western Taiwan, Angelier et al. (1986), drew the extrapolated trajectories of the maximum compressional stress σ_1 in Taiwan and reconstructed two main compressional events (the younger one in the direction of 300° and the older one in the direction of 335°) which have contributed to the present-day structures of the fold-thrust belt. Therefore, they proposed that a counterclockwise rotation of compressional paleostress might have occurred in western Taiwan during the past. Furthermore, from reconstructing the stress trajectories with respect to the recent direction of plate convergence, they mentioned that a clockwise rotation of about 20° might have occurred in northern and northeastern Taiwan. Recently, Angelier et al. (1990) analyzed the brittle microtectonics in the Hsuehshan Range in more detail. They distinguished five different compressional events with different paleostress orientations and then proposed a model of five stages to interpret the tectonic evolution of northern Taiwan.

The magnetic fabric analysis carried out in the present study indicated that the AMS of samples has been under the same influence which caused the reorientation and/or deformation to form the magnetic lineation in the sediments. Two events of lineations with different trends have been investigated in this way: one lineation is normal to the paleostress direction N113°E, which represents approximately the present-day convergent direction of the Philippine Sea plate relative to the Eurasian plate; the other lineation is normal to that of the compression in the direction N150°E, which apparently corresponds to an earlier stage of plate convergence. These results support the observations of Angelier et al. (1986, 1990) on microtectonics and confirm that rotation of the paleostress field or rotation of structures should have occurred in northeastern Taiwan.

However, from analyses of the paleomagnetic directions, only a clockwise rotation of at least 15° has been observed in the study area. Besides, the general trend of the major structures in western Taiwan is about NNE–SSW, although the northeast Taiwan belt trends N70°E, which represents an apparent torsion of about 55°. From the structural point of view, this change in trend certainly suggests that a clockwise rotation phenomenon has occurred in northeastern Taiwan, although a significant amount may be due to the existence of an inherited structural bend of the collision belt. All these results improve the proposition of a 20° clockwise rotation. However, it is possible that a counterclockwise rotation occurred in the fold-thrust belt of the western Foothills. Because the spatial distribution of our sampling sites is clustered in the northeastern part, we could not investigate this phenomenon from this preliminary paleomagnetic study.

What is the driving mechanism of the clockwise rotation in northeastern Taiwan? From the geotectonic point of view, the Ryukyu arc probably extends to the Ilan Plain in northeastern Taiwan, i.e. in the area studied. Toward the northeast of this area, the extensional Okinawa Trough is present. We know that the Okinawa Trough has begun to open from at least 2 Ma (Letouzey and Kimura, 1986). The opening direction is generally NW–SE, but the movement towards the southeast was larger than that towards the northwest. The southeast opening direction is probably an important factor for the clockwise rotation of the studied area. Besides, from analyzing the Tertiary rock formations, Sasajima (1977) indicated a clockwise rotation (about 40°) in the southwestern part of the Ryukyu arc, and he correlated this rotation to the development of the west Philippine basin. This might have also contributed to the clockwise rotation of northeastern Taiwan. Thus, we think the clockwise rotation shown in the present study is probably due to the combined effects of opening the Okinawa Trough and of collision at the northwestern tip of the Philippine Sea plate in northern Taiwan. However, further studies are still needed and should be conducted in the whole northern part of Taiwan.

In addition, we know that the study area of northeastern Taiwan, is characterized by a spectacular bend, convex to the northwest, so that all major structural trends turn clockwise by about 55° between 24°N and 25°N. However, from this preliminary paleomagnetic study, only a dispersive clockwise rotation (from 15° to 45°) is observed, i.e. on average, only about 30° of the regional clockwise rotation is identified. It is much less than that proposed from the difference in major structural trends. So further investigations need to be made to determine whether there are some other factors that affected the rotation phenomenon besides the bend of northeastern Taiwan and the paleomagnetism. Moreover, for detailed studies of the tectonic evolution in northeastern Taiwan, the timing of the events is undoubtedly the most important factor. Unfortunately, this preliminary study could not provide any information about it because most of the compressional deformation is late Cenozoic and especially Plio-Quaternary in age, whereas most rock formations that could be successfully sampled and analyzed for paleomagnetism were Paleogene in age. So, for further paleomagnetic studies, sequential magnetostratigraphic and/or biostratigraphic studies are needed. Of course, the study of a broader area (i.e. the whole of northern Taiwan including all the different tectonic units of the collision belt) is also needed, especially for the purpose of investigating in more detail the rotations identified from the paleomagnetic analysis.

Conclusions

From this preliminary study, several important results have emerged:

(1) Results of AMS have shown three different types of magnetic ellipsoids acquired by our samples: the first one is of sedimentary-diagenetic origin with K_{min} axes well grouped to be normal to the bedding plane and the other two axes dispersed in the bedding plane; the second one is also of sedimentary-diagenetic origin but in addition has been significantly influenced by tectonic paleostress so that the three principal axes of AMS are well-grouped individually instead of the single axes K_{min} as in the previous case; the last one is of tectonic origin with K_{max} axes well-grouped but the other two axes scattered to form a girdle perpendicular to it. The comparison between these results and the distributions of tectonic σ_1 axes independently reconstructed by means of fault-slip data analysis (Angelier et al., 1990) reveals good consistency.

(2) The magnetic fabric analysis indicated that the magnetic lineation resulted from the tectonic influence which implies that, within the framework of a more extensive regional analysis, a paleomagnetic method such as the strain indicators in northern Taiwan can be used.

(3) Magnetic lineations show that two different events of paleostress have played a major role. One is almost the same as the present-day convergent direction of the Philippine Sea plate relative to the Eurasian plate, another is normal to the major structural trend in northeastern Taiwan. Incidentally, these two events are consistent with the counterclockwise change in σ_1 trends. This change occurred during the Plio-Quaternary and was related to a similar change in the direction of plate convergence according to Angelier et al. (1986 and 1990).

(4) Paleomagnetic results show that a clockwise rotation of at least 15° has occurred in northeastern Taiwan. The clockwise rotation is probably due to the combined effects of the opening of Okinawa Trough and of the collision of the northwestern tip of the Philippine Sea plate in northeastern Taiwan. The existence of this rotation was previously suspected for tectonic reasons (Angelier et al., 1986) but could not be firmly established in the absence of paleomagnetic data.

(5) Among the magnetic minerals of our samples, magnetite is predominent. However, the amount contained in our samples is probably very small because very low intensities of NRM were observed. This low NRM level in sedimentary rock formations of northern Taiwan makes all paleomagnetic studies in this area difficult.

Although the above investigations have yielded some results, further studies are still needed and should be conducted in the whole northern part of Taiwan. In addition, sequential magnetostratigraphic studies and/or biostratigraphical analyses are needed to provide the time base for studying the tectonic evolution in northern Taiwan.

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References

Angelier, J., Barrier, E. and Chu, H.T., 1986. Paleostress trajectories related to plate collision in the foothills fold-thrust belt of Taiwan. Mem. Geol. Soc. China, 7: 201–217.

Angelier, J., Bergerat, F., Chu, H.T. and Lee, T.Q., 1990. Tectonic analysis and the evolution of a curved collision belt: the Hsuehshan Range, northern Taiwan. Tectonophysics, 183 (1–4): 77–96.

Barrier, E., 1985. Tectonique d'une chaine de collision active: Taiwan. Thèse Sci., Mém. Sci. Terre, Univ. Pierre et Marie Curie, Paris, 492 pp.

Barrier, E. and Angelier, J., 1986. Active collision in eastern Taiwan: the Coastal Range. Tectonophysics, 125: 39–72.

Biq, C.C., 1971. Some aspects of post-orogenic block tectonics in Taiwan: recent crustal movements. R. Soc. N. Z. Bull., 9: 19–24.

Chen, C.H., Chu, H.T., Liou, J.G. and Ernst, W.G., 1983. Metamorphic facies map (scale 1: 500,000) of Taiwan and explanatory note. Spec. Publ. Cent. Geol. Surv., M.O.E.A., Taipei.

Dunlop, D.J., 1972. Magnetic mineralogy of unheated and heated red sediments by coercivity spectrum analysis. Geophys. J. R. Astron. Soc., 27: 37–55.

Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc. London, 217: 295–305.

Graham, J.W., 1966. Significance of magnetic anisotropy in Appalachian rocks. In: J.S. Steinhart and T.J. Smith (Editors), The Earth beneath the Continents. Geophys. Monogr., Am. Geophys. Union, 10: 627–648.

Ho, C.S., 1976. Foothills tectonics of Taiwan. Bull. Geol. Surv. Taiwan, 25: 9–28.

Ho, C.S., 1979. Geologic and tectonic framework of Taiwan. Mem. Geol. Soc. China, 3: 57–72.

Ho, C.S., 1982. Tectonic evolution of Taiwan. Explanatory text of the tectonic map of Taiwan. M.O.E.A., Taipei, 126 pp.

Ho, C.S., 1986a. Geological map of Taiwan. Explanatory text of the geological map of Taiwan. M.O.E.A., Taipei, 225 pp.

Ho, C.S., 1986b. A synthesis of the geologic evolution of Taiwan. Tectonophysics, 125: 1–16.

Hrouda, F. and Janak, F., 1976. The changes in shape of the magnetic suscep- tibility ellipsoid during progressive metamorphism and deformation. Tectonophysics, 34: 135–148.

Hrouda, F., Janak, F. and Rejl, L., 1978. Magnetic anisotropy and ductile deformation of rocks in zones of progressive regional metamorphism. Geol. Beitr. Geophys., 87: 126–134.

Kligfield, R., Lowrie, W. and Dalziel, I.W.D., 1977. Magnetic susceptibility as a strain indicator in the Sudbury basin, Ontario. Tectonophysics, 40: 287–308.

Kligfield, R., Owens, W.H. and Lowrie, W., 1982. Magnetic susceptibility anisotropy, strain and progressive deformation in Permian sediments from the Maritime Alps (France). Earth Planet. Sci. Lett., 55: 181–189.

Kissel, C., Laj, C. and Muller, C., 1985. Tertiary geodynamical evolution of Northwestern Greece: paleomagnetic results. Earth Planet. Sci. Lett., 72, 190–204.

Kissel, C., Barrier, E., Laj, C. and Lee, T.Q., 1986. Magnetic fabric in "undeformed" marine clays from compressional zones. Tectonics, 5: 769–781.

Lee, T.Q., 1989. Evolution tectonique et géodynamique néogène et quaternaire de la chaîne côtière de Taiwan: apport du paléomagnétisme. Thèse Doct., Univ. Paris VI, Paris, 500 pp.

Lee, T.Q., Tsai, P.F. and Tsai Y.B., 1985. Paleomagnetic study of the Tatun Volcano Group. Bull. Inst. Earth Sci., Acad. Sin., 5: 137–172.

Lee, T.Q., Kissel, C., Horng, C.S., Lue, Y.T. and Laj, C., 1986. Paleomagnetic study of the sedimentary rocks along the Hsiukuluan river, eastern Taiwan. Bull. Inst. Earth Sci., Acad. Sin., 6: 169–184.

Lee, T.Q., Chi, W.R., Kissel, C. and Barrier, E., 1988. Magnetic polarity zonation of two sedimentary rock sequences in the middle and southern parts of eastern Coastal range, Taiwan. Acta Geol. Taiwanica, 26: 179–192.

Lee, T.Q., Kissel, C., Laj, C., Horng, C.S. and Lue, Y.T., 1990. Magnetic fabric analysis of the Plio-Pleistocene sedimentary formations of the Coastal Range of Taiwan. Earth Planet. Sci. Lett., 98 (1) 23–32.

Lee, T.Q., Kissel, C., Barrier, E., Laj, C. and Chi, W.R., 1991. Paleomagnetic evidence for a diachronic clockwise rotation of the Coastal Range, eastern Taiwan. Earth Planet. Sci. Lett., in press.

Letouzey, J. and Kimura, M., 1986. The Okinawa Trough: genesis of a back-arc basin developing along a continental margin, Tectonophysics, 125: 209–230.

Lowrie W. and Heller, F., 1982. Magnetic properties of Marine limestone. Rev. Geophys Space Phys., 20: 171–192.

Ozdemir, O. and Banerjee, S.K., 1982. A preliminary magnetic study of soil samples from west-central Minnesota. Earth Planet. Sci. Lett., 59: 393–403.

Piper, J.D.A., 1988. Paleomagnetic database. Open Univ. Press, Milton Keynes, 264 pp.

Sasajima, S., 1977. Tertiary paleomagnetism of the Ryukyu islands and its relevance to the developments of the Philippine basin. Rock Magn. Paleo- geophys., 4: 108–113.

Suppe, J., 1980. A retrodeformable section of northern Taiwan. Proc. Geol. Soc. China, 23: 46–55.

Suppe, J., 1981. Mechanics of mountain building and metamorphism in Taiwan. Mem. Geol. Soc. China, 4: 67–89.

Tsai, Y.B., Teng, T.L., Chiu, J.M. and Liu, H.L., 1977. Tectonic implications of recent seismicity in the Taiwan region. Mem. Geol. Soc. China, 2: 13–41.

Zijderveld, J.D.A., 1967. AF demagnetization of rocks: analysis of results. In D.W. Collinson, R.M. Creer and S.K. Runcorn (Editors), Methods in Paleomagnetism. Elsevier, Amsterdam, pp. 254–286.