Doctoral Thesis

Paleomagnetism of the Huanan and Yangtze Blocks, se China

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Publication Date:
1991

Permanent Link:
https://doi.org/10.3929/ethz-a-000604472

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PALEOMAGNETISM OF THE HUANAN AND YANGTZE BLOCKS, SE CHINA

A Dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY
for the degree of Doctor of Natural Science

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Zürich, 1991
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I would first like to thank my advisor, Prof. Dr. Ken Hsü for giving me the opportunity to come to Zürich. His support during the last four years was instrumental in the completion of this project. Prof. Dr. William Lowrie accepted me into the paleomagnetic group and my discussions with him about various topics related to this thesis greatly improved my understanding of paleomagnetism. I am especially grateful to Prof. Dr. Friedrich Heller. His insight into the problems of this project were of great benefit to me and it was a pleasure working closely with him during my time here.

I would also like to thank the other members of the magnetics group: Dr. Ann Hirt, Dr. Ellen Platzman, Dr. Andreas Gehring, Dr. Maja Haag, and (soon-to-be Dr.) Peter Keller for their helpful and friendly discussions. I am grateful to Wolfgang Gruber for his help in the lab and for letting me occasionally beat him at tennis. Thanks to my friends in the Geology Institute and elsewhere: Benoit, Djordje, Gilles, Stefano, Tracey, Ko, Alex, Guy, The Dead Ants (Dani, Dave, André, Philip, Pietsch), Peter, The Institute for the Advanced Study of Deviant Behaviour -H49- (Ulrich, Hans, Thomas, & Teresa), Cinzia, Jamie, Dave, The Unbelievaalbe, and the Beisbol Club for making it a fun four years. Thanks go to Daniel "Ray Banana" Ariztegui for allowing me to be seen with him. Many thanks for the uniforms to Debbie and Cathay Pacific - "The only airline with regular flights to Mars".

Acknowledgement is also owed to the many people who assisted me during my field work in China. Dr. Lin Jin-lu and Dr. Shui Tao organized the first sampling trip and accompanied me in the field. Dr. Sun Shu of the Academia Sinica provided encouragement and logistical help. Dr. Chen Haihong organized the second sampling trip and taught me the ways of the the Yatzee Master. I also thank him for the many hours of good conversation and for some wonderful Chinese food.

I would especially like to thank my parents for their love and support during my time here. They are great. I am grateful to my sister, Carrie, for her encouragement and for the help she gave the rest of the family in my absence. The courage and strength of character of my brother, Bryan, inspired me to remain in Zürich and finish this project. My fiancée, Sue, also supported me through all of this and I look forward to spending the rest of my life with her.
Southeastern China may be thought of as a collage of small continental tectonic blocks which have collided with each other throughout the geologic past. The major blocks of southeastern China are - from northwest to southeast - the Yangtze, Huanan, and Dongnanya Blocks. The Yangtze and Huanan Blocks are thought to have collided during the early Mesozoic eliminating an open ocean which had separated them since the early Paleozoic. This interpretation is relatively recent and represents a radical departure from earlier theories which held that all of southeastern China had existed as a single platform since the early Paleozoic.

For this study, extensive paleomagnetic sampling was carried out on both the Yangtze and Huanan Blocks spanning a time period from the Devonian through the Jurassic. The results of the laboratory analyses of this sample collection provide reliable data for the lower Triassic of the Huanan Block. Samples taken from five sites from this time period, though rotated, place the block at a latitude of approximately 10°S and pass the fold test at the 99% confidence level. This is compared with reliable data from other workers which indicates that the Yangtze Block is at about 2°N to 5°N during this time, confirming separation of the two blocks in the lower Triassic. Results from the Triassic of the Yangtze Block indicate that large scale rotations may have taken place in south China since the Late Triassic.

Other data from this study indicate that the two blocks were separated throughout the Permian as well. These results are less reliable since no fold test may be applied due to similar bedding attitude between sites. These data are not, however, consistent with any remagnetization scenario and agree well with the geologic evidence.

The problem of remagnetization encountered by other workers in south China was not escaped in this study. In addition to a recent remagnetization direction prevalent in many samples, a remagnetized direction associated with a Jurassic overprint was also recognized. This Jurassic overprint is likely a result of the collision and suturing of the Huanan and Yangtze Blocks and mechanisms which may have facilitated the remagnetization process are discussed.
The recent overprint is especially important as it has been recognized in the Permian-Triassic type section in the Meishan Quarry at Changxing. Viscous magnetization experiments show that a viscous remanent magnetization acquired during the Brunhes may account for most of the natural remanent magnetization of these samples. It is also possible that fine-grained hematite is forming in these sediments from conversion of goethite and acquiring a remanence in the present field as it grows through the critical volume. The results of this study indicate that the remanence preserved in the rocks at Changxing is an overprint which makes a resolution of the primary signal impossible.
ZUSAMMENFASSUNG


Für diese Arbeit wurden im Devon bis Jura des Yangtze- und Huanan-Blocks intensive paläomagnetische Studien durchgeführt. Die Resultate dieser Messungen zeigen, dass nur die Untere Trias im Huanan-Block vernünftige Werte ergibt. Proben aus dieser Periode, die an fünf verschiedenen Stellen genommen wurden, ergeben für den Block eine Paläobreite von ca. 10°S und erfüllen den Fold Test mit einem Vertrauenswert von 99%. Verglichen man dies mit Daten von anderen Autoren, die für den Yangtze-Block Paläobreiten von 2°N bis 5°N während dieser Zeit ergeben haben, bestätigt sich, dass die beiden Blöcke in der Unteren Trias getrennt waren.

Weitere Daten aus dieser Arbeit weisen darauf hin, dass die zwei Blöcke auch während des Perms getrennt waren. Diese Daten sind weniger sicher, weil kein Fold Test durchgeführt werden konnte, da das Schichteinfallen sehr ähnlich ist. Die Resultate scheinen nicht das Produkt von einer Remagnetisierung zu sein und stimmen auch gut mit anderen geologischen Arbeiten überein.


Das rezente Signal ist sehr wichtig, weil es auch im Perm-Trias Profil in der Meishan Quarry (Changxing) festgestellt wurde. Die Resultate von viskösen
Magnetisierungsexperimenten zeigen, dass eine visköse Magnetisierung während der Brunhes Periode hauptsächlich für die natürliche remanente Magnetisierung dieser Proben verantwortlich ist. Die Remanenz könnte aber auch von feinkörnigem Hämatit stammen, der im Sediment durch die Umwandlung aus Goethit im rezenten Feld entsteht. Die Resultate zeigen, dass die Remanenz, die in den Changxing Proben erhalten ist, eine reizente Magnetisierung ist, und somit nicht für die Interpretation des primären Signals gebraucht werden kann.
CHAPTER I
GEOLOGY OF SOUTH CHINA

INTRODUCTION

China has proven to be an interesting tectonic puzzle with its highly varied geology and accretionary tectonic history. Geologic studies conducted by western scientists as well as Chinese scientists, have revealed several different geologic units which today are thought to represent distinct tectonic blocks (e.g. McElhinney et al., 1981; Lin et al., 1985; Yang et al., 1986; Hsu et al., 1987). The most drastic changes in the interpretation of the tectonic history have occurred as a result of geologic investigations by Hsu and others (1988). The major tectonic blocks - the Tarim Block, the North China Block, the South China Block (now thought to be comprised of three smaller blocks) - have throughout the geologic past collided with Siberia and each other to form China and give it its complex and unique geology (Figure 1.1). In addition to these major blocks a number of smaller blocks have recently been recognized and their role in the accretionary tectonic history of China is only now coming to light. The focus of this study is centered on the tectonic evolution of the South China Block.

The South China Block - on the basis of the latest tectonic analyses - consists of at least three geologically distinct tectonic units: The Yangtze Block, The Huanan Block, and the Dongnanya Block (Hsü et al., in press). The Yangtze Block - which is composed of the Sichuan foreland basin and the Yangtze deformed belt - comprises a single tectonic plate. The deformed belt is made up of detached and thrusted sedimentary cover. The block has remained a single tectonic unit for at least part of, and perhaps the entire Paleozoic until its collision and suturing with the Huanan Block and the North China Block in the early Mesozoic.

The Huanan Block (formerly the South China Fold Belt) is a strongly deformed tectonic plate lying to the southeast of the Yangtze Block. Large scale folds and thrusts are common throughout the block, as are granitic intrusions. Deformation of sediments as young as Jurassic is seen and these deformed sediments are overlain by Cretaceous red beds.

The Coastal Volcanic Province is a foreland basin consisting of Mesozoic and Cenozoic volcanics skirting the southeast coast of China. It is separated from a southern continent - Dongnanya - by a suture zone defined by the Quanzhou melange. The Dongnanya Block
FIGURE 1.1 Tectonic plates of China. The Sino-Korean Platform is equivalent to the North China Block and the Huanan and Yangtze Blocks together make up the South China Block (from Hsü et al., 1987).
(Chinese for southeast Asia) is believed to comprise the Phillipines and parts of Indonesia, as well as at least part of Hainan Island (Hsu et al., in press).

At the contact between the Yangtze and Huanan Blocks, a collision melange has been discovered which contains metamorphosed rocks of the Banxi Group as well as ophiolites (Hsü et al., 1988). These rocks were thought to be Precambrian basement (Anonymous, 1973; Gupta, 1989). Hsu and others (1988) presented evidence to support the postulate that at least some of what is called the Banxi Group belongs to a collision melange created during the collision of the two blocks in the late Triassic - Jurassic time.

SEDIMENTARY FACIES AND TECTONIC EVOLUTION

Facies changes have been well documented in the sedimentary record throughout southeastern China (Yang et al., 1986; Hsü et al., 1987). The tectonic processes responsible for some of these changes may sometimes be inferred from the sedimentary record. The style of deformation and the ages of the deformed sediments can also lead to some conclusions about the tectonic development. From observations of this deformation as well as the facies changes and sedimentary history, a general interpretation of the tectonic history of the region may be proposed.

A brief account of the sedimentary and deformational history of South China is necessary in order to understand the lines of evidence which have led to the formation of new hypotheses regarding the tectonic history of the South China Block and the new models which have arisen from these hypotheses. For a comprehensive, detailed overview of the sedimentary and paleontological history of south China, the reader is refered to Yang and others (1986).

PRE-DEVONIAN

Shallow water sediments dominate the late Precambrian (Sinian) and early Paleozoic of the Yangtze Block, consisting mainly of carbonate and siliciclastic rocks along with phosphates. Turbidites and hemipelagic shales are seen in the Cambrian on the southeast margin of the Yangtze Block as are pebbly mudstones indicating that a deep marine environment existed off the southeast flank of the block. Some evaporite deposits are seen in the interior of the block during the early Paleozoic but for the most part the interior of the Yangtze block is submerged under shallow seas (Hsü et al., 1987).

Not as much is known about the pre-Devonian of the interior of the Huanan Block due to the extensive cover of Jurassic-age volcanics. Of the rocks of pre-Devonian age that are seen, some are metamorphic, such as slates, gneisses, and schists. On the northern margin of Huanan are flysch sediments which are seen in Jiangxi, Hunan, and other provinces in their slightly metamorphosed state (Hsu et al., in press). These flysch deposits are typical of
those laid down in a trench on the northern active margin of the Huanan Block. An angular unconformity, however, separates the Silurian from the Devonian on the Huanan Block and may be used to distinguish Huanan sediments from those of the Yangtze Block. The hiatus in the Yangtze section is a disconformity without the angular disturbance.

THE DEVONIAN SYSTEM

The early Devonian is missing throughout most of the Yangtze Block. Terrestrial sandstones of middle Devonian age indicate a time of marine regression. By the late Devonian to early Carboniferous time, transgression had resulted in the resumption of carbonate deposition and limestone and dolomite sequences with siltstone, mudstone, and sandstone interbeds are common (Yang et al., 1986).

Similar sedimentation was occurring on the Huanan Block during the early and middle Devonian. Thin, shallow marine sandstones are especially prevalent in the interior of the block (Hsü et al., in press). In Jiangxi and Fujian provinces, continental sediments - conglomerates, Quartz sandstones and red beds - are seen in some areas throughout the middle and upper Devonian indicating as well, that parts of Huanan were emergent during the Devonian. This is a time of plate reorganization, the result of which was the cessation of subduction along the northern edge of the Huanan Block.

This is also believed to be the time when Huanan began to be separated from the Dongnanya Block to the south. This resulted in extensional forces on the Huanan Block creating rift basins in which clastic sediments were deposited (Hsu et al., in press).

THE CARBONIFEROUS SYSTEM

In the Carboniferous the south China region was dominated by neritic carbonate sedimentation over much of the Yangtze and Huanan Blocks during a time of marine transgression (Yang et al., 1986). Individual species of marine fauna which are regionally distributed in South China during the Lower Carboniferous are seen spreading to other regions of Asia and the Pacific rim. At the height of the transgression a few West European and North American faunas are present. A series of platforms and troughs are evidenced by reefs and shallow water carbonates as well as some deeper marine sediments. This indicates a time of extension for the Yangtze Block.

At this time the Huanan Block was also a site of deposition of these shallow-water platform carbonates (Hsu et al., 1990). Sedimentological evidence suggests that a deep sea was now in existence between the Huanan and Yangtze Blocks in the region of Guangxi Province at least. Carboniferous radiolarites are found in the Tianyang Window and flysch deposits seen in Fujian Province also indicate that deep marine sedimentation was taking place on the southeast flank of the Yangtze Block as well (Hsu et al., in press).
THE PERMIAN SYSTEM

Platform carbonates were laid down in the interior of the Yangtze block during the Permian. On the margins of the Huanan and Yangtze Blocks, however, the lithologies vary significantly. Black shale and radiolarian chert as well as limestones, all dominated by pelagic faunal assemblages, were first seen in Anhui province on the Yangtze Block (Anhui, 1987). This facies, known as the Gufeng, has been used to designate the pelagic Permian of South China (Hsü et al., 1987). These sediments were deposited at the northern margin of the Yangtze Block, but the same pelagic facies is also seen in northern Guanxi indicating that a deep ocean existed off the south flank of the Yangtze Block during this time as well.

Above the Gufeng, Permian coal beds are seen. The existence of these beds is difficult to explain if it is assumed that a deep ocean existed at the time. Hsü and others (1987) propose that the coal beds - which are interbedded with chert - represent allochtonous marine coal deposits brought into contact with the Gufeng by thrusting.

The extrusion of the Emeishan basalts also occurred during the Permian. These basalts of continental origin, cover a large area of south China and have been extensively sampled for paleomagnetic studies (McElhinney et al., 1981; Lin et al., 1985; Zhao and Coe, 1987).

THE TRIASSIC SYSTEM

During the lower Triassic, marine sedimentation continued in this region and mainly limestone, shales and some marly facies are recognized (Yang et al. 1986). Very thick middle Triassic flysch sediments are deposited in foredeeps in front of the advancing Huanan Block. Marine passive margin sedimentation continues to dominate the southeastern part of the Yangtze Block.

By the late Triassic the marine influence is apparently on the wane on both the Yangtze and Huanan Blocks. Grey, white and red sandstones with interbedded coal seems begin to be seen in the latest Triassic sequences. Triassic evaporites are also formed on the Yangtze Block which may have acted as detachment horizons for thin-skinned thrusting of the Yangtze sedimentary cover in the Jurassic (Hsü 1981).

Hsu and others propose that this change from a marine to a more continental influence in the late Triassic indicates the convergence and initial collision of the Yangtze and Huanan Blocks. This postulate is further supported by the occurrence of ophiolite sequences and flysch deposits - which will be discussed shortly - along the suture zone.

The cause of the apparent emergence of the central part of southeast China during this time has been the source of some controversy. Some workers argue that the deformation was not a result of collision but that folding in the region took place within an already coherent platform (Ren, 1984; Hamilton, 1979; Huang, 1980). If the postulate of the Hsü group is correct, there should still be substantial displacement between the Yangtze and
Huanan Blocks in the Permian and early Triassic. A major goal of this study is to verify or falsify that postulate.

THE POST-TRIASSIC

After the Triassic the sedimentary facies of south China are mainly terrestrial and similar for both the Yangtze and Huanan Blocks. The thick deposits of lower Jurassic marine sediments in Guangdong and Hunan Provinces were laid down in a foredeep between the two blocks before the Huanan was thrust onto the Yangtze.

Folding and deformation is seen in strata as young as Jurassic and Cretaceous throughout most of the Huanan Block as well as in the south-east region of the Yangtze Block. This deformation is the thin-skinned deformation of the former passive margin sediments after collision (Hsü, 1981). Above the Jurassic sediments in Huanan thick-bedded, flat-lying Cretaceous red sandstones are prevalent.

THE BANXIGROUP

Until recently the Banxi Group was thought to represent the basement of the Sinian and Paleozoic cover sediments of the Yangtze Block (Anonymous, 1973) (Figure 1.2). The identification and stratigraphic mis-classification of the Banxi Group had led to quite a bit of controversy (Hsü et al., 1989; Gupta, 1989; Rodgers, 1989). This group of metamorphic rocks is now interpreted to be a collision melange containing not only metamorphosed flysch and other sediments but ophiolites as well (Hsü et al., 1988).

Ophiolitic rocks of the Banxi Group have been dated and appear to be mostly late Precambrian (approximately 850 m.y.b.p.) or Devonian. They were underthrust along the active margin north of the Huanan Block during late Precambrian and early Paleozoic subduction. During the collision of the Huanan and Yangtze Blocks they were carried along in the collision melange.

GRANITIC INTRUSIONS

S-type and I-type granitic intrusions are seen throughout south China although the I-type granites are not common (Jahn et al., 1976). S-type granites are commonly thought to be formed from the melting of continental crust while I-type granites result from the melting of oceanic crust. S-type granitic batholiths of Mesozoic age are seen in the eastern Yangtze fold and thrust belt and are related to the partial melting of the underthrust, thickened continental crust (Pitcher, 1983; Hsü et al., in press). Precambrian granites are seen as klippes along the contact between the Huanan and Yangtze Blocks and appear to be parts of the Huanan basement thrust over the Yangtze sediments.
FIGURE 1.2  Geralized map of south China showing the location of the tectonic melange of the Banxi Group (from Hsü et al., 1987).
THE COLLISION OF THE YANGTZE AND HUANAN BLOCKS

One of the major controversies surrounding south China geology had arisen as a result of a new theory proposed by K.J. Hsü and others (1987, 1988). The classic interpretation of the Banxi as south China basement had led down a blind alley. A recognition that the Banxi is a melange implies a collision of the Yangtze and Huanan Blocks. In this study an attempt is made to use paleomagnetic methods to determine the validity of this postulate.

For many years the South China Block was thought to have been a large platform or paraplatform existing since the middle Paleozoic (Caledonian) and extending from the Coastal Volcanics province, northwest to its contact with the North China Block (Huang, 1978 and Hamilton, 1979). The extensive deformation seen in south China was postulated to be the result of a Caledonian orogeny which sutured the Huanan and Yangtze Blocks together to form the South China Block (Yang et al., 1986).

Huang (1980) and Ren (1984), however, recognized that sediments much younger than middle Paleozoic were also deformed. The age of these folded strata and magmatic intrusions indicated to Ren a Mesozoic age of deformation likely associated with the Indosinian (Triassic-Jurassic) orogeny. But he held to the accepted theory that South China existed as a single platform since the Caledonian and concluded that the deformation had taken place within the platform and was not a result of continental collision and suturing during the Indosinian. These deformational features were attributed to an east-west dipping Jurassic and Cretaceous subduction complex which was thought to lie buried under the East and South China Seas (Hamilton, 1979). Based on this theory Ren interpreted the deformation as "folds in a platform".

In 1981, however, while reviewing geologic maps of south China, Hsü discovered an outcrop pattern of Paleozoic rocks at the northern margin of the South China Fold Belt in the center of the South China Block (Hsü, 1981 & 1982). The outcrop pattern was similar to that of the Appalachian Mountains of the eastern United States (Figure 1.3). Using comparative tectonics he concluded that this pattern suggested a similar type of collision history between the Huanan Block - which was then known as the South China Fold Belt - and the Yangtze Block. It was also proposed that a second suture - southeast of the Huanan Block - may be represented by a belt of ultramafic rocks which outcrop in Zhejiang and Fujian provinces.

Klimetz (1983) also suggested that the North and South China Blocks collided during the Indosinian orogeny. He recognized that deep marine sediments were seen farther inland on the South China Block - south of the suture between the two blocks - than would be expected based on the area of collision between the blocks, but did not attribute this fact to an Indosinian suturing of the Huanan and Yangtze Blocks. Rather he postulated a southern
FIGURE 1.3 New tectonic map of south China. The suture zone between the Yangtze and Huanan Blocks is along the Banxi melange, which is shown in black (from Hsü et al., 1990).
fragment, Indosinia, which was rifted away during subduction by the onset of back-arc spreading and then re-accreted during the Indosinian orogeny along a northwest-southeast trending suture zone.

Part of Indosinia was to include some of the Emeishan basalt flows used by McElhinney and others (1981) to determine a paleolatitude for the South China Block in the Permian. For this reason, Klimetz concluded that the paleomagnetic vectors used to determine the paleolatitude may not have been representative of the South China Block as a whole. Klimetz also noted the existence of early Mesozoic age granites along Hsü’s proposed suture. He failed, however, to relate these granites to any orogenic activity.

During a field excursion in 1985, the first evidence of an ophiolite melange within the South China Block was found in the rocks of the Banxi Group overlying carbonate platform sediments, which was in turn overthrust by Precambrian granites (Hsü et al., 1988). These ophiolites were thought to represent the suture zone between two small lithospheric plates, or blocks, and had been squeezed out of a subduction trench and carried as part of the collision melange below the overriding block. The two tectonic blocks - the Yangtze in the north and the Huanan in the south - are thought to have collided in the late Triassic or early Jurassic eliminating a Paleotethyan seaway which existed between the two (Figure 1.4). In 1988 Hsü and others presented evidence that these ophiolite blocks were indeed part of a collision melange and not part of the Precambrian basement as previously thought (Anonymous, 1973).

The Banxi group was thus reinterpreted to be not a time stratigraphic unit, but rather a melange which had been thrust into contact with rocks of various ages from the Precambrian to the late Paleozoic. The Precambrian granites which are now found on top of the Banxi Group were interpreted as klippes of the overthrust rigid basement nappes of the Huanan Block.

The proposed collision between the two plates resulted in thin-skinned deformation of the sediment cover of the Yangtze Block as the overriding Huanan Block pushed detached passive margin sediment layers northwestward (Hsü, 1981). Triassic evaporites of the Yangtze Block apparently acted as detachment layers which facilitated the thin-skinned deformation (Hsü et al., 1987).

Hsü’s new model explained some unresolved discrepancies in the previous interpretation. The folded strata seen on the South China block includes not only Precambrian and early Paleozoic but also rocks as young as Triassic. If the suturing of these two blocks took place in the Mesozoic rather than the Paleozoic then deformation of the Triassic and Jurassic sediments would be expected. As discussed earlier, deep water facies seen in the Permian and Triassic of south China also provide evidence for the existence of a seaway between the Huanan and Yangtze Blocks during this time as well as submarine volcanics of this age, which are also present in some areas (Yang et al., 1986).
FIGURE 1.4 Collision history of the Yangtze and Huanan Blocks from the new model of Hsiü and others (1988).
In the new model proposed by the Hsü group, the onset of subduction began some 850 m.y.b.p. along the northern margin of the Huanan Block. The lack of an accretionary wedge during the initial stages of subduction increased the friction associated with the subducting slab thus causing the oceanic crust to fragment. These fragments of oceanic crust were eventually mixed with the accretionary wedge sediments and during collision carried along as part of the collision melange. This part of the model is supported by age dating of some of the ophiolites of the Banxi Group that provides results which concur with this age (Zhou, personal communication).

During the late Precambrian until the Devonian subduction ceases. After the Devonian renewed subduction - possibly associated with the rifting of Huanan from Gondwanaland - results in more fragmentation of newly subducting oceanic crust. These fragments are the Devonian-age ophiolites (mainly pillow lavas) which are today found in Guanxi Province. Also at this time subduction of the Banxi Flysch results in the emplacement of S-type granites which are not, however, associated with continental collision (Zhou, personal communication).

Investigations of the granitic intrusions also support a collision of the two blocks during the Indosinian. The Mesozoic granites of south China were found to be S-type granites, which are normally associated with continental collision rather than I-type granites which form from the subduction of oceanic crust (Pitcher, 1982 and Jahn et al., 1976). Older, early Paleozoic S-type granites are thought to represent the melting of flysch sediments carried down during subduction of the oceanic slab as just discussed. Once the flysch sediments had been melted and emplaced the melting of the remaining oceanic crust resulted in the emplacement of I-type granites also in the early Paleozoic.

THE TECTONIC HISTORY OF HAINAN ISLAND AND THE COLLISION OF THE HUANAN AND DONGNANYA BLOCKS

The possibility that another suture zone exists on the south China coast was proposed by Hsiü and others (1990). This postulate is supported by the discovery by Yu Ziye (1989) of a Permian-Carboniferous diamictite in the Echa Formation of southwestern Hainan Island (Figure 1.5). The Echa Formation is mainly a siltstone and conglomerate and is overlain by the Eding Formation (cherty limestone) and the Nanlong Formation (siltstone and conglomerate).

Yu and others (in prep) suggest, based on abundant Parafusilina and the lack of warm water fauna, a cool water origin for the limestones of the Eding Formation. They also interpret the diamictite of the Nanlong Formation as glacial in origin, possibly related to lacustrine glaciation.
FIGURE 1.5 Location map of Hainan Island with the sampled provinces from the mainland shown in heavy outline.
These deposits are similar to the tillites of the same age which are seen in North Tibet, west Yunnan and Southeast Asia and are thought to be contemporaneous with the tillites of Gondwanaland (Australia, New Zealand, and the Cimmerian regions). This is supported by the brachiopod fauna which is compatible with the northern margin of Gondwanaland. The flora of the Nanlong Formation, however, is similar to flora of the Cathayan Province but still very different from the Coastal south China floras. Most paleomagnetic results for the Huanan and Yangtze Blocks places both at shallow to equatorial latitudes during the Permian.

Based on this evidence, Yu (1989) has proposed that at least this region of Hainan Island was a part of Gondwanaland during the late Paleozoic and rifted away during the Permo-Carboniferous, fragmenting and moving north until its suturing with the Huanan Block (Figure 1.6).

Another source of controversy surrounding Hainan Island is the origin and stratigraphy of the so-called Shilu Group. Yu postulated that the Shilu represents not a stratigraphic unit - as was previously suggested - but rather a tectonic melange associated with collision and suturing of two parts of the island. Field work by Hsiü, Chen, and Yu in December, 1989, verified the suggestion that the melange occurs in a suture zone.

Hsiü and others postulate that this is the suture between the Huanan and Dongnanya Blocks. The collision is thought to have taken place during the Jurassic as evidenced by the deposition of continental red beds of Cretaceous age on both sides of the suture zone.

PURPOSE AND SCOPE OF THIS THESIS

OBJECTIVES

The goal of this study was to examine the problem of south China tectonics through the use of paleomagnetic methods. Paleomagnetic results would provide a method of determining the relative motions as well as the temporal relationships of the Dongnanya, Huanan, and Yangtze Blocks. An attempt would be made to construct an apparent polar-wander (APWP) for the Huanan Block and compare this with the APWP constructed by Lin and others (1985, 1989, 1990) for the Yangtze Block. It would then be possible to determine if the two blocks were separated during the late Paleozoic and earliest Mesozoic as proposed by Hsiü and others. New results would also be obtained from some important formations from the Yangtze Block in an attempt to fill in gaps in some of the data from that block as well as further constraining some of the pole positions.

The second objective was to employ a similar approach to test Yu's postulate of a Gondwanaland origin for southern Hainan Island as part of the Dongnanya Block. Samples from the Permian sediments overlying the proposed tillites were to be recovered and
FIGURE 1.6  Location of suture and tillites on Hainan Island (after Yu et al., 1989).
analyzed by paleomagnetic methods in order to provide a paleolatitude for the site. This could then be compared with data from Gondwanaland.

As in any paleomagnetic study, it is important to determine the origin of remanence directions seen in the samples. These directions are critical to our analyses of the spatial and temporal relationships of tectonic blocks. In order to examine the validity of the results of this work, the magnetic mineralogy of many of the samples would be investigated, mainly through the use of rock magnetic methods.

SIGNIFICANCE

This study provides the first paleomagnetic results from the Huanan Block. The results from this block are important in determining not only the overall tectonic evolution of south China, but also provide additional data for the interpretation of the geology of the region and the formulation of the previously discussed new models. Recent paleomagnetic work on the Yangtze block has led to conflicting results and the reliability of some of this data is in question (Lin et al., 1985; Zhao & Coe, 1987; Steiner et al., 1989; Dobson & Mauritsch, 1989). For this reason this study also examines existing paleomagnetic data from the Yangtze Block and provides new data for this block as well. The reexamination of an important Permian-Triassic site by rock magnetic methods also provides the first clues as to the origin of widespread remagnetization in south China. New paleomagnetic results are obtained from Hainan Island which may prove important for the interpretation of Yu's new model for the tectonic history of the island.
CHAPTER II
PALEOMAGNETIC PRINCIPLES AND EARLIER RESULTS
FROM SOUTH CHINA

INTRODUCTION

The application of paleomagnetic methods has been shown to be an important tool for helping to resolve tectonic problems and determine plate motions, especially when used in conjunction with geologic studies (e.g. Klootwijk, 1973; Morel and Irving, 1978; McElhinney et al., 1981). Paleomagnetic pole positions and paleolatitudes, derived after progressive demagnetization of rock specimens, can be used to determine the positions and motions of tectonic blocks through geologic history. With this information it may then be possible to examine the movements and interactions of these blocks.

MAGNETIZATION IN ROCKS

Most sediments contain small amounts of ferromagnetic minerals which were either introduced during deposition or chemically precipitated at some later time in the rock's history. Igneous rocks usually also contain ferromagnetic minerals which were crystallized from a melt. These minerals - especially the iron oxides magnetite and hematite, the iron oxyhydroxide goethite, and the iron sulphide pyrrhotite - are able to preserve the intensity and direction of the earth's magnetic field as it was during the time of their formation or deposition (Figure 2.1). The phenomenon of ferromagnetism is due to the electron spin configurations and is related to the bonding between the iron ions and the oxygen or sulfur as well as the lattice structure and lattice defects of the ferromagnetic minerals (for more on this subject refer to Neel, 1949; Nagata, 1964; O'Reilley, 1984; Stacey and Banerjee, 1974).

When a sample containing ferromagnetic minerals is exposed to a magnetic field the magnetic moments of the grains align themselves, to a certain degree, along the field direction. At this point, while the sample remains in the field, the magnetization resulting in the mineral is the sum of both an induced ($J_i$) and remanent ($J_r$) magnetization.

The induced magnetization is lost upon removal of the field. Remanent magnetization, however, may remain even after removal of the applied field. This implies that some of the magnetic moments retain their alignment in the field direction. The magnetization which is preserved in this manner is known as natural remanent magnetization (NRM).
FIGURE 2.1 The FeO - TiO₂ - Fe₂O₃ ternary system with the Curie (Néel) temperatures (From Merrill and McElhinney, 1983).
The different physical properties of magnetic minerals determine their stability and aid in their identification (Table 2.1). In addition to recording the earth's magnetic field, it is also possible to give a sample a remanence in the laboratory. Minerals which can preserve a remanence are usually ferrimagnetic or antiferromagnetic with a parasitic ferromagnetism. There are several types of remanent magnetization which are important in paleomagnetic studies.

**REMANENT MAGNETIZATION**

**DETRITAL REMANENT MAGNETIZATION (DRM)**

This is a remanent magnetization acquired during deposition of the sediment. As the magnetic particles fall through the water column they preferentially align themselves to the magnetic field and as the sediment consolidates the magnetization is recorded by the particles. The alignment of the particles may, however, be affected by current motions and movement of the particles on the sea bottom.

**POST-DETRITAL REMANENT MAGNETIZATION (PDRM)**

After deposition of the sediments the remanent direction may be affected by bioturbation, compaction, or other post-depositional effects. The remanence preserved by this method is called PDRM and is fixed in the sediment upon de-watering and compaction. After de-watering and compaction the ferromagnetic particles are not free to rotate in the water-filled pore spaces any longer and the magnetic field present at this time is preserved. This is usually not long after deposition and though there will then be a slight lag in the magnetic signal it is fairly insignificant for tectonic studies.

**CHEMICAL REMANENT MAGNETIZATION (CRM)**

As a magnetic mineral grows it passes through a critical volume beyond which it reaches a stable ferromagnetic structure. This ferromagnetic behavior is necessary to preserve the magnetic field and the critical volume at which stable ferromagnetism is achieved is known as the blocking volume. This is usually a secondary remanence acquired during chemical alteration of the sediment by means such as oxidation or authigenic growth of new minerals.

**THERMOREMANENT MAGNETIZATION (TRM)**

Upon cooling below the Curie temperature, a magnetic mineral will pass through its blocking temperature \( T_b \). This is the critical temperature below which the remanent magnetization becomes preserved in the mineral in a similar manner to growth through the blocking volume in the case of CRM. At temperatures above the blocking temperature the effects of thermal agitation act to randomize the magnetic moments and are too great to allow
<table>
<thead>
<tr>
<th>MINERAL</th>
<th>COMPOSITION</th>
<th>MAGNETIC STATE</th>
<th>T_c °C</th>
<th>M_s 10^3 A/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>Fe_3O_4</td>
<td>ferrimagnetic</td>
<td>578</td>
<td>476</td>
</tr>
<tr>
<td>Ulvospinel</td>
<td>Fe_2TiO_4</td>
<td>antiferromagnetic</td>
<td>-153</td>
<td></td>
</tr>
<tr>
<td>Haematite</td>
<td>α- Fe_2O_3</td>
<td>antiferromagnetic</td>
<td>680</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(parasitic ferromagnetism)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO_3</td>
<td>antiferromagnetic</td>
<td>-223</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(parasitic ferromagnetism)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maghemite</td>
<td>γFe_2O_3</td>
<td>ferrimagnetic</td>
<td>675</td>
<td>426</td>
</tr>
<tr>
<td>Goethite</td>
<td>α- FeOOH</td>
<td>antiferromagnetic</td>
<td>80-120</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(parasitic ferromagnetism)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe_{1+x}S</td>
<td>antiferromagnetic</td>
<td>320</td>
<td>90</td>
</tr>
</tbody>
</table>

**TABLE 2.1** The major rock-forming magnetic minerals and their properties. T_c is the Curie temperature, M_s is the spontaneous magnetization at room temperature.
a remanence to be preserved and the mineral remains in a superparamagnetic state. At
temperatures below $T_b$ the magnetic moment which is aligned to the field present during
cooling may be preserved and a stable ferromagnetic state is preserved. TRM and CRM may
be very stable over geologic time and their decay is governed by the equation:

$$(\text{Eq 1.1}) \quad \tau = \tau_0 \exp \left( \frac{v \cdot M_s \cdot H_c}{2kT} \right)$$

where:
$\tau = $ relaxation time
$\tau_0 = $ lattice vibration frequency
$v = $ grain volume
$M_s = $ spontaneous magnetization
$H_c = $ coercivity
$k = $ Boltzmann's constant
$T = $ temperature

ISOTHERMAL REMANENT MAGNETIZATION (IRM)

This is the acquisition of remanence at a constant temperature (usually room temperature)
by exposure to high magnetic fields. When the sample is placed in a magnetic field the
magnetic moments of the grains will align themselves to the field. The degree to which they
may align is dependent on the coercivity of the grains and the strength of the field.

VISCOUS REMANENT MAGNETIZATION

Exposure to weak fields - such as the earth’s - over long periods of time can result in the
acquisition of a viscous remanence if the rock contains minerals with unstable magnetic
moments. The VRM intensity increases logarithmically according to the relation:

$$(\text{Eq. 1.2}) \quad \text{VRM} = S \log(t/t_0)$$

where:
$S = $ viscosity factor
$t = $ time

VRM is always a secondary magnetization and is usually aligned to the present or recent
magnetic field. It can normally be effectively cleaned by thermal demagnetization but may be
difficult to clean using alternating field demagnetization and may partially or wholly mask a
primary component (Dunlop and Stirling, 1977; Rimbert, 1958).
DEMAGNETIZATION TECHNIQUES

The NRM of a rock sample - which has a direction as well as an intensity and is, therefore a vector quantity - may be carried by more than one mineral phase and may have been acquired by one or more of the previous mechanisms due to a wide range of blocking temperatures of volumes. The progressive demagnetization of remanence, using thermal or alternating field techniques, can be used to isolate individual components of magnetization which comprise the NRM and usually reveals a characteristic component of magnetization (ChRM) which is associated with the deposition or crystallization of the rock.

THERMAL DEMAGNETIZATION

During thermal demagnetization a sample is heated to incrementally increasing temperature intervals until the NRM is gradually destroyed. Since the rock usually contains a range of magnetic mineral grain sizes and blocking temperatures, the thermal agitation created by each heating step acts to randomize that portion of the NRM which has a blocking temperature below the particular heating step. This unblocking occurs because the increase in temperature reduces the relaxation time, thus causing the remanence to become unstable according to the relationship seen in equation 2.1. This is done in a field-free space so that when the sample is again cooled through the blocking temperature, this portion has no field with which to align and remains randomized, no longer contributing to the overall intensity of the sample. The change in the vector after each step can then be plotted and the components which comprise the NRM may be isolated and the directions analyzed.

Thermal demagnetization is the most effective method of resolving individual components since the Neel temperature of hematite - the highest of the ferromagnetic minerals at 678°C - can easily be achieved. Although generally effective, problems may still be encountered with this method.

Upon heating to high temperatures, iron-sulfides which may be present in the rock can oxidize to form other ferromagnetic minerals, such as hematite. Hematite may also be formed by dehydration of goethite or the conversion of clays when heated. Viscous magnetite may also be formed in this manner. These new minerals may be present in sufficient amounts to contribute significantly to the NRM of the sample and make the primary component of remanence difficult to resolve.

ALTERNATING FIELD DEMAGNETIZATION

Alternating field (A.F.) demagnetization applies a similar approach but affects the coercivity spectrum of the rock rather than its blocking temperature spectrum. Coercivity is the opposition of the magnetic mineral to being magnetized. Normally the rock contains magnetic minerals of varying coercivities just as it contains minerals with a range of blocking...
temperatures. Exposure to incrementally increasing alternating fields has the same randomizing effect on the magnetic grains with coercivities below these fields as heating does on grains with blocking temperatures below the particular heating step. Increasing the alternating field past the value of $H_c$ eliminates the contribution of ferromagnetic minerals with coercivities below $H_c$. The remaining NRM is progressively carried by grains with higher coercivities as the contribution of lower coercivity grains is eliminated. Grains of a specific mineral type with higher coercivities have longer relaxation times and preserve older components of magnetization according to the relationship expressed in equation 2.1.

While A.F. demagnetization does not produce the mineral conversion problems sometimes encountered when applying thermal techniques, it is not always sufficient to resolve high-coercivity components. Peak alternating fields available in the laboratory are too small to affect hematite or goethite - both important magnetic minerals with high coercivities. In rocks which contain neither of these two minerals but rather have an NRM carried by magnetite or pyrrhotite, A.F. demagnetization can be most effective.

In order to decide which of the isolated components is likely to carry a primary magnetic signal associated with deposition, it is necessary to understand something about the magnetic mineralogy of the samples. For this reason, the magnetic mineralogy of the samples from south China has been studied using mainly rock magnetic methods - which will be discussed in later chapters - in an effort to determine whether or not the characteristic components of magnetization are carried by a mineral phase which is likely to have acquired its remanence during deposition of the sediment.

FIELD TESTS OF THE STABILITY OF REMANENCE

In addition to rock magnetic experiments, field tests can provide an indication of the stability of remanence carriers and, most importantly the minimum age of magnetization. Of the several tests that are commonly used, three are applicable to this study.

THE FOLD TEST

During deposition of the sediment or cooling of the magma, the magnetic particles, dispersed over a horizontal area within one bed or one lava flow will all record the same field and hence, have the same NRM vectors - pointing to the field at that time. If, subsequent to the deposition or cooling, folding of the beds takes place the NRM vectors will then become dispersed. By taking samples from two or more limbs of a fold or fold system, a test can be made to determine if the magnetization pre-dates the folding.

The values of Fischer's precision parameter "k" before and after correction for bedding attitude are compared to determine the amount of scatter in the data (Fischer, 1953). If the sample directions group significantly better after correction for the bedding attitude, then the
site is said to pass the fold test and the magnetization is presumed to predate the deformation (Graham, 1949; McElhinney, 1963; McFadden and Jones, 1981) (Figure 2.2). In cases where the dip of the beds is shallow or the magnetization direction lies along the fold axis this test may not be a valid indication of the age of remanence and is considered indeterminate.

Passing a fold test at a given confidence level is only an indication that the remanence was acquired before the deformation. A positive result does not exclude the possibility that the remanence direction is a secondary direction acquired after deposition but before folding.

THE REVERSAL TEST

Since the earth's magnetic field is known to reverse, sites which represent sufficiently large intervals of time should contain both normal and reverse polarities. If the two ChRM directions are grouped antiparallel after demagnetization, the component which has been isolated has been acquired during times of both normal and reversed polarity and is more likely a stable NRM associated with deposition. This is not always the case, however, since a secondary CRM can be acquired by mineral growth over long periods of time, therefore encompassing both polarities.

THE ATTITUDE TEST

This is similar to the fold test, however, rather than sampling from two limbs of a fold, samples are taken from rocks of the same age but from exposures with different bedding attitudes. The same criteria hold true for comparing the directions before and after correction for the bedding attitude. If the bedding attitudes are diverse enough throughout the sites then an attitude test may be applied. This test is not as commonly applied as the fold test but can be useful in giving an indication of the age of remanence.

APPARENT POLAR WANDER AND PLATE MOTIONS

Since the earth's magnetic field has both a horizontal and a vertical component - declination and inclination respectively - the location of the magnetic pole relative to the site during the time of remanence acquisition may be recorded as the NRM vector during deposition or crystallization and is then preserved in the rock. The magnetic minerals act something like compass needles, with their remanent directions pointing to the paleopole.

Declination is defined as the angle between the axis of rotation and the magnetic pole. Inclination is the angle made between the magnetic field and the horizontal (Figure 2.3). Inclination is 0° at the equator and 90° at the magnetic pole. Over a period of time, the drift of the magnetic pole is averaged out and its location is coincident with the pole of rotation. This is known as the Geocentric Axial Dipole hypothesis.
FIGURE 2.2 The fold test: (a) uniformly magnetized flat-lying beds (b) pre-folding directions become dispersed after folding (c) remagnetization results in uniformly magnetized folded beds (from Collinson, 1983).
FIGURE 2.3 Graphic representation of Declination and Inclination.
The NRM vector, or combination of vectors, is measured by the magnetometer in the laboratory. The direction and intensity of the primary component of NRM associated with deposition or crystallization from a melt, defines the pole and, once blocked in, can be used to trace plate motions. As the plate moves, so does the apparent position of the pole (Figure 2.4).

Following this principle, as progressively younger rocks are sampled and measured the location of the paleopole changes and the pole appears to move. This phenomenon is known as Apparent Polar Wander (APW) and is not actually representing the motion of the earth’s magnetic pole, but rather the motion of the sampling site or the plate on which the site is located. From this data Apparent Polar Wander Paths (APWP) may be constructed to show the motion of plates relative to one another throughout the geologic past.

The poles which are actually plotted using the ChRM directions are virtual geomagnetic poles (VGP) and represent a spot reading of the position of the earth’s magnetic pole at that time. When measurements from several samples from a site are averaged, the effects of secular variation are eliminated. The average of the VGPs represents, therefore, the geomagnetic pole position during the time of deposition of the sediment and is considered to have been coincident with the axis of rotation of the earth - the geographic pole - during deposition.

The paleolatitude for the site during the time of deposition may be calculated from the inclination of the characteristic direction using the equation:

\[
\tan I = 2 \tan \text{Paleolat.}
\]

In tectonically active areas such as South China and especially the Huanan Block local rotations between sites or geographic locations may make it difficult to construct an APW path using poles derived from different site locations. This problem will be discussed in detail in Chapter VII. In this case it is most useful to compare the paleolatitudes of the blocks by looking at the inclinations.

**PREVIOUS PALEOMAGNETIC STUDIES IN SOUTH CHINA**

**THE SOUTH CHINA BLOCK**

The first major paleomagnetic study in China was undertaken by Lin Jin-lu during his doctoral studies under Prof. Mike Fuller at the University of California at Santa Barbara (Lin et al., 1985 and Lin, 1987 & 1990). He was the first to construct APW paths for the North and South China blocks which laid the foundation for further work (Figure 2.5). Data was
Present North Pole

Present position of plate

Northward plate motion

Plate position 150 m.y.b.p.

Apparently shifted North Pole from 150 m.y.b.p.

FIGURE 2.4 Graphic representation of the concept of apparent polar wander. The northward motion of the plate results in an apparent shift of the pole position since the remanence is blocked in 150 m.y.b.p.
FIGURE 2.5  Apparent Polar Wander path for the South China (Yangtze) Block (from Lin and Fuller, 1990).
presented which showed that these two blocks were separate plates until their collision with Siberia and each other in the early Mesozoic.

At about the same time in the mid-1980’s, paleomagnetic work in China was begun by other western and Chinese scientists. Most of the work in southern China, however, was concentrated on the Yangtze Block with little or no data from the Huanan Block, the Coastal Volcanics Province, or Hainan Island. While Lin’s data provided a preliminary APW path for the North and South China blocks, no samples were collected from the Huanan Block. Subsequent plate reconstructions by Lin also show the South China Block as one plate (Lin, 1987; Lin, 1990).

Working in southwestern China, Chan and others (1984) presented some of the first results from the Permian and Triassic. Earlier, McElhinney and others (1981) had sampled the Permian Emishan basalt flows. These results contradicted, somewhat, Lin’s later results and were subsequently reinterpreted by McElhinney to be rotated (Lin, personal communication). This particular time period was later studied in detail by many other authors, often leading to controversial results (McElhinney, 1985; Lin et al., 1985; Opdyke et al. 1986; Heller et al., 1988; Li, 1988; Dobson and Mauritsch, 1989; Steiner et al., 1989; Haag, 1989). Recently, Li (1988) has presented lower Triassic data which compares favorably with the results of Opdyke and others (1986) as well as Zhang (1984) and appears to constrain the lower Triassic pole for the Yangtze Block quite well.

Zhao and Coe (1987) presented data from the Emishan basalt flows which contradicted somewhat, Lin’s interpretation of the tectonic motions of the North and South China Blocks. Their pole position for the late Permian lies far to the east of Lin’s and this led them to postulate a point collision and scissors-type closure between the two blocks. The paleolatitudes are, however, similar and rotations in the Emishan basalts have been postulated which may account for this discrepancy (McElhinny, 1985; Lin et al., 1985; Li, 1988; Steiner et al., 1989).

There are also discrepancies in much of the other data. In recent studies it has been shown that some of Lin’s original APW path and, in particular, his pole for the Permian-Triassic for South China may be erroneous. Dobson and Mauritsch (1989) have shown that the Changxing section, on which Lin’s pole was based, is likely to be remagnetized. Steiner and others (1989) also presented evidence that the pole was remagnetized. They also stated, however, that lack of apparent polar wander - and thus plate motion - during the entire Triassic is suggested by the coincidence of their poles and the late Triassic pole position (Opdyke, 1986). It is more likely, however, that one or both poles are remagnetized.

While there is a large amount of Permo-Triassic data from southern China, the remainder of the Paleozoic and Mesozoic have been studied in much less detail. One study from Kent and others (1986) presented data from the Cretaceous and Courtillot and Besse (1986) examined Mesozoic and Cenozoic paleomagnetic results. Lin’s original work and his
updated versions (Lin et al., 1985; Lin, 1987; Lin, 1990), however, remain the main source of information for pole positions and paleolatitudes for the rest of the Paleozoic and Mesozoic. Unfortunately, there are important gaps in this data set and the statistical constraints on the Paleozoic pole positions leave, in most cases, quite a bit of ambiguity.

New data from the Huanan Block from the work of Chen indicates that this block was situated at shallow latitudes in the southern hemisphere during the early Triassic (Chen, H.H., personal communication). These samples are, however, from only one site and no fold test is possible. A fairly large amount of scatter is also seen in the data.

Most authors working in south China have reported problems with remagnetization of the sediments (Lin et al., 1985; Opdyke et al., 1986; Heller et al., 1988; Haag, 1989). This problem is especially prevalent in samples from the Upper Permian. In almost all studies the Upper Permian is remagnetized while the early Triassic appears, in some instances, to preserve a primary direction. While weathering surely plays an important role in the remagnetization process in the region, the reasons for this are not completely clear, although some investigations into the remagnetization process in south China have been done (Dobson and Mauritsch, 1989; Dobson and Heller, in prep). This important subject will be addressed in this study.

HAINAN ISLAND

The only paleomagnetic study conducted on Hainan Island was done by Yang and others (1989). The results of this work on the Echa Formation indicate that the island was at near equatorial latitudes during the lower Permian. This is in contradiction to the hypothesis of Yu based on the discovery of apparent glacial tillites. The data from this formation is, however, incompatible with other data presented and may be remagnetized. These results are then, inconclusive in determining the relationship between Hainan Island and Gondwanaland and the interpretation of Yu remains tentative.
CHAPTER III
SAMPLING METHODS

INTRODUCTION

For paleomagnetic sampling it is necessary to devise a sampling scheme which will average out the effects of secular variations of the earth's magnetic field leaving the geocentric dipole component for analysis. In order to accomplish this several cores or oriented blocks from different beds of nearly the same age must be sampled (Figure 3.1). Depending on the sedimentation rate these effects may be averaged out in the time interval contained in one core.

For tectonic applications, a hierarchical sampling procedure is best suited. The sampling should first be on the site level taking seven to ten samples per site in order to average out this secular variation. Several sites must then be taken from each formation in order to calculate a formation mean. This formation mean may then be used to calculate a pole position or paleolatitude representative of the age of deposition of the sediments. The poles calculated in this manner may then be used to construct an APW path for use in tectonic interpretations.

FIELD PROCEDURES

Sites were sampled from the provinces of Zhejiang, Fujian, Hunan, and Hainan Island (Figure 1.5). Between seven and ten samples were normally taken at each site in order to average out the above mentioned effects of secular variation of the earth's magnetic field. While most of the sites were located south of the proposed Yangtze - Huanan suture zone, they were distributed over as wide a geographic area as possible in an attempt to recognize local rotations of the ChRM directions.

In choosing sampling sites, several factors had to be taken into consideration. Ideally, sites would be chosen where the rock units were fresh and a fold test was possible. However, due to our limited access to certain areas and the lack of reconnaissance during our first of two trips this was not always the possible. Several sites were sampled in rocks where the bedding was difficult to obtain but no other outcrops were available. Most of the sites north of the suture zone from the Yangtze block, however, were taken at locations where a fold test was possible.
Standard 2.5 cm diameter core samples taken for paleomagnetic investigation were drilled using a water-cooled, hand-held rock drill. When possible long cores were drilled so that two to three samples could be cut from each core. A diamond-tipped drill bit was used on all samples. The samples were then cut into from one to three cores, each 2.2 cm in length.

After drilling, the cores were oriented in place with an orientation device and a Brunton compass. As no volcanic rocks were drilled it was possible to use the Brunton compass for orientation of all samples. The orientation was then marked on the core and recorded in a field notebook. This provides the azimuth and dip data used for later calculations to restore the NRM directions of the cores to their original attitude in the field.

FIGURE 3.1 (a) Magnetization components in sample coordinates (b) Relationship between sample axes and present geographic coordinates. A is the azimuth of the core and C is the dip (from Lowrie, unpublished).
CHAPTER IV
SAMPLING SITES

INTRODUCTION

Most of the sites were collected from south of the proposed suture zone between the Huanan and Yangtze Blocks in order to compare the results with those already obtained by other workers from the Yangtze block (Lin, 1985; Opdyke & Chan, 1986; Steiner, 1989; Coe & Zhao, 1987; McElhinney, 1984). There is however, still a lot of ambiguity in the Yangtze results. For this reason, when possible, some sampling was done north of the proposed suture - mostly in outcrops where a fold test could be applied - in an effort to gauge the reliability of the data obtained from the Yangtze block and to attempt to construct a composite APW path for that block for comparison purposes.

On Hainan Island 77 samples from eight sites were taken from the southern-most part of the island. This is the region which is thought to have belonged to Gondwanaland until the Permian (Yu, 1989).

Rocks ranging in age from Devonian to lower Jurassic were sampled on the Huanan and Yangtze blocks as well as Permian sediments and upper Paleozoic granites from Hainan Island (Figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.6).

SOUTH CHINA

DEVONIAN

Three sites from the Middle Devonian (D2) Taomajian Formation were sampled near the Banshan Reservoir in southern Hunan Province (Ningyuan County). Only one outcrop in the area was suitable for sampling and many of the beds showed signs of surficial weathering. The bedding attitude for the three sites was very similar (az 310/dip 26) and, therefore, a fold test would not be possible for these sediments.

In addition, two sites from the Qizhiqiao Formation (D2) near Dasangtang village were sampled. This formation conformably overlies the Taomajian. Both formations are representative of the uppermost Middle Devonian Dongganglingian stage and are characterized chiefly by clastics with limestone in the lower part and limestone and marl in the upper part. These outcrops appeared more fresh than the underlying Taomajian sediments, however, the bedding attitude of the two sites was again the same (010/15) and a fold test for this formation is not possible.
FIGURE 4.1 Location of sampled sites in Zhejiang Province.
FIGURE 4.2 Location of sampled sites in Fujian Province.
FIGURE 4.3 Location of sampled sites in Hunan Province.
FIGURE 4.4 Location of sampled sites on Hainan Island.
### HAINAN ISLAND

<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
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<tbody>
<tr>
<td>Upper Perm.</td>
<td>Nanlong Formation</td>
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<td>Lower Perm.</td>
<td>Erding Formation</td>
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<tr>
<td>Lower Perm.</td>
<td>Ercha Formation</td>
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<tr>
<td>Paleozoic</td>
<td>Paleozoic granites</td>
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</tbody>
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- **GRANITE**
- **SILTSTONE**
- **LIMESTONE**
- **CONGLOMERATE**
- **CHERT**
- **TILLITES**

### YANGTZE BLOCK

<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
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<tbody>
<tr>
<td>Middle Triassic</td>
<td>Jianlingjiang Formation</td>
</tr>
<tr>
<td>Lower Triassic</td>
<td>Daye Formation</td>
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<tr>
<td>Lower Triassic</td>
<td>Yingken Formation</td>
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<td>Lower Permian</td>
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<td>Lower Permian</td>
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<tr>
<td>Upper Carb.</td>
<td>Huanglong Formation</td>
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</tbody>
</table>

- **LIMESTONE**
- **DOLOMITIC LIMESTONE**
- **MARL**
- **BRECCIATED DOLOMITE**
- **MUDSTONE**

**FIGURE 4.5** Composite stratigraphic column of sampled formations from the Yangtze Block and Hainan Island.
### FIGURE 4.6 Composite stratigraphic column of sampled formations from the Huanan Block.
The Upper Devonian Xikuangshan Formation was sampled north of Shaoyang in Hunan Province. Only one site appeared suitable for paleomagnetic study. This formation consists mainly of limestone and shales, however, hematite-bearing sandstone is also common. A reddish limestone unit was sampled from the formation. The bedding at this site is 008/65.5.

CARBONIFEROUS

The lower-Carboniferous (C1) Gelaohe Formation is a dark argillaceous limestone with shale interbeds bearing brachiopods, rugose corals, and conodonts and may actually span from the Upper Devonian into the Carboniferous. This formation was sampled at five sites from two different quarries near Shaoyang and Dutouqiao village. The first three sites had the same bedding attitude (340/50) and came from one quarry. The dip of the last two sites was about 21° steeper (327/63.5) and these were sampled from the second quarry. Both locations were active quarries and all five sites appeared fresh.

The Upper Carboniferous (C3) Huanglong Formation was sampled at five sites outside of Hangzhou in Zhejiang Province near the village of Zhuji and is correlated with the Maping stage. It is a fusilinid limestone containing coral-brachiopod faunas. The bedding attitude was the same for all five sites (070/13). These outcrops appeared fresh but were fractured and bedding was difficult in some places because of heavy vegetation.

Four sites from the Chuanshan Formation (C3) were sampled in Fujian Province near the village of Shangcao. The Chuanshan also correlates with the Mapping Stage, which is the uppermost Carboniferous, and consists mainly of light colored, fusilinid-bearing limestones similar to the Huanglong Formation. The outcrops appeared fresh. The bedding attitudes for the four sites were somewhat similar, however, the dips varied from 12° to 49° indicating that an attitude test may be possible. The bedding was well defined.

PERMIAN

The Lower Permian Qixia Formation was sampled most extensively. In total, 13 sites were sampled - 11 from Fujian Province and two from Hunan Province. It was hoped that this large geographic coverage would provide some information on local rotations within the Huanan Block and the differing bedding attitudes would allow for an attitude test.

The Qixia Formation overlies the Chuanshan and consists of three members - a grey limestone, siliceous rocks, and a nodular limestone. At all sites the grey limestone was sampled. The formation is rich in fusilinids and brachiopods and some of the sites exhibited thin calcite veins. Bedding orientation was difficult to obtain for site three from Fujian Province due to heavy vegetation.

The Maokou Formation overlies the Qixia and was sampled on the Yangtze Block south of Hangzhou near the village of Jiande. The Maokou is a massive, grey limestone, thick-
bedded and richly fossiliferous. Fusilinids are abundant and corals and brachiopods are also present. Five sites were sampled to compare these Yangtze Permian results with the results from the Huanan Block's Qixia and Wenbinshan Formations. All outcrops appeared fresh but the bedding was the same for all five sites (010/35). The Lengjiawu Formation, equivalent to the Maokouan stage, was also sampled in this area at three sites.

The Wenbinshan Formation - equivalent to the Maokouan Stage in Fujian Province was sampled at 10 sites at two different geographic locations. This formation consists of approximately 307m of siltstone and sandstone which contains brachiopods and ammonoids. The first five sites were sampled south of Sanming near the village of Yongan. These samples were taken from a reddish brown sandstone which appeared slightly weathered. These five sites all had similar bedding attitudes and appeared slightly fractured (av. 140/50).

The next five sites were sampled near the village of Yongding and were taken from a light grey siltstone unit. All of these outcrops appeared very fresh and, again, the bedding attitude for the sites was the same. These five sites did, however, have a different attitude from the first five so that an attitude test would be possible for the formation as a whole (av. 170/64).

Six sites of the Upper Permian (P2) Cuipingshan Formation were sampled from Fujian Province on the Huanan block. The Cuipingshan is one of four lithofacies of the Longtanian Stage. It is the lowest member of the Longtanian and is made up of fine sandstone, siltstone, arkose and shale with coal seams. The dark-grey silt-stone was sampled exclusively. The first site was sampled near Jiafu, about 32km from Yongan. The remainder of the sites were sampled near Yongding further to the south. The bedding attitudes varied only slightly and mainly in the dips (293/61 to 306/80) and the outcrops appeared fresh. Upon drilling, however, reddish colored veins were seen in several samples.

The Longtan Formation itself was sampled at four sites in Hunan Province. This formation consists of siltstones, mudstones, sandstones, and thick-bedded limestones. These sediments are rich in fusilinids, ammonoids, conodonts, and fossil plants. At these four sites, the sandstone and limestone units were sampled. Site one was sampled in the thick-bedded limestone near Shaoyang at Xian cuo qiao village. The sandstone units were sampled in overturned beds just north of Liuyang village. The samples were from a recent road cut although they appeared slightly weathered. Site one had a different bedding attitude (138/32) from the other three (av. 300/44 overturned).

Near the village of Tantou in Hunan Province the Upper Permian Dalong Formation was sampled at one site with a bedding attitude of 325/38. This formation is only 32m thick in south China and is equivalent to the Changxingian Stage. The sediments are comprised of
siltstone, sandstone and mudstone with ammonoids and brachiopods common. The grey siltstone was sampled at one outcrop that appeared rather fresh.

**TRIASSIC**

The lowermost Triassic Yingken Formation was sampled in a folded section of the Baoqing quarry near Changxing in Zhejiang Province. This is about 200 meters to the west of the section which was used by Lin and others (1985, 1990) to determine a Permian-Triassic pole position for the Yangtze Block. Thirteen samples were taken across the tight fold in three beds of the light grey-brown, thin-bedded limestone (Figure 4.7).

Six sites from the Lower Triassic Daye Formation were sampled in Hunan Province. The first four sites were taken on the Huanan Block near Shaoyang. The bedding attitudes varied between the first two sites (313/23), the third site (303/34 overturned), and the fourth site (134/39).

The last two were taken north of the suture zone on the Yangtze Block near the village of Hongjiaoguan. The Daye Formation consists of medium-grey limestones and blue-grey marls with intercalated mudstone. Bivalves and ammonids are the dominant taxa. Limestones were sampled from the Huanan Block but both the limestones and the marls were sampled from the Yangtze Block. The last two sites - from the Yangtze Block - were sampled from two limbs of a large syncline in order to perform a fold test (006/47 and 109/38).

The Xikou Formation was sampled at 10 sites from Fujian Province. One of the sites were sampled across folds of about three to five meters width. Most sites were taken in quarries and appeared quite fresh, though some sites were drilled from roadcuts. This formation consists of both siltstones and muddy limestones, both of which were sampled. The sites were taken from several locations near Yongan and Qingliu and the bedding attitudes varied, which would enable an attitude test to be performed along with the fold tests.

The Middle Triassic Jianlingjiang Formation was also sampled at two sites near Hongjianguan Village on the Yangtze Block. It overlies the Daye Formation and was sampled from both limbs of the same syncline as well. It was hoped that the fold test would provide some of the first reliable paleomagnetic results for the Middle Triassic of South China. The Jianlingjiang is made up mostly of limestones, dolomitic limestone and brecciated dolomites. Bivalves, ammonoids, conodonts and foraminifera are seen in these rocks. Both sites were taken from the limestone units (350/55 and 131/38).

Due to the presence of a large unconformity, the middle Triassic as well as some of the late Triassic of the Huanan Block is largely absent. One formation - which was thought to be late Triassic and was sampled at several sites - was later identified as the lower Permian Wenbinshan Formation. No other sites from this time period were recovered from the Huanan Block.
FIGURE 4.7 The folded section located 200m west of the Meishan Permian - Triassic type section.
JURASSIC

Four sites from the Lower Jurassic Lishan Formation were recovered from Fujian Province near Yongding. This is a coal-bearing formation consisting chiefly of greyish yellow sandstone which was sampled at all four sites. Unfortunately, the outcrops appeared weathered and no fold or attitude test was possible as the sites were taken from outcrops with the same bedding attitudes (201/57).

HAINAN ISLAND

Three Permian sites were sampled in southwestern Hainan Island in Dongfang County near the village of Nanlong. The lowermost Permian Ercha Formation, which was sampled by Yang and others (1989) was also sampled at one site near Nanlong for this study (032/58). The Ercha outcrop that we sampled consisted of a light grey limestone which directly overlies the beds which Yu has described as glacial tillites. This outcrop appeared fairly fresh, although it was sampled from very near a river and the roundness of the outcrop itself suggested that the river periodically flows over it.

In addition, the lower Permian Erding Formation was sampled at one site (022/55). This formation is a cherty limestone, light grey in color with an abundance of silica veins throughout. The upper Permian Nanlong formation was also sampled at one site (025/80). This outcrop consisted of purple-red siltstone with interbedded conglomerates. Very distinctly strained reduction spots were seen in these siltstones as were numerous striations in the conglomerate beds. Neither outcrop appeared to be badly weathered.

Two granites which are widespread in the south and central parts of Hainan Island were also sampled. A fine-grained late Paleozoic granite was sampled at three sites, all within 20 km of Tongzha along the main central highway. One site from a more coarse-grained Mesozoic granite was sampled near Yalong Bay on the southern coast of the island. These sites also appeared fairly fresh.
CHAPTER V
LABORATORY METHODS

PALEOMAGNETIC METHODS AND EQUIPMENT

Samples were incrementally demagnetized using both thermal and alternating field techniques as described in Chapter II. Detailed thermal demagnetization of pilot samples was accomplished using between 13 and 18 temperature increments usually at 50°C intervals until 400°C and then 25°C intervals or smaller thereafter. The remainder of the samples were demagnetized using between eight and 13 increments. In many cases, 25°C or smaller increments were used below 400°C due to low unblocking temperatures exhibited in those samples.

In all cases of thermal demagnetization the Schonstedt Model TSD-1 Thermal Specimen Demagnetizer was used. The heating and cooling chambers have a rest field of less than 10nT and are shielded with mu metal.

Some samples which exhibited new ferromagnetic mineral growth upon heating were demagnetized using alternating fields. An A.F. tumbling demagnetizer constructed at the E.T.H. was used. The A.F. demagnetizer was shielded from the ambient earth field by Helmholtz coils. The samples were demagnetized at 5 or 10 mT intervals up to a maximum of 100 mT.

All samples were transported from the TSD-1 or the A.F. demagnetizer in a mu metal shield and were contained inside a large Helmholtz coil during the measurement process. Within the Helmhotz coil the effects of the earth's magnetic field are reduced to less than 1%.

The NRM of the samples was measured using an ScT 3-axis SQUID Magnetometer and a 2G Enterprises 3-axis SQUID magnetometer. (Goree and Fuller, 1976). Both magnetometers are interfaced with a Hewlett Packard HP-1000 computer. Three positions were normally measured for each sample, however, some samples which exhibited viscous behavior or appeared to be affected by a small field trapped in the measuring space of the 2G instrument, were measured in six positions.

ROCK MAGNETIC METHODS AND EQUIPMENT

In paleomagnetic studies it is not only important to determine the NRM of the samples but also how the NRM was acquired, how stable it is and, most important, whether or not
the direction obtained from the measurements is primary or secondary. These questions may sometimes be answered by the results of rock magnetic experiments. These experiments can provide indirect insight into the magnetic mineralogy of the rocks and thus the stability of the NRM.

As discussed in Chapter II, NRM can be acquired in a variety of different ways. This primary signal can be altered after deposition by the formation of new minerals, prolonged heating after burial, acquisition of viscous magnetization and tectonic deformation of the rocks.

**ISOTHERMAL REMANENT MAGNETIZATION**

Isothermal Remanent Magnetization (IRM) acquisition curves were generated for several representative samples from each formation. The shape of the curve and the value of the saturation field may be used as a diagnostic tool in determining the sample's coercivity spectrum and thus, also the magnetic mineralogy. Magnetite, for example, becomes saturated when exposed to relatively low field strengths, usually on the order of 0.01 to 0.1 Tesla (T). Hematite and goethite, on the other hand, remain unsaturated even at a field strength of 1.0 T - the highest normally available in the laboratory.

A combination of high and low coercivity minerals in one sample may sometimes lead to IRM results which are difficult to interpret. By the same token complications may also arise due to the fact that the coercivity of a mineral is strongly influenced by grain size. Various grain sizes of the same mineral within a sample - especially in the case of hematite - will cause the coercivity to vary within a certain range as well.

All of the samples for which normal IRM acquisition curves were generated were exposed to incrementally increasing D.C. magnetic fields up to 1.0 T in an Oxford Instruments electromagnet. The field generated between the pole tips of the magnet was measured with a standard Hall Probe.

The samples were oriented so that they could be magnetized along the same axis in the same direction each time. The IRM was measured on the 2G magnetometer in three positions, as well as on the Molspin flux-gate magnetometer for stronger samples (Molyneux, 1972). After exposure to the 1.0 T field the samples were thermally demagnetized to determine the blocking temperature spectrum.

**LOW TEMPERATURE TRANSITION EXPERIMENTS**

The decay of IRM acquired at liquid nitrogen temperature (-196°C) as the temperature of the sample increases, is another useful guide to determining the presence and domain state of magnetite and hematite, as well as the presence of superparamagnetic grain sizes (Nagata et al., 1964, Mauritsch and Turner, 1975).
Hematite and multi-domain magnetite both have low temperature transitions associated with changes that take place in the crystal lattice structure at these temperatures. For hematite, the transition occurs at about \(-20^\circ\text{C}\) and for multi-domain magnetite, about \(-150^\circ\text{C}\). These transitions manifest themselves as abrupt decreases in remanence intensity and indicate the presence of the minerals in the multi-domain state.

Due to the presence of lattice defects and impurities the transitions are not always seen. The absence of the transition is, therefore, not considered proof that the mineral is not present, however, the presence of the transition is clearly diagnostic.

The smooth decay of intensity upon warming is often observed and can, in most cases, be attributed to the unblocking of superparamagnetic grains. At liquid nitrogen temperature these grains become aligned to the field and also acquire an IRM. As the sample warms, thermal agitation acts to randomize the magnetic moments of these grains, reducing their contribution to the measurable intensity.

Samples for low temperature experiments were given an IRM with the Oxford Instruments electromagnet at 1.0T. The intensity was measured in the ScT magnetometer and monitored under computer control. Time vs. temperature curves were constructed using a thermocouple to determine the rate of warming of the samples. The computer was then programmed to measure the intensity at time intervals which were correlated to temperatures.

**BULK SUSCEPTIBILITY MEASUREMENTS**

Monitoring of the bulk susceptibility changes during thermal demagnetization can be used as a diagnostic tool for determining the formation of new ferromagnetic minerals (Jelinek, 1977). An increase in bulk susceptibility upon heating is indicative of formation of ferromagnetic minerals in the oven, either through oxidation or dehydration. These new minerals may acquire a remanence when passing from the heating to the cooling chamber of the Schonstedt furnace where a relatively large field (approximately 200 nT) exists due to the termination of some of the mu metal layers. This remanence may greatly increase the sample's intensity and can often mask the characteristic remanence (ChRM) when enough new minerals are formed and makes the isolation of the ChRM impossible above these temperatures.

For pilot samples the bulk susceptibility was monitored after most heating steps. A KLY-1 magnetic susceptibility bridge interfaced with the HP-1000 was used for these measurements. This instrument has a sensitivity level of \(4 \times 10^{-8}\) S.I. units.

**CURIE POINT MEASUREMENTS**

One of the most diagnostic features of any magnetic mineral is its Curie temperature (\(T_C\)) [or, for hematite, the Neel temperature (\(T_N\))]. This is the temperature where spontaneous
magnetization occurs and below this temperature a remanent magnetization may become blocked in the mineral. The temperatures given in Table 2.1 are for the pure end-members of the solid solution series, however, the presence of other elements may also affect the Curie temperature. The Curie temperature of magnetite, for example, is greatly affected by the titanium content which acts to lower $T_c$.

An important concept in the measurement of the Curie temperature is reversibility of the $M_S$ vs. $T$ curve measured in a strong applied field. If new magnetic minerals are formed during heating, the curve of the plot of temperature vs. intensity will not be the same upon cooling as it was during heating. These new minerals may have a different $T_c$ from the original mineral making the $T_c$ of the original difficult to determine.

Curie point measurements for samples from the Changxing Permian-Triassic section as well as selected samples from other sites were measured using a horizontal balance designed and built in the ETH paleomagnetic laboratory (Lebel, 1985). Whole rock samples were crushed to a fine powder and between 0.15 and 0.20g were measured. The powder was measured in a field of 0.25T and to temperatures of 700°C. The heating and cooling rate was 18 °C/min.

**VISCOUS REMANENT MAGNETIZATION EXPERIMENTS**

The acquisition of viscous magnetization was measured for four samples from the Changxing Permian-Triassic section - two before thermal demagnetization and two after. As discussed in Chapter II, a VRM acquired in unstable magnetic minerals by extended exposure to weak magnetic fields may often mask primary directions of remanence associated with deposition. Any VRM present in the rock has usually been acquired since the last reversal of the earth's magnetic field some 730,000 years ago and is therefore likely to be aligned to the calculated theoretical axial dipole field for that period. Sometimes a VRM may be acquired in the laboratory during storage before measurement of the samples.

The predisposition of a sample to acquiring a VRM may be examined in the laboratory by measuring the change in intensity of a sample during long term (usually on the order or many hours or days) exposure to a relatively weak magnetic field (Rimbert, 1959; Dunlop, 1983). With the results of these experiments it is not always possible to make a qualitative interpretation. The plot of intensity vs. time, however, can give a good indication of a sample's viscous behavior.

For these experiments, a field of 40μT was set up along one axis of the ScT cryogenic magnetometer. The sample was then introduced into the measuring space of the magnetometer and the intensity was monitored under computer control at logarithmic intervals over a time of 10 to 12 hours. The results were plotted in the form of intensity vs. time.
ANISOTROPY OF MAGNETIC SUSCEPTIBILITY MEASUREMENTS

It is possible that during the deformation of a sedimentary layer a physical distortion - such as flattening or elongation - of the magnetic minerals will occur which will give rise to a magnetic fabric and consequently have a deflecting effect on the NRM of the sample. The anisotropy of magnetic susceptibility (AMS) in a rock can be represented by a triaxial ellipsoid with minimum ($k_{\text{min}}$), intermediate ($k_{\text{int}}$), and maximum ($k_{\text{max}}$) principal axes (Bathai, 1971; Lowrie and Hirt, 1987).

To measure this effect, the sample is placed in a magnetic field and is rotated through 360°. If a magnetic fabric is present in the sample then as the sample is rotated, the alignment of the fabric will, at a certain angle, come into alignment with the field creating a maximum intensity. The measurements are made in the three orthogonal directions so that the orientation of the fabric may be obtained and an ellipsoid of the principal axes may be calculated (Hrouda, 1976).

Many studies have shown that there is a good, qualitative correlation between the axial directions of the anisotropy and the fabric of the rock (Graham, 1966; Hrouda, 1982; Kligfeld et al., 1981). The amount of effect this magnetic fabric has on the NRM direction may be negligible or may be large. If an expected NRM direction is known, this can be compared with the actual NRM and the fabric direction to determine the fabric's effect. If no expected direction is known, the estimates of the effect of the fabric on the NRM is somewhat subjective.

The effect of paramagnetic minerals in the sample must also be considered. Paramagnetic minerals present in the samples may be more easily aligned with the fabric if they are in clay layers. When samples containing paramagnetic minerals are measured, the contribution of these minerals may cause the axes of the susceptibility ellipsoid to display a magnetic fabric. This fabric, which is a result of the paramagnetic contribution, may not accurately represent the magnetic fabric present in the remanence carrying minerals.

STATISTICAL ANALYSIS AND PRESENTATION OF DATA

The intensity of a sample is measured in the cryogenic magnetometer in each of the orthogonal directions (x,y,z) and a vector endpoint in three-dimensional space is defined by the measured intensities. From repetition in three or six positions, the dispersion can be expressed by the angular standard deviation, psi. The NRM directions may be plotted on a stereonet or, more commonly, a Zijderveld diagram (Zijderveld, 1967; Dunlop, 1979). Zijderveld diagrams project each vector endpoint in three-dimensional space to a horizontal and vertical plane which is then "unfolded" into a two-dimensional projection of horizontal (H) and a vertical (V) components.
Linear, high temperature segments of the Zijderveld diagrams usually represent the demagnetization of a single NRM component. In most cases the highest temperature, linear segments are taken as the ChRM for the sample. Curved sections represent the demagnetization of two or more components with overlapping blocking temperature or coercivity spectra (Collinson, 1983).

The directions associated with the linear segments, which were defined from visual inspection, were calculated using the least squares linear regression analysis (Kirschvink, 1980). These stable component directions were then plotted on an equal area stereonet and a mean direction before and after correction for bedding attitude was calculated using Fisher statistics (Fisher, 1953). Fisher's precision parameter, k, was also calculated and is a measure of the randomness of the distribution of the vector points on a sphere. k is zero if all vector points are uniformly distributed on the sphere and infinity if they are all identical to the mean. This is analogous to the invariance in a Gaussian distribution and may be estimated using the formula:

(Eq. 5.1) \[ k = \frac{N-1}{N-R} \]

where:
N = the total number of observations
R = the resultant vector or vector sum

The 0.05 value is also given for the mean and has been calculated based on the methods of Watson (1956) and Irving (1964). This value represents the radius of a circle of confidence about the mean. There is a 95% probability that the true mean lies within this circle of confidence.

The corrected inclinations were used to calculate a paleolatitude for a particular time period according to equation 2.3. These paleolatitudes are representative of the latitudes of the sites for which they were calculated and may be corrected to a common reference for comparison.
CHAPTER VI
RESULTS AND INTERPRETATIONS

THE YANGTZE BLOCK

While most of the sampling was concentrated on the Huanan Block, several sites were sampled north of the suture zone on the Yangtze Block. The lower Permian Maokou and Lengjiawu Formations, the early Triassic Daye Formation and the middle Triassic Jianlingjiang Formation were all sampled in order to help clarify the position of the Yangtze Block during this critical time interval. The latter two formations were sampled from two limbs of a large syncline in the hope that a fold test could provide valuable data which is sparse for this block during the Triassic.

In addition, the Changxing Permian-Triassic section, used by Lin and others (1985) to determine a pole for this time, was reexamined. Samples from the earliest Triassic were taken along a fold located approximately 200m to the west of the type section used in the original study. These samples were examined using both paleomagnetic and rock magnetic methods in order to determine the validity of the pole position and paleolatitude derived from this site.

PALEOMAGNETIC AND ROCK MAGNETIC RESULTS

The Lower Permian Maokou Formation

The mean NRM intensities of the Maokou samples (Figures 4.1 & 4.5) vary by two orders of magnitude and group about a geometric mean of $5.17 \times 10^{-4}$ A/m. The NRM directions for the formation lie near the Brunhes dipole field and very little scatter is seen, with an $\alpha_95$ of only $5.2^\circ$ (Figure 6.1).

Nearly all of the samples behave similarly during thermal demagnetization and two-components of magnetization are seen in many of the Zijderveld diagrams. The specimens are demagnetized by 350$^\circ$C to 500$^\circ$C with the ChRM being isolated between 100$^\circ$C and 500$^\circ$C. The directions of the two components are very similar and may represent remanence acquired by authigenic growth of new minerals or viscous remagnetization during the Brunhes. In a few cases, however, where a distinctly different component is seen it is usually removed by 100$^\circ$C. This component is not a present field overprint and may be a VRM acquired during storage of the samples before measuring.
FIGURE 6.1 The Maokou Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
For all samples a high temperature ChRM was isolated and analyzed and these directions were plotted on an equal area projection both before and after correction for bedding attitude. The in situ mean for the formation is similar to the NRM mean and appears to be a Brunhes direction. There is very little scatter and the $\alpha_{95}$ is only 3.5°. The tectonically corrected mean exhibits slightly more scatter among individual samples (Figure 6.2). The larger $\alpha_{95}$ after correction indicates that the samples may have been magnetized after the folding event, although the actual attitude test is indeterminate due to the similar bedding orientations for the five sites.

Bulk susceptibility was monitored during heating and in most samples a moderate increase was seen above 350°C. The heating process apparently is producing new magnetic minerals either through oxidation of iron-bearing minerals, dehydration of goethite or conversion of paramagnetic clay minerals. Since no large drop in remanence intensity is seen by 150°C during the demagnetization process, it is likely that goethite - whose Curie temperature is about 120°C (Hedley, 1968) - is not present in significant amounts in the samples. The oxidation of iron sulfides, which may be present in these samples, to magnetite is another possible cause of the increase in susceptibility. An increase in NRM intensity during thermal demagnetization in zero field is not seen above 350°C, however, indicating that the formation of new ferromagnetic minerals is not affecting the ChRM of the samples.

IRM acquisition curves show that the remanent magnetization is dominated by low coercivity minerals and saturation is reached by about 0.3 to 0.4 T. These values are not typical for magnetite and even exceed the theoretically largest possible coercivities ($H_{c,max.} = 0.3$ T) of extremely elongated single-domain magnetite particles. The presence of pyrrhotite, however, could cause the effect of increasing the overall coercivity of the samples. This would be consistent with the bulk susceptibility data - the increase in those values being due to the oxidation of iron sulfides. The higher unblocking temperatures for these samples - exceeding the Curie temperatures of iron sulfides ($T_{c,max.} = 325°C$) - would point to, however, the presence of some amounts of magnetite or maghemite as well. It is unlikely that the samples contain significant amounts of hematite or goethite since no contribution from high coercivity minerals is seen in the curves.

Thermal demagnetization of the IRM shows a steady decrease until temperatures between 450°C and 500°C. This temperature range is too high to represent only pyrrhotite and indicates again, that magnetite or maghemite may be present in significant amounts. If these minerals are present they must contain a significant amount of impurities such as titanium or they must be present in fine grain sizes in order to lower the blocking temperatures.

The tectonically corrected mean direction for the formation gives a Permian paleolatitude for this block of 50.4° - though it is difficult to determine if this is a north or a south latitude since the tectonically corrected declination, if primary, would be rotated approximately 90°.
FIGURE 6.2 The Maokou Formation (a) Equal area projections of ChRM directions (b) IRM acquisition and demagnetization.
In either case, this paleolatitude is not in agreement with other paleomagnetic results - which place the Yangtze Block at shallow latitudes - or with either of the two geological theories. It is likely that this formation preserves a recent remagnetization acquired during the Brunhes.

The Lengjiawu Formation

Twenty two samples form three sites from this formation were thermally demagnetized (Figures 4.1 & 4.5). The NRM intensities of these samples are almost an order of magnitude higher than the Maokou Formation with a geometric mean of $2.77 \times 10^{-3}$ A/m. The NRM directions when plotted on an equal area projection revealed that all of the samples preserved a normal direction of remanence with a mean direction corresponding to the Brunhes dipole field (Figure 6.3).

The Lengjiawu Formation is correlated with the Maokouan stage and the behavior during thermal demagnetization was very similar for both formations. The ChRM directions were, again isolated between 200°C and 500°C (Figure 6.4). As with the Maokou Formation, the in situ formation mean corresponds to the Brunhes dipole and very little scatter is seen. Upon correcting for bedding attitude the directions are considerably more scattered indicating that the ChRM was acquired after tectonic deformation which occurred during the middle to late Mesozoic. These data indicate that this formation, like the Maokou, preserves a recent overprint acquired during the Brunhes.

The Lower Triassic of Changxing

The NRM intensities for the samples from Changxing (Figures 4.1 & 4.5) showed a bimodal distribution with a mean intensity of $9.47 \times 10^{-4}$ A/m. The NRM directions coincide with the present earth's field and very little scatter is seen (Figure 6.5).

The demagnetization of pilot samples using both thermal and alternating field techniques revealed thermal treatment to be most effective in resolving individual components of ChRM. Attempts to incrementally demagnetize the samples using alternating field methods with a maximum field of 90 mT were ineffective, even after heating to 150°C to remove the contribution of goethite from the samples. The samples must contain a high coercivity component other than goethite that is not resolved at fields up to 90 mT. This mineral is likely hematite. There was, however, slight unblocking seen during A.F. treatment indicating that a low coercivity mineral may contribute a small amount to the NRM of these samples (Figure 6.5).

The monitoring of bulk susceptibility during thermal demagnetization showed no increase at temperatures up to 400°C. Up to this temperature no increase NRM in intensity was seen either, indicating that no significant formation of magnetic minerals during the heating
FIGURE 6.3  The Lenjiawu Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Equal area projection of ChRM directions.
FIGURE 6.4  Representative Zijderveld diagrams for the Lengjiawu Formation.
FIGURE 6.5  The Changxing section (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative A.F. Zijderveld diagrams.
process was taking place. Above this temperature the susceptibility does increase significantly.

Upon thermal demagnetization, stable ChRM components were resolved for nine of the 13 samples (Figure 6.6). In all samples a very large portion (up to 90%) of the remanent intensity was lost by 100°C. This phenomenon is likely due to the contribution of goethite - whose Curie temperature is about 120°C - to the remanence. In the nine samples with stable, high temperature components, most displayed stable decay towards the origin which persisted to temperatures between 400°C and 525°C. At higher temperatures an increase in intensity is often seen and the demagnetization behavior becomes very unstable resulting in large psi values.

Several rock magnetic experiments were performed on these samples in order to determine which mineral phase is carrying the ChRM component. IRM acquisition curves show that the samples are not saturated at the maximum available field strength of 1.0 T. The fairly constant slope of the curve and the fact that the samples do not reach saturation, indicates the dominance of high coercivity minerals with little indication of low coercivity minerals being present (Figure 6.7). These data suggest the presence of goethite, hematite, or both in the samples.

Thermal demagnetization of the IRM reveals a large decrease at 125°C due to the contribution of goethite to the remanence. Upon further demagnetization measurable intensity persists to at least 630°C indicating the presence of hematite in the samples. A large decrease to 300°C is also seen and may be due to the contribution of pyrrhotite in significant amounts.

The results of the viscous magnetization experiments show an intensity increase of between $1 \times 10^{-4}$ A/m and $4 \times 10^{-4}$ A/m over the 10 to 12 h duration of the experiment (Figure 6.8). Changes in the slope of the acquisition curves are seen and these changes, or kinks, have been documented in other studies (e.g. Markert et al., 1976; Lowrie and Kent, 1976). These kinks are usually attributed to the presence of multi-domain magnetic grains with two or more superposed, discreet relaxation times (Markert et al., 1976; Lowrie and Kent, 1978). These changes in the slopes make extrapolation of the VM acquisition curves through the Brunhes tenuous.

It has been suggested by Markert and others (1976) that the gradient of the slope before the kink point be used for extrapolation purposes. The logic for this decision, however, was based on the fact that the kinks were seen in experiments conducted in fields significantly higher than the earth's magnetic field. The experiments in this study show that the kinks are present in these samples even during VM experiments in low fields.

Extrapolation of the slopes before the kink point - as suggested by Markert and others - reveals that a VRM between $2.8 \times 10^{-4}$ and $7.0 \times 10^{-4}$ A/m could have been acquired by these samples during the Brunhes. This is, in all samples, a significant portion of the NRM.
FIGURE 6.6 The Changxing section (a) Equal area projections of ChRM directions. (b) Representative thermal Zijderveld diagrams after heating to 100°C.
FIGURE 6.7 IRM acquisition and demagnetization from the Changxing section. The demagnetization curves represent the demagnetization of sample M05 with and without the initial 125°C demagnetization step.
FIGURE 6.8 Viscous magnetization acquisition curves for samples (a) M05A (b) M05B (c) M12A (d) M12B from the Changxing section. The "A" samples were thermally demagnetized before the experiments and the "B" samples were not. The experiments were conducted in a field of 0.4 Oe.
indicating that the NRM of these samples may well be a viscous remanence acquired during the Brunhes. The extrapolation, however, makes the assumption that the induced magnetization is constant during the experiment and is not affected by the magnetic after effect. Since the slope of the curves after the kinks are greater in all cases, the use of either slope, or an average of both, for the extrapolation would result in a VRM which is either a significant portion of the NRM of the samples or greater than the NRM.

Interestingly, the VM acquisition curve of sample M12A - a sample heated to over 600°C - shows little evidence of the kinks seen in the other curves. It has been shown previously that goethite is present in these samples and the heating of M12A would have destroyed the goethite. In the unheated sister sample, M12B, the kinks are clearly present. It is possible then, that the kinks seen in the curve from this sample are a result of the presence of goethite and another magnetic mineral whose discreet relaxation times are superposed. Heating the sample destroyed the goethite and eliminated the kinks.

If a VRM has been acquired by fine grained hematite it may be fairly resistant to thermal demagnetization if the VRM was acquired over long periods of time. A VRM residing in hematite which was acquired over the 730,000 years since the last reversal of the earth's magnetic field, could persist to temperatures of 375°C (Dunlop and Sterling, 1977). Since many of the samples are completely demagnetized by 350°C to 400°C the primary component of remanence may be masked by this process.

The warming of samples from liquid nitrogen temperatures after the application of a 1.0 T field showed no indication of the sharp drop in intensity associated with the crystallographic inversion of multi-domain magnetite (Figure 6.9). While this multi-domain magnetite transition is not seen, a gradual decrease in intensity upon warming may be an indication of the presence of superparamagnetic grain sizes, though the composition of these grains cannot be determined from these data.

In some low temperature studies of sediment samples, this type of gradual decrease in magnetic intensity is seen upon warming from liquid nitrogen temperatures after exposure to a strong magnetic field (usually on the order of 1.0 T). This behavior is normally attributed to the unblocking of superparamagnetic grains which had acquired a remanent magnetization at low temperatures during exposure to the field. Upon warming, the contribution of these superparamagnetic to the magnetic intensity is lost.

During this experiment, however, the samples were reintroduced into the liquid nitrogen and the intensity upon warming was again measured but without reexposure to the strong field. In the case of two samples which appear to contain a significant amount of goethite, the intensity increased as if it had been introduced into the field and, again, decreased during warming. This behavior may be tentatively attributed to an increase in spontaneous magnetization of goethite at low temperatures due to the reduction of magnetocrystalline anisotropy at these temperatures and not the unblocking of superparamagnetic grains.
FIGURE 6.9  Graph of change in magnetic intensity upon warming from liquid nitrogen temperature for samples from the Changxing section.
Equal area projections of the stable components of remanence show that the in situ direction for the nine samples coincides closely with the present day axial dipole direction expected for this site (Figure 6.6). Using the $k$ values obtained before and after tectonic correction the section was found to fail the fold test ($k_{bef.} \gg k_{after}$). These data indicates that the section has been remagnetized during the Brunhes and no longer preserves a measureable primary direction associated with deposition during the early Triassic.

The Early Triassic Daye Formation

This formation was sampled at two sites on the opposite limbs of a large northeast-southwest trending syncline just to the north of the suture zone on the Yangtze Block (Figures 4.3 & 4.5). The NRM intensities varied little and had a mean intensity of $7.45 \times 10^{-4}$ A/m (Figure 6.10). The NRM directions are all normal polarity with only one exception but do not appear to be representative of a recent overprint.

The samples from the southeast limb (site one) were taken from a grey marl unit and had higher blocking temperatures than the samples from the limestone unit of the northwest limb (site two). The samples from site one also exhibited a more stable - usually two-component - decay to the origin at temperatures between 400°C and 500°C. A large decrease in intensity at 100°C is seen in most samples from site two, indicating the presence of goethite. These samples had low blocking temperatures on the order of 350°C. Some samples from site two, however, had a high blocking temperature component that was removed at about 650°C.

Bulk susceptibility monitored during thermal demagnetization, reveals a large increase above 500°C. This behavior is probably due to the conversion of paramagnetic clay minerals to magnetite or hematite.

The carriers of remanence in these samples appear to vary even within samples from the same site, as seen in the IRM acquisition curves (Figure 6.11). Some samples are dominated by a low coercivity component which reaches saturation by about 0.1 T, while high coercivity components clearly contribute significantly to others. Thermal demagnetization of the IRM confirms the different magnetic mineralogy even within the same site. The high coercivity samples appear to contain goethite which accounts for the marked decrease in intensity at 125°C. The low coercivity dominated samples have unblocking temperatures between 525°C and 575°C indicating the presence of magnetite. No remanence remains above 575°C in the samples and hematite, therefore, is probably not present.

Equal area projections of the ChRM directions show that the sites do indeed pass a fold test at the 99% confidence level and both normal and reversed polarities are seen. The mean direction is, however, not the expected early Triassic direction for the Yangtze Block based on previous results (Lin et al., 1989; Opdyke et al., 1986). The pole position for these sites
The Daye Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.11 The Daye Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
is 205°E and 32°N, which is in close agreement with early Triassic results obtained from two of the four formations studied by Steiner and others (1989). Their results are, however, displaced from the APWP for the Yangtze Block and are thought to be rotated approximately 15° clockwise. The sense of this rotation is supported by structural data but the amount of rotation can only be postulated from the paleomagnetic evidence (Steiner et al., 1989).

The ChRM, which was isolated well above the blocking temperature for goethite, is probably carried by magnetite. Considering the agreement with the results of Steiner and others (1989) and the fact that these sites pass a fold test, it appears that these sediments preserve a primary magnetization acquired during the early Triassic but the sites have been subsequently rotated. This formation was also sampled on the Huanan Block and those results will be presented and discussed in the next section.

The Middle Triassic Jianlingjiang Formation

The middle Triassic Jianlingjiang Formation, which directly overlies the Daye, was also sampled at two sites from the same syncline (Figures 4.3 & 4.5). The NRM intensities closely grouped around a geometric mean of \(1.07 \times 10^{-3} \text{ A/m}\) (Figure 6.12). The NRM directions were fairly scattered, as seen in the rather large α95 value and most of the directions do not appear to be related to the Brunhes field.

Samples from both sites were demagnetized using thermal and A.F. treatments which were equally effective at resolving a ChRM (Figure 6.12). Moderately low blocking temperatures - between 400°C and 525°C - are seen in almost all of the samples (Figure 6.12). The effectiveness of A.F. treatments indicates that many of the samples are dominated by low coercivity minerals. Bulk susceptibility, monitored during thermal demagnetization, showed a slight increase at 450°C but NRM properties were not influenced by this change.

IRM acquisition curves also indicate that the remanence is dominated by low coercivity minerals without contribution from minerals with high coercivities (Figure 6.13). The samples are saturated by 0.2 T which is slightly high for magnetite but may indicate the presence of pyrrhotite. Unblocking temperatures of above 500°C are seen in the thermal demagnetization of IRM. This evidence shows that the ChRM directions are probably carried by magnetite, however, a change in slope between 300°C and 325°C may result from the presence of pyrrhotite in the samples.

As seen in the equal area projections of the ChRM directions, this formation also passes the fold test at the 99% confidence level (Figure 6.13). The paleopole position calculated for these sites is 196°E and 36°N, similar to the Daye formation in the previous section. It appears again, that the sites have been rotated in the same sense and by a similar amount as the Daye and the Steiner and others (1989) results. The rotation is again in the clockwise sense.
FIGURE 6.12 The Jianlingjiang Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.13 The Jianlingjiang Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
THE HUANAN BLOCK

Since no paleomagnetic data exists for the Huanan Block, most of the sampling for this study was concentrated there. The intention was to compare these results with the results which are already available for the Yangtze Block and come to some conclusions about the relationship of the two blocks during the mid-Paleozoic and on through the early Mesozoic. Many of the sediments sampled during the two campaigns were not suited to this purpose, mostly due to widespread remagnetization problems, the cause of which is still not clear. However, some useful paleomagnetic and rock magnetic data was, however, obtained and the following is a detailed presentation of these results.

PALEOMAGNETIC AND ROCK MAGNETIC RESULTS

Devonian

Three Devonian formations were sampled at six sites from Hunan province (Figures 4.3 & 4.6). The middle Devonian Taomajian Formation was sampled near the Banshan Reservoir and the NRM intensities are distributed with a geometric mean of $1.74 \times 10^{-3}$ A/m (Figure 6.14). The NRM directions group around the present field and some scatter is seen. This present field direction is also seen in the NRM of the Qizhiqiao Formation ($D_2$) with less scatter. The NRM intensities for this formation are tightly grouped about a mean of $5.61 \times 10^{-4}$ A/m.

The NRM directions from the upper Devonian Xikuangshan Formation are widely scattered and the $\alpha_{95}$ did not encompass the present field direction. This scatter may be related to a viscous contribution acquired during storage before measurement, during which time the samples were reandomly oriented. The mean intensity for 13 samples from this formation is $1.67 \times 10^{-3}$ A/m.

Most samples exhibit decay to the origin with measurable intensity persisting to temperatures well above $600^\circ$C - due to the presence of hematite in significant amounts. A few samples from the Qizhiao Formation, however, lost their intensity at around $575^\circ$C indicating the possible presence of magnetite in these samples. (Figure 6.15). For all samples a stable, high-temperature ChRM was well defined.

Again, monitoring of bulk susceptibility during thermal demagnetization shows an increase in samples from the Taomajian and Xikuangshan Formations upon heating. The Qizhiao Formation, however, shows a slight decrease in some cases.

IRM acquisition curves are dominated in most cases by high coercivity minerals but in the case of the Qizhiao Formation, low coercivity minerals contribute a significant amount (Figure 6.16). Thermal demagnetization of the IRM reveals unblocking temperatures above $600^\circ$C, which is due to the presence of hematite. Goethite also appears to be present in some
FIGURE 6.14 Histogram of NRM intensities and equal area projections of NRM directions for the three Devonian formations.
FIGURE 6.15 Representative Zijderveld diagrams for the three Devonian formations. HT = Taomajian Formation, HD = Xikuangshan Formation, and HQ = Qizhiao Formation.
FIGURE 6.16 IRM acquisition and demagnetization for the three Devonian formations.
samples as evidenced by a large drop in intensity at 125°C. The ChRM then, appears to reside in this hematite component and is stable and well defined above temperatures of 125°C.

Equal area plots of the ChRMs indicate that the two middle Devonian formations are probably remagnetized during the Brunhes as the in situ mean corresponds to that direction (Figure 6.17). The precision parameter (k) decreases after application of a tectonic correction - though only slightly - indicating that the remanence may have been acquired after tectonic deformation, which is consistent with a Brunhes remagnetization.

The Xikuangshan Formation, however, is not influenced by the Brunhes field and the site passes an attitude test at the 66% confidence level. The tectonically corrected mean places this site at 27° northern latitude during the upper Devonian if the least amount of rotation is assumed.

The Lower Carboniferous Gelaohe Formation

The lower Carboniferous Gelaohe Formation (Figures 4.3 & 4.6) had NRM intensities of $1 \times 10^{-4}$ A/m to $9 \times 10^{-3}$ A/m with a geometric mean of $6.28 \times 10^{-4}$ A/m. The NRM directions are scattered throughout the northern lower hemisphere, apparently influenced by the Brunhes dipole field (Figure 6.18).

In nearly all of the samples the ChRM is isolated at temperatures of 350°C to 500°C and multi-vectorial decay of NRM is seen in all samples. The low temperature component seen in the Zijderveld vector diagrams is either a present field overprint, a reversed component of this recent overprint (Figure 6.18c), or a spurious direction, probably resulting from a VRM acquired during storage.

Bulk susceptibility was measured in some pilot samples during thermal demagnetization and, in most cases, no appreciable increase was seen at temperatures below 400°C to 500°C. Above these temperatures, an increase in bulk susceptibility is seen and indicates the formation of new ferromagnetic minerals during the heating process. This is reflected in an intensity increase seen in a few samples at higher temperatures during thermal demagnetization and, in those samples, the NRM directions are affected.

The acquisition of IRM - at room temperature - indicates that low coercivity minerals are present in these samples with little or no influence from high coercivity minerals (Figure 6.19). The samples became saturated at fields of about 0.2 T to 0.4 T, which is probably too high to be the result of the presence of only magnetite. These values are more consistent with pyrrhotite, however, thermal demagnetization of the IRM implies that both minerals may be present in some of these samples. This being the case, the ChRM directions isolated at temperatures above 300°C would be carried by magnetite.
FIGURE 6.17 Equal area projections of the ChRM directions for the three Devonian formations.
FIGURE 6.18 The Gelaohe Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Bulk susceptibility curves. (d) representative Zijderveld diagrams.
FIGURE 6.19 IRM acquisition and demagnetization curves for the Gelaohe Formation.
ChRM components were isolated for 48 samples from this formation and an attitude test proved indeterminate - although a better grouping of the directions occurs after tectonic correction. The in situ sample directions are dispersed and do not appear to carry a recent overprint. At the site level, the samples break into two distinct populations. The five sites from this formation come from two geographic locations separated by about 12 km. A separate analysis of these two locations was made since it appears from the equal area plot of all samples from the formation that the two sites preserve different mean directions. It may be possible that one of the locations has been remagnetized while the other may preserve a primary magnetization.

The first group of samples have negative inclinations and northerly declinations after correction for bedding attitude (Figure 6.20). This population may preserve a primary, lower Carboniferous direction acquired in the southern hemisphere at approximately 90°S latitude.

The second population has a mean declination of 22.5° and a mean inclination of 42.8° after tectonic correction. This corrected mean direction yields a paleopole which is coincident with the middle to late Jurassic of the Yangtze Block indicating that this site was probably remagnetized at that time. The fact that the sites pass an attitude test is consistent with geologic evidence that folding took place as late as Cretaceous in many parts of south China. This implies that the secondary overprint was acquired before folding of the beds. This Jurassic overprint has important implications for remagnetization in south China and its significance will be discussed in the next chapter.

**The Upper Carboniferous Huanglong Formation**

Twentyfour samples from the Huanglong Formation (Figures 4.1 & 4.6) were thermally demagnetized and high temperature ChRM directions were resolved in 11 of the samples. The remainder exhibited unstable behavior during demagnetization and no ChRM could be isolated. The NRM intensities showed a bimodal distribution with a geometric mean of $9.31 \times 10^{-5}$ which is quite low (Figure 6.21). The bimodal distribution, however, appears to have no relation to the stability of the samples or to the different sites sampled.

The NRM directions plotted on an equal area projection group around a mean direction near the Brunhes dipole field. The mean inclination, however, is slightly higher than the 45° which would be expected for this site based on theoretical calculations of the dipole field. Some scatter is seen in the data with an $\sigma_{95}$ of 7.5°.

Only one, or in some cases two components of magnetization are seen in the Zijderveld plots. Most samples lose a large amount of their measurable remanence by 400°C to 500°C but in many cases some of the intensity remains above these temperatures. However, above these temperatures a remanence increase makes it impossible to isolate any higher temperature component. This behavior is reflected in the bulk susceptibility measurements
FIGURE 6.20 Equal area projections of the ChRM directions from the Gelaohe Formation.
The Huanglong Formation (a) Histogram of NRM intensities (b) Equal area projections of NRM directions (c) Bulk susceptibility curve (d) representative Zijderveld diagrams.
which show an increase above 300°C. Apparently new ferromagnetic minerals are forming during the heating process in significant amounts and are acquiring a remanence either in the cooling chamber or when they are brought out for measurement. Alternating field demagnetization was ineffective at isolating a ChRM even after heating to 150°C, indicating that both goethite and hematite may be present in the samples, though the blocking temperatures appear quite low for hematite.

Isothermal remanent acquisition curves indicate that the remanence is dominated by high coercivity minerals with only a small contribution from minerals with low coercivity (Figure 6.22). Saturation is not reached by 1.0 T and a nearly linear increase in intensity is seen in the curves. Thermal demagnetization of the IRM shows that measurable intensity persists above 600°C. It is likely that the ChRM isolated in these samples is carried by hematite with unusually low blocking temperatures.

Equal area projections of the ChRM components yield a mean in situ direction near the present earth field (Figure 6.22). The α95 is small indicating little scatter in the data points and it does not encompass the Brunhes direction. No reversely magnetized samples are seen in this plot. Upon application of tectonic correction the mean direction moves to nearly the same direction that was seen in the Gelaohe Formation and yields a similar pole position. Two scenarios for the ChRM directions are then possible; the first being that the samples have been overprinted during the Brunhes and no longer preserve a primary direction. This would explain the coincidence of the in situ direction with the Brunhes direction. The second possibility is that these samples have been remagnetized during the middle to late Jurassic and preserve an overprint acquired during this time. Since this direction is revealed after application of the tectonic correction, it would have been acquired before folding as was already seen in the Gelaohe Formation. From the data at hand, it is not possible to determine which is the more likely origin of the ChRM. Both scenarios, however, exclude the possibility of identifying a primary, middle Carboniferous component.

**The Upper Carboniferous Chuanshan Formation**

Many samples from the upper Carboniferous Chuanshan Formation (Figures 4.2 & 4.6) had relatively low NRM intensities on the order of 10^-5 A/m, however, the distribution of intensities was bimodal with other sites exhibiting significantly higher NRM intensities. Again, the bimodal distribution was not related to stability during demagnetization but was related to the site locations. Samples from sites five through eight exhibited the highest intensities.

The NRM directions group around the present field - which has an inclination of about 45° in this region (Figure 6.23). This inclination is, however, a bit too shallow to represent a Brunhes dipole direction. Several samples deviate significantly from the mean and this may
FIGURE 6.22 The Huanglong Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
FIGURE 6.23 The Chuanshan Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
be an indication that they have acquired a VRM during storage before measuring while they were randomly oriented.

The Zijderveld demagnetization diagrams reveal multi-vectorial demagnetization of all samples. An initial component is removed by 100°C and is probably a laboratory VRM carried by goethite. One or two more components are seen in most of the samples and in 21 of the samples a ChRM was resolved.

Most of the samples from this formation are demagnetized by 450°C to 500°C. For site one, the NRM intensity was extremely weak and by 100°C was no longer measurable. In some samples a large decrease in intensity was seen by 350°C which represented the unblocking of a reversed component of the ChRM which was isolated above this temperature. This component may be carried by pyrrhotite.

The dominance of low coercivity minerals is seen in the IRM curves, however, the samples are not completely saturated by 1.0 T, indicating at least partial contribution of high coercivity minerals to the remanence (Figure 6.24). The high coercivity component is probably goethite as evidenced by an abrupt drop in intensity during NRM demagnetization after heating to temperatures around 100°C. This abrupt drop is not seen in the demagnetization curves of the IRM, indicating that goethite may not be present in all samples. Instead, demagnetization of IRM shows a steady decay to temperatures of about 550°C probably representing magnetite.

Equal area projections of the 21 samples for which high temperature characteristic directions were resolved shows considerable scatter in the in situ directions and the mean is close to the Brunhes dipole direction indicating that the formation may be overprinted during recent times. Again, however, the α95 of the tectonically corrected mean overlaps with the α95 circle of confidence of both the Gelaohe and Huanglong Formations after correction for bedding attitude. This may be an indication that this formation too, has been overprinted in the middle to late Jurassic. Since the k values are nearly the same before and after correction for bedding attitude, the attitude test is indeterminate.

**The Lower Permian Qixia Formation**

The lower Permian Qixia Formation (Figures 4.2, 4.3, & 4.6) was sampled extensively at 13 sites in both Fujian and Hunan provinces. NRM intensities have a geometric mean of 6.92 x 10^-4 A/m (Figure 6.25). An equal area plot of the NRM directions showed that most of the samples cluster near the Brunhes dipole directions although there is some scatter.

Univectorial decay toward the origin was seen in some samples, however, others samples exhibited a two-component decay. The first component in these samples was usually removed by 100°C to 150°C. This low temperature appeared in many cases to be influenced by the present field although it was not always consistent and may also be
FIGURE 6.24 The Chuanshan Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
FIGURE 6.25  The Qixia Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
influenced by a laboratory VRM. All samples were completely demagnetized by 500°C and most by only 350°C.

The low blocking temperatures seen during the demagnetization of the samples from the Qixia Formation may provide some information about the magnetic minerals which are carrying the remanence. Many of these samples are demagnetized by 350°C. This is close to the Curie temperature of pyrrhotite and may indicate the presence of that mineral in these samples. An increase in bulk susceptibility at higher temperatures is consistent with the oxidation of iron sulfides during the heating process although this does not necessarily confirm their presence.

IRM acquisition curves show that these samples are dominated by minerals with low coercivities but 0.3 T, the maximum coercivity of magnetite, is always exceeded (Figure 6.26). The coercivity spectrum has an upper limit of 0.6 T which may, again indicate the presence of pyrrhotite. Thermal demagnetization of the IRM reveals that the blocking temperatures of about 550°C to 575°C. This is typical behavior for magnetite and magnetite or pyrrhotite or both are the likely carriers of remanence in these sediments.

Equal area projections of the ChRM directions cluster tightly around the present earth field before tectonic corrections are applied (Figure 6.27). Upon correcting for bedding attitude the tight group breaks up into a number of smaller clusters representing sites with different bedding attitudes. This behavior is typical for a formation whose characteristic remanence was acquired after tilting of the beds. This fact is borne out when the attitude test is applied. A comparison of the k values before and after correction reveals that the formation as a whole fails the attitude test and the ChRM is likely secondary, having been acquired some time after deformation of these sediments. The ChRM seen in these samples appears then, to have been acquired during the Brunhes.

**The Lower Permian Wenbinshan Formation**

The geometric mean of the NRM intensities of 64 samples taken from ten sites of the Wenbinshan Formation (Figures 4.2 & 4.6) is $2.66 \times 10^{-3}$ A/m and the distribution is, again, bimodal (Figure 6.28). The bimodal variation, however, is small and the relation to the rock type sampled is weak. In general, though, the siltstones have a slightly lower NRM intensity. The NRM directions plotted on equal area projection are quite scattered but almost all fall in the eastern lower hemisphere and appear unrelated to the Brunhes dipole field direction with a mean declination of 92.2° and a mean inclination of 45.8°.

The demagnetization behavior was variable between the two geographic locations. Sites one through five, taken from a reddish-brown sandstone unit, exhibited unblocking temperatures near or above 600°C. Univectorial decay towards the origin was seen, usually above 400°C. The remaining sites, taken from dark grey siltstones, behaved differently. In all of these samples, stable, two-component decay was seen. A present field direction was
FIGURE 6.26  IRM acquisition and demagnetization curves for the Qixia Formation.
FIGURE 6.27 The Qixia Formation (a) Equal area projections of the ChRM directions. (b) Bulk susceptibility curves.
FIGURE 6.28 The Wenbinshan Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
removed by about 400°C followed by a stable, high-temperature ChRM which decayed to
the origin by 550°C (Figure 6.28). This blocking temperature indicates that a nearly pure
magnetite is the carrier of the ChRM components in these samples.

Bulk susceptibility, monitored during thermal demagnetization showed little or no
increase in either of the two rock types. These data indicate that no significant formation of
ferromagnetic minerals occurs during the heating process. This is also seen in the
demagnetization curves which exhibit stable decay with no increase in intensity, even at
higher temperatures.

IRM curves for samples from each location show both to have a strong influence from
low coercivity minerals (Figure 6.29). Sites one through five, however, also contain a very
small contribution from high coercivity minerals which are not saturated at 1.0 T. The
second five sites are almost completely saturated by 0.1 T, which taken along with the
demagnetization data, indicates the presence of magnetite in these samples. Thermal
demagnetization of the IRM from sites one through five reveal unblocking temperatures near
600°C. This is probably the result of the presence of hematite in the samples, though the
steepening of the slope at 550°C indicates that magnetite is the low coercivity mineral.

Equal area projections of the ChRMs show that the formation, as a whole, fails the
attitude test although the two populations, having different bedding attitudes, appear quite
distinct from each other both before and after bedding corrections are applied (Figure 6.30). In
light of this and the fact that two different rock types from two different localities were
sampled, and analysis of the two groups was done separately.

Sites one through five fail the attitude test and are, therefore, likely remagnetized after
folding. The in situ direction is, however, not coincident with the present earth's field, nor
is either the corrected direction or the in situ direction similar to the Jurassic overprint seen
in other formations. Considering that folding took place in the Jurassic to Cretaceous, when
this block was already likely at low latitudes in the northern hemisphere, any remagnetization
subsequent to this folding would preserve an inclination corresponding to a latitude which
would fall between 20°N - its Jurassic paleolatitude - and its present latitude of 28°N. The
steep in situ inclination places these sites at approximately 50° latitude, although it is
difficult to ascertain whether it is a north or south latitude. This is not consistent with a
remagnetization after the Jurassic folding or during the late Paleozoic and the origin of this
remagnetization remains unclear. It is possible that the bedding was mismeasured, although
this is unlikely since it was measured at each individual site.

Sites six through ten also do not appear to be remagnetized during the Brunhes since the
in situ direction is significantly different from the present earth's field. The bedding attitudes
of these sites are too similar to apply an attitude test. It is difficult to determine if these
samples carry an ancient remagnetization direction associated with some time after the lower
Permian. The negative in situ inclinations are shallower than the late Triassic / early Jurassic
FIGURE 6.29 IRM acquisition and demagnetization curves for the Wenbinshan Formation.
FIGURE 6.30 Equal area projections of the ChRM directions for the Wenbinshan Formation.
overprint seen in other formations and the declinations are not strictly antipodal to that overprint. It is possible, however, that the samples were remagnetized during the middle Triassic since the paleolatitude calculated from the inclination is similar to middle Triassic paleolatitudes for the Yangtze Block.

If it is assumed that the directions are primary, analysis of the bedding corrected directions for sites six through ten places this location at 42°S latitude and a significant amount of rotation - more than 70° - is seen in the declinations. This latitude would appear to agree somewhat with data which places the Yangtze Block in the southern hemisphere during this time (Lin, 1990), though very little is known about the locations of either the Yangtze or the Huanan Block during this time period since most of the Permian paleomagnetic data is remagnetized and little data is available for the Carboniferous.

The Upper Permian Cuipingshan Formation

Thirty five samples from the upper Permian Cuipingshan Formation (Figure 4.2 & 4.6) were demagnetized using both thermal and A.F. techniques. Intermediately strong NRM intensities were seen with a mean intensity of 4.35 x 10^-4 A/m (Figure 6.31). The NRM directions, when plotted on an equal area projection have a mean declination of 354.4° and a mean inclination of 22.4°, however, considerable scatter is seen by the large α95 value. Most of the directions do not appear to be a Brunhes overprint but are, rather spurious directions probably related to VRM acquisition during storage of the samples.

During demagnetization most samples exhibited very unstable decay of NRM directions and a ChRM was not seen. Alternating field demagnetization was ineffective for resolving a ChRM even after heating to 150°C to remove any contribution of goethite. For eight samples from three sites, however, stable demagnetization at high temperatures was seen. The low temperature components of these eight samples were randomly oriented and probably associated with the laboratory VRM. The ChRMs normally persisted to temperatures above 600°C, indicating that hematite is present in the samples.

The presence of both low and high coercivity minerals is evidenced by the IRM acquisition curves (Figure 6.32). A moderate increase in intensity is seen until 0.1 T which may be related to the presence of magnetite, however, the intensity continues to increase after exposure to the 0.1 T field and is not at all saturated by 1.0 T. Thermal demagnetization of the IRM shows a large drop in intensity at 125°C which is most likely due to goethite. The remainder of the intensity persists to 650°C, consistent with the presence of hematite, a change of slope at 550°C reflecting the presence of magnetite.

The eight ChRMs yield a mean declination of 349.7° and an inclination of -20.2° after correction for bedding attitude (Figure 6.32). The northerly declinations together with negative inclinations indicate that, if the remanence is primary, the samples acquired their
FIGURE 6.31 The Cuipeingshan Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.32 The Cuipingshan Formation (a) Equal area projections of ChRM directions for the Cuipingshan Formation. (b) IRM acquisition and demagnetization.
ChRM in the southern hemisphere during a time of normal polarity. This direction would place the Huanan Block at about 10.5°S latitude during the upper Permian.

While there is a tendency for better grouping of the samples after tectonic correction - as seen by the larger k value and the smaller α95 - it is not statistically significant at the 95% confidence level. The in situ mean has an inclination too shallow for the present earth’s field but the α95 would come very close to encompassing the Bruhnes dipole direction. This could indicate a recent post-folding remagnetization acquired since the time of the last reversal of the earth's magnetic field.

The better grouping after correction would certainly argue, however, that there is some chance these samples preserve a pre-folding direction.

Since the results from this formation are ambiguous, the anisotropy of magnetic susceptibility was measured to determine if the samples possess a consistent magnetic fabric, however, none was seen (Figure 6.33). Thus the inclination to be used to accurately calculate a paleolatitude for the sites, will not be influenced by a magnetic fabric in the rocks.

If the samples preserve a VRM acquired during the Bruhnes, it is not likely that this overprint would persist to such high demagnetization temperatures as are seen in these samples, as most hard VRMs residing in hematite are usually easily cleaned thermally by temperatures of above 400°C (Dunlop and Stirling, 1977). It is probable then, that these high temperature directions are not viscous overprints. The possibility still exists, however, that hematite is forming or has recently formed in these sediments - possibly from conversion of goethite - and is preserving a remanence in the direction of the present field as the grains grow through the critical volume (see Chapter II).

The Upper Permian Longtan Formation

The upper Permian Longtan Formation was sampled at four sites in Hunan Province (Figure 4.3 & 4.6). The NRM intensities are relatively low and are grouped tightly around the mean of 1.80 x 10^-4 A/m (Figure 6.34). The NRM directions are very scattered with an α95 of 22.9°. The α95 of the mean direction encompasses the present field direction but the large amount of scatter indicates that most NRM directions are not related to a present field overprint.

IRM acquisition curves show that these samples become saturated to 95% by about 0.1 T to 0.2 T, which indicates the presence of a low coercivity mineral, probably magnetite (Figure 6.35). Demagnetization of the IRM is also consistent with the presence of magnetite as the samples are unblocked at 575°C.

For sites two through four, the demagnetization behavior was very erratic during both A.F. and thermal demagnetization and during measurement, the samples behaved viscously. This erratic behavior is probably not due to formation of new minerals during heating - at
FIGURE 6.33 Equal area projection of the maximum, intermediate, and minimum axes of magnetic susceptibility for samples from the Cuipingshan Formation.
FIGURE 6.34 The Longtan Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.35 The Longtan Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
least up to 450°C - as very little increase in bulk susceptibility is seen for these samples below this temperature. Most of the samples have lost their measurable intensity by temperatures of about 350°C to 450°C and no characteristic directions could be isolated from these sites.

Site one, however, exhibited stable, two-component decay to the origin and a high temperature ChRM was well defined for samples from this site. Most samples from site one decayed rather steadily in intensity to a temperature of 450°C. Above this temperature, large increases in intensity are seen and are likely related to formation of new magnetic minerals during the heating process. This is further evidenced by an increase in bulk susceptibility above 450°C. The in situ mean direction for this site is very well defined and shows that the site has been overprinted during the Bruhnes (Figure 6.35).

The Upper Permian Dalong Formation

Only one site of the Dalong Formation was sampled near Shaoyang in Hunan Province (Figure 4.3 & 4.6). The mean of the NRM intensities is 1.27 x 10^{-3} A/m and little scatter is seen (Figure 6.36). The NRM directions group tightly about a mean declination of 29.3° and an inclination of 45.8° and do not appear to represent the Bruhnes dipole direction. Although the inclination is the same, the mean direction appears to be rotated about 30° to the east.

The samples from this site exhibit two-component decay to the origin by temperatures of 450°C to 500°C. A low temperature present-day direction is removed by 300°C. Two-component behavior is again seen using A.F. demagnetization methods. Both A.F. and thermal demagnetization isolated a similar ChRM component for the site.

Low coercivity minerals dominate the magnetic signal as evidenced by the IRM studies (Figure 6.37). The samples reach saturation by 0.2 T to 0.3 T, although only a slight increase in intensity is seen above 0.1 T. Thermal demagnetization of the IRM reveals an unblocking temperature of 500°C. This unblocking temperature is too low for pure magnetite but could be due to a titanomagnetite or impure maghemite. No evidence for the presence of pyrrhotite - which also has a relatively low coercivity - is seen in the curves.

Seven samples yielded a stable ChRM whose mean in situ direction was not coincident with the present earth's field. Since the samples for this site were taken from the same uniformly dipping outcrop there is no variation in the bedding attitudes for different samples. For this reason an attitude or fold test is not possible for this formation. The corrected direction is similar to the late Triassic - early Jurassic overprint seen previously in other formations. The mean direction is, however, rotated and slightly shallower than would be expected for that overprint. Since the tectonically corrected direction is inconsistent with any other paleomagnetic data from the upper Permian from either block under consideration, it
FIGURE 6.36 The Dalong Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.37 The Dalong Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
seems likely that the site has been remagnetized. Also, the $\alpha_{95}$ circle of confidence easily encompasses the expected inclination of the Jurassic overprint and is consistent with a pre-folding overprint, further supporting remagnetization during this time.

The Early Triassic Xikou Formation

Ten sites from the early Triassic Xikou Formation were sampled in Fujian Province at several different geographic locations (Figure 4.2 & 4.6). The NRM intensities exhibited a bimodal distribution with a mean intensity of $1.16 \times 10^{-3}$ A/m (Figure 6.38). All samples from site 10 had high NRM intensities and some of the samples from sites eight and nine also fall into this group. A large amount of scatter is seen in the NRM directions when plotted on an equal area projection. A group of the samples plots near the present earth field and probably have acquired a VRM during the Brunhes.

During demagnetization most samples exhibited multi-vectorial decay of NRM. In many cases a spurious component was removed by 100°C. Alternating field demagnetization, in general, was not as effective as thermal treatment for this formation and, therefore, was not used to a large extent. High temperature ChRM directions were obtained for 52 samples from the formation. The temperatures at which these components were isolated varies greatly but most of the blocking temperatures were well above 500°C and, in many cases, above 600°C (Figure 6.39).

Bulk susceptibility was monitored in many samples from this formation during thermal demagnetization. In most sites no increase was seen until temperatures above 600°C, however, in sites one through five an increase was seen above 450°C. In some cases the increase in bulk susceptibility was correlated with an increase in remanence intensity during heating making the isolation of the high temperature ChRM impossible for some samples. In these cases the component isolated before the intensity increase was analyzed.

IRM acquisition curves show different behavior within this group of sites. Some are clearly dominated by low coercivity minerals while others indicate the presence of high coercivity minerals (Figure 6.39). Thermal demagnetization of the IRM also indicates the presence of magnetite and hematite. While some samples have unblocking temperatures between 525°C and 575°C, others become unblocked well above 600°C and, in some cases, near 700°C.

The ChRM directions show a very large amount of scatter both before and after tectonic corrections (Figure 6.40). Many of the samples have an in situ direction related to the present field while others are clearly not related. The formation as a whole fails the attitude test at the 95% confidence level. However, in view of the scatter seen in the directions and the departure of many of the in situ directions from the present field, it is appropriate to analyze this data as more than one population. This approach is also valid considering that two outcrops were sampled from widely separated geographic areas.
FIGURE 6.38 The Xikou Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Bulk susceptibility curves.
FIGURE 6.39 The Xikou Formation (a) IRM acquisition and demagnetization. (b) Representative Zijderveld diagrams.
FIGURE 6.40 The Xikou Formation (a) Equal area projections for the formation. (b) Equal area projections for sites one through five only.
Sites one through five were sampled relatively close to each other and the ChRM directions from these sites have been plotted (Figure 6.40). The mean of the \textit{in situ} directions lies near the present field direction, though there is considerable scatter in the individual directions. Two polarities are seen in these samples which are not strictly antipodal due to scatter in the data. The corrected mean may again, be a Jurassic overprint, though the inclination is a bit shallow.

Eleven samples from site five were taken along a fold in order to perform a fold test. An equal area projection of the ChRM directions shows that the fold test is indeterminate (Figure 6.41). This is probably due to the fact that the fold was small and gentle.

An analysis of the ChRM directions from sites six through ten shows clearly that these sites do not carry a recent overprint, as the \textit{in situ} directions lie nowhere near the present field direction (Figure 6.41). Furthermore, the two distinct populations seen in the before correction plot, move together after tectonic correction and, an analysis of the k values shows that these sites pass an attitude test at the 99% confidence level. The remanence was, therefore, acquired before folding and the samples may preserve a primary direction.

The northerly declinations and negative inclinations seen after application of a bedding correction, are interpreted as evidence that these sediments acquired their remanence in the southern hemisphere during a time of normal polarity. Calculations of a mean paleolatitude places these five sites at 10° south latitude during the early Triassic, though there is some scatter in the data. Comparison with data from the Yangtze Block indicates a separation between the Yangtze and Huanan Blocks of about 12° of latitude in the early Triassic.

The declinations of these sites are rotated about 50° to the west. This may have occurred during collision and thrusting. In tectonically active areas such as the Huanan Block, it is important to examine rotations not only of the block as a whole, but also local rotations of sites relative to one another. These local rotations can present serious problems when constructing an APW path for a block and the effects of these rotations on the results for the Huanan Block will be examined in detail in the next chapter.

\textit{The Early Triassic Daye Formation}

The NRM directions of 29 samples from four sites of the Daye Formation (Figures 4.3 & 4.6) group near the present field, however, there is a fairly large amount of scatter in the data (Figure 6.42). NRM intensities exhibited bimodal behavior with a geometric mean intensity of $5.47 \times 10^{-4}$A/m. Samples mainly from site four fall into the high NRM intensity group.

Most samples from these sites - which were taken from Hunan Province - exhibited stable, two-component behavior during thermal demagnetization with intensities decaying to the origin by temperatures of 400°C to 450°C. Alternating field treatment was also effective
FIGURE 6.41  The Xikou Formation (a) Equal area projections for site five fold test. (b) Equal area projections for sites six through ten.
FIGURE 6.42 The Daye Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
in resolving a ChRM for the samples. For all samples demagnetized using A.F. methods, measurable intensity was lost by 60 mT indicating the presence of low coercivity minerals.

The presence of low coercivity minerals is confirmed by the IRM acquisition curves for samples from this formation (Figure 6.43). Thermal demagnetization of the IRM shows that the samples become unblocked between 525°C and 550°C which is consistent with the presence of magnetite or, possibly - in some cases - impure maghemite, in these sediments.

High temperature ChRM along with A.F. ChRM components were observed for 27 samples from these four sites (Figure 6.44). The α95 of the in situ mean does not encompass the present field and nearly all samples lie well away from the Brunhes direction. This direction, however, is very similar to the in situ mean observed for the Dalong Formation and both inclinations are close the present field inclination. Analysis of the k values before and after tectonic correction show that the sites fail the attitude test.

Site three, however, exhibits negative inclinations and northerly declinations in all of the samples and these directions are the reason the sites fail the fold test. Upon checking field notes for the formation, site three was described as overturned bedding and difficulties were encountered when trying to measure the bedding attitude. It is possible then, that the bedding for this site was misoriented. When a mean direction is calculated for the formation with site three not overturned, the grouping of all samples before and after bedding correction is very similar. The k values are 10.9 after correction and 12.1 in situ.

These new calculations reveal that the tectonically corrected mean has an inclination of 35.4° and a declination of 52.5°. This direction is not consistent with expected early Triassic directions from either the Yangtze or the Huanan Block. In addition, the in situ mean is not a Brunhes overprint. The direction is, however, again similar to the rotated early Triassic directions seen by Steiner and others (1989) as well as the mean for this same formation which was sampled on the Yangtze Block and discussed earlier. It appears possible that these sites - sampled very near the suture zone - may preserve a rotated, early Triassic direction as seen on the Yangtze Block.

Since the mean direction from this formation is difficult to interpret and the directions appear to be streaked along a small circle, the anisotropy of magnetic susceptibility was measured. If the rocks possess a strong, well-defined magnetic fabric, it could be that this fabric has affected the NRM directions accounting for the difficulties in interpreting the mean directions. AMS measurements, however, indicate that there is no appreciable magnetic fabric in the sediments (Figure 6.45) and the directions must be explained in terms of rotations or remagnetization. These possibilities will be discussed further in the next chapter.

The Early Jurassic Lishan Formation

The NRM intensities for the Lishan Formation (Figures 4.2 & 4.6) are relatively high with a mean intensity of $1.59 \times 10^{-3}$ A/m. The NRM directions are tightly grouped about the
FIGURE 6.43  IRM acquisition and demagnetization from samples from the Daye Formation.
FIGURE 6.44 Equal area projections of the CnRM directions for the Daye formation (a) and for site three only (b).
FIGURE 6.45 Equal area projection of the maximum, intermediate, and minimum axes of magnetic susceptibility for the Daye Formation.
Bruhnes dipole field direction but a couple of samples are scattered well away from the mean (Figure 6.46).

During thermal demagnetization most samples appeared to have a narrow blocking temperature spectrum with unblocking temperatures in all samples above 600°C. In some cases a spurious component was removed at lower temperatures but most samples exhibited univectorial, although slightly unstable, decay to the origin.

The IRM results reveal a dominance of high coercivity minerals in the samples and thermal demagnetization of the IRM indicates that the unblocking temperatures are consistent with the presence of hematite though evidence of some goethite is seen (Figure 6.47). It appears then, that the ChRM isolated at high temperatures is carried by hematite.

Equal area projections of the ChRM directions group near the Brunhes direction indicating that the samples preserve a recent overprint. One sample plots away from the mean and may have been misoriented in the field. Upon application of tectonic correction the small cluster of directions breaks up and the individual samples are scattered over three quadrants. These sites, therefore, fail the attitude test and have been remagnetized after tectonic deformation preserving a recent overprint.

**HAINAN ISLAND**

*The Permian Ercha, Erding, and Nanlong Formations*

Of the three formations, the Ercha and Nanlong (Figures 4.4 & 4.5) samples had relatively high NRM intensities, while the Erding Formation had very low intensities (Figures 6.48, 6.49, 6.50). The NRM directions of the Erding are very scattered and this behavior is reflected in the large $\alpha_95$ value of 29.5. The $\alpha_95$s of the other two formations overlap although more scatter is seen in the Ercha Formation.

No ChRM directions could be isolated for the Erding Formation because the low intensities were below the accurate resolution of the cryogenic magnetometer either at the NRM intensity or after heating to only low temperatures. The Ercha and Nanlong Formations normally showed two component decay to the origin at temperatures above 600°C and usually near 690°C. A ChRM was usually isolated above 500°C.

The acquisition of isothermal remanence for samples from the Erding Formation show a dominance of low coercivity components but there is also a contribution from a high coercivity component which is not saturated at 1.0 T. Thermal demagnetization of the IRM reveals that most of the intensity is lost by about 550°C but a small component remains and persists to temperatures above 600°C (Figure 6.49). This is an indication that magnetite or maghemite as well as hematite are probably present in these samples.
FIGURE 6.46 The Lishan Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.47 The Lishan Formation (a) Equal area projections of ChRM directions. (b) IRM acquisition and demagnetization.
FIGURE 6.48 The Ercha Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.49  The Erding Formation (a) Histogram of NRM intensities for the Erding Formation. (b) Equal area projection of the NRM directions. (c) IRM acquisition and demagnetization.
FIGURE 6.50 The Nanlong Formation (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
Samples from the Ercha and Nanlong Formations were given an IRM in a 5.0 T field and reach saturation at about 1.5 T (Figure 6.51). This is consistent with the presence of hematite. Thermal demagnetization of the IRM reveals a dominance of minerals with blocking temperatures well above 600°C which also indicates that hematite is present in the samples.

The α95 circle of confidence around the mean directions from both the Ercha and Nanlong formations overlap both before and after correction for bedding attitude (Figure 6.52). The in situ directions for the formations do not reveal a Brunhes-age remagnetization and they exhibit some streaking along a small circle after tectonic correction. This behavior may be related to a magnetic fabric in the rocks and elongated reduction spots were seen in the Nanlong Formation. In light of these facts, AMS measurements were made on samples from these two formations and the results indicate that both formations posses a well-defined magnetic fabric (Figures 6.53, 6.54). The smearing out of ChRM directions along small circles, as seen in the equal area projections, may be a result of the effects of the magnetic fabric. The fabric does not appear, however, to be related to bedding and no other deformation is seen in the samples.

The Upper Paleozoic Granites of Hainan Island

The NRM intensities of the granite samples (Figures 4.4 & 4.5) fell into three distinct groups with a mean intensity of 1.21 x 10^-3 A/m. The NRM directions are fairly well grouped about a mean direction which is coincident with the Brunhes for these sites (Figure 6.55).

The IRM curves give an indication that both high and low coercivity components are present in the samples (Figure 6.56). Thermal demagnetization of the IRM reveals that the intensity is unblocked only above 600°C, a clear indication of the presence of hematite in at least some of the samples.

During both thermal and A.F. demagnetization the samples from both granites behaved unstably. A.F. demagnetization was unsuccessful due to the presence of high coercivity minerals - even after heating to 150°C to remove any goethite component which may be present. The unstable behavior during thermal demagnetization made the isolation of any ChRM directions impossible. During the measurement process viscous behavior was noted by the rapidly changing intensity during measurement. However, even allowing a long time in the measuring space the unstable decay persisted and no useful data could be obtained from these granites.
FIGURE 6.51 IRM acquisition and demagnetization of samples from (a) the Ercha Formation and (b) the Nanlong Formation.
FIGURE 6.52 Equal area projections of the ChRM directions for the Nanlong and Ercha Formations.
FIGURE 6.53  Equal area projection of the maximum, intermediate, and minimum axes of magnetic susceptibility for the Ercha Formation.
FIGURE 6.54  Equal area projection of the maximum, intermediate, and minimum axes of magnetic susceptibility for the Nanlong Formation.
FIGURE 6.55  The Hainan Paleozoic Granites (a) Histogram of NRM intensities. (b) Equal area projection of NRM directions. (c) Representative Zijderveld diagrams.
FIGURE 6.56 IRM acquisition and demagnetization of Paleozoic granites from Hainan Island.
CHAPTER VII
DISCUSSION AND CONCLUSIONS

REMAGNETIZATION

Of all the sites and formations discussed in the previous chapter, very few appear to accurately preserve the geomagnetic field direction at the time of deposition. The majority of the sites have been remagnetized subsequent to deposition and this widespread remagnetization has been a factor in nearly all studies of south China paleomagnetism (e.g. Lin et al., 1985; McElhinney et al., 1985; Opdyke et al., 1986; Heller et al., 1988; Steiner et al., 1989; Dobson and Mauritsch, 1989; Haag, 1989).

It is not always sufficient, however, just to state that the sites or formations are remagnetized and leave it at that. The age of remagnetization, as well as the mechanism which caused it, may provide us with important information. An understanding of the processes of remagnetization can only benefit further paleomagnetic and tectonic studies since, in many cases, the remagnetization can be related to a tectonic event. Recent studies have shown that remagnetization process may be related to fluid migration during tectonic events, thermoviscous remanence acquired by prolonged heating during burial, or conversion of clay minerals to magnetite by prolonged heating during burial (e.g. Pullaiah and Irving, 1976; McCabe et al., 1983; Kent, 1985; Hirt and Gehring, in prep).

Although a complete and detailed study of all of the rock magnetic properties and magnetic mineralogies of the 21 formations examined in this study is beyond the scope of this project, it is nonetheless, possible to examine the remagnetization of the sediments based on their behavior during paleomagnetic analyses and the rock magnetic analyses which have been performed. The more detailed rock magnetic work done on the Changxing section may serve as a stepping stone towards understanding this problem in other sediments in south China.

The remagnetized results discussed in Chapter VI appear to fall into two broad categories; 1) formations remagnetized during the Jurassic, and 2) those which have been remagnetized during the Brunhes. In the first case, the timing of remagnetization may provide information about tectonic activity which has led to this Jurassic overprint.

THE JURASSIC OVERPRINT

The Gelaohe and Huanglong, and possibly the Chuanshan Formations, collected in the Huanan Alps of Carboniferous age, appear to preserve a ChRM direction which coincides
with Jurassic pole positions reported for the Yangtze Block (Figure 7.1). This overprint is recognized in these formations after correction for bedding attitude, indicating that the sediments preserve a magnetization acquired before the folding. In the Gelaohe Formation this direction passes an attitude test and progressive unfolding of the beds reveals that the k value is greatest when the beds are completely unfolded (Figure 7.2). This shows that the ChRM preserved in these sediments is not syn-deformational.

The Dalong and Daye Formations may carry a similar pre-deformational overprint as discussed in the previous chapter, however, the pole for the Daye Formation is closer to some reportedly rotated early Triassic poles for the Yangtze Block. The results from this formation do not lead to a straightforward interpretation and will be discussed in detail towards the end of this chapter. None of these formations have a ChRM which is consistent with a primary magnetization preserving the age of deposition based on what is known about the geology of the region, as well as previous paleomagnetic studies. It is possible that this remagnetization resulted from processes which affected these sediments during the early to middle stages of collision between the Yangtze and Huanan Blocks. According to geologic evidence, the initial collision and deformation of the two blocks occurred in many regions of south China during the late Triassic but deformation continued into the lower Cretaceous (Hsu et al., 1988).

The mechanism for remagnetization in these sediments is difficult to determine but some conclusions may be drawn from the evidence at hand. In some of the samples from these formations - especially the Dalong and Daye Formations - the carrier of ChRM appears to be magnetite or possibly maghemite in some cases. This secondary magnetite could have been precipitated during the tectonically-driven migration of fluids (namely, hydrocarbons) as seen in the Appalachians (e.g. McCabe et al., 1983; Oliver, 1986; Elmore and Crawford, 1990). It has also been shown that as two continental units collide hydrodynamic circulation of groundwater is initiated resulting in the oxidation of pyrite to magnetite (Hornafius, 1984; Suk et al., 1990; Hsü, personal communication).

The presence of hematite carrying the ChRM in other samples, however, could indicate a secondary chemical remanence has occurred - possibly through oxidation during subaerial exposure when the sediments were uplifted during collision and suturing or through direct precipitation during the onset of hydrodynamic circulation of groundwater (Channell et al., 1982; Oliver, 1986; Cochran and Elmore, 1987; Elmore and Crawford, 1990). This would suggest that the Late Triassic was a time of emergence during the onset of collision. During the Jurassic, uplift and overthrusting continued and the onset of hydrodynamic groundwater circulation was initiated as the tectonic profile of the region changed. The heat from the warm, saline groundwater is now thought to be one of the major factors facilitating the conversion to ferromagnetic minerals (Lu et al., 1990; Bethke and Marshak, 1990; Perry et al., 1991).
FIGURE 7.1 Pole positions for the early Mesozoic remagnetization. Closed circles represent the APWP of Lin and Fuller (1990), G = Gelaohe Formation, H = Huanglong Formation, C = Chuanshan Formation.
FIGURE 7.2 The relationship of Fischer's k to progressive unfolding of beds from the Lower Carboniferous Gelaoge Formation.
The low unblocking temperatures seen in many of the sites indicate that the NRM may be preserved in small grains or very large, multi-domain grains. These grains would tend to be more unstable making them more susceptible to remagnetization through the acquisition of a viscous component. This brings forth the possibility that the NRM of some of these sites may be of a thermoviscous origin.

Calculations of the stability of a thermoviscous remanence (TVRM) acquired by magnetite in the Middle Triassic using the thermal activation nomogram of Pullaiah and others (1975), shows that these sediments would have to have been heated to temperatures between 350°C and 400°C during burial to preserve a TVRM with the observed blocking temperatures (Figure 7.3). These temperatures correspond to a greenschist degree of metamorphism that is not seen in the sediments.

Recent debate has arisen, however, concerning the ability of the Pullaiah method to accurately predict the behavior of magnetite grains during thermal activation, as their nomogram is constructed based on calculations using Neel's single-domain theory (Middleton and Schmidt, 1982; Dunlop, 1983; Kent, 1985). Kent (1985) demonstrated that the Middleton and Schmidt curves - which were calculated based on Walton's (1980) thermal activation theory - were more accurate at predicting the burial temperature for the rocks he studied. Using the Middleton and Schmidt thermal activation nomogram, a burial temperature of less than 250°C could result in a TVRM in the Daye and Dalong sediments. Temperatures on this order are more plausible, however, the thermal maturity of these sediments is not known. The TVRM question, however, remains unresolved and Jackson (1989) has recently shown that Kent's analysis may not sufficiently explain the source of late Paleozoic overprint in his samples.

It has also been recently proposed that exposure to low burial temperatures may convert clay minerals to magnetite (Hirt and Gehring, in prep). During collision it is possible that burial of the sediments elevated the temperatures enough to produce these changes, though little is yet known about these conversion processes.

The acquisition of a TVRM or conversion of clays to magnetite after the tectonic event of collision, requires that many of the sediments be buried during collision, enough to elevate the temperature of the rocks by at least 200°C to 250°C. The Huanan Block, however - from which all of these remagnetized sediments come - was thrust over the Yangtze Block during the initial stages of collision and prolonged deep burial of all of these sediments is not likely.

A more reasonable solution appears to be that the sediments were affected by migrating tectonic brines and the onset of groundwater circulation which led to the precipitation of secondary magnetite and hematite or that uplift and subaerial exposure resulted in oxidation of iron bearing minerals to form hematite and maghemite. Both of these minerals are readily formed through low temperature oxidation of sedimentary minerals. Hydrodynamic
FIGURE 7.3 Thermal activation nomograms of Pullaiah and others (1975) represented by solid curves and Middleton and Schmidt (1982) represented by the dashed curves. These represent the theoretical relaxation time - blocking temperature relations for magnetite. The heavy dashed line represents a TVRM component which is demagnetized in the laboratory at 450°C and which was acquired over a duration of approximately one to five million years.
circulation of groundwater can account for the secondary formation of both magnetite and hematite.

The difficulties in determining the actual mechanism of remagnetization in these sediments are many. Even with detailed studies of the magnetic mineralogy the actual processes of remagnetization are still not well understood. Whether the mechanism for remagnetization was one or a combination of these processes, however, the evidence for tectonic activity and collision of the Huanan and Yangtze Blocks at this time is compelling.

The fact that the Dalong Formation appears to preserve a slightly older overprint may be a relic of its magnetic mineralogy. These sediments appear to contain only low Tₐ magnetite or maghemite while the Carboniferous formations contain some hematite, as well as high Tₐ magnetite. It is possible that a different mechanism has caused the remagnetization of the Dalong sediments. It should also be kept in mind, however, that the α₀⁹₅ circles of confidence for the Dalong and Huanglong Formations overlap, while the α₀⁹₅ of the Huanglong overlaps not only the α₀⁹₅, but also the mean direction of the Gelaohe.

The chemical remagnetization of these sediments may be similar to that which has been recognized in the Appalachians (McCabe et al., 1983; McCabe and Elmore, 1989). The acquisition of a TVRM - although less likely - also draws upon an analogous situation seen in the rocks of the Appalachian mountains (Kent, 1985). In both cases, the remagnetization has been shown to be a result of tectonic activity in the Appalachian region.

It is interesting to note that Hsu's early ideas regarding the collision and suturing of the Huanan and Yangtze Blocks, occurred to him upon recognizing similarities between the south China region and the Appalachians while comparing geologic maps. Are these comparisons between south China and the Appalachians valid? The paleomagnetic and geologic evidence supports this contention, however, detailed study of the magnetic mineralogies of these formations is certainly one area for further study.

THE RECENT OVERPRINT

In addition to this early Mesozoic overprint a recent remagnetization is prevalent in most of the formations studied. The Changxing Permian - Triassic section used by Lin and others (1985) to define a pole position for this age, upon closer examination appears to be remagnetized during the Brunhes. The remagnetization of this section had been suggested earlier (Dobson and Mauritsch, 1989; Steiner et al., 1989) and samples from this section were studied in more detail in order to help explain the recent overprint which masks the ChRM directions in so many formations in south China.

The results of the rock magnetic experiments performed on this section, together with the thermal and alternating field demagnetization indicate that the high temperature ChRM directions are preserved in hematite. The disappearance of measurable remanence by 500°C,
lower than would normally be expected for hematite, may be a grain size phenomenon in which the majority of measurable remanence is carried mostly in the fine grain sizes, however, the possibility that some magnetite and pyrrhotite are present cannot be ruled out. This behavior is observed in other formations which contain hematite but have low unblocking temperatures of NRM. In most of these formations the thermal demagnetization of IRM confirms the presence of hematite.

The results of the viscous magnetization experiments have shown that a VRM acquired during the Brunhes may account for the total NRM intensity in most of the samples. This would explain the recent overprint which persists during demagnetization. It is also possible that hematite is forming in fine grain sizes from conversion of goethite - which appears to be abundant in these samples. As the goethite is converted to hematite, the new mineral preserves an NRM which is aligned to the present earth's field. In the future, SEM observation and x-ray fluorescence analysis may be usefull in determining which mechanism is at work.

These data then indicate that the stable ChRM component that is seen in the Changxing section is a secondary magnetization, probably residing in late diagenetic hematite. This component is a remagnetized direction and the direction associated with deposition, at least during the Triassic, is not preserved at Changxing. These processes may also be the cause of Brunhes remagnetization seen in other formations in this study, although in some of the other formations - such as the Qixia and the Maokou - the overprint is apparently carried by magnetite or maghemite. In those sediments VRM overprint is a likely possibility, however, a different mechanism - such as low temperature oxidation of magnetite to maghemite - may also be responsible for the recent overprint.

**PRIMARY PALEOMAGNETIC RESULTS AND THEIR BEARING ON THE HUANAN, YANGTZE AND HAINAN COLLISION HYPOTHESES**

So far discussion has centered on those sediments which are remagnetized. Fortunately, some sites appear to preserve a primary magnetization associated with the time of deposition. The information gleaned from these sites provides us with crucial evidence which sheds some light on the tectonic development of south China - specifically, the collision history of the Huanan and Yangtze Blocks and the position of Hainan Island in the Permian.

Though some of these formations pass a fold test, local rotations appear to have affected most of the sites making the construction of a general APW path for the Huanan Block impossible. This is unfortunately, an almost inescapable hazard of paleomagnetic studies in tectonically active regions where large scale folding and thrusting is common. This fact has been recognized before (Steiner et al., 1989; Lin, 1990; Opdyke, personal communication) and for these reasons the paleolatitudes of the two blocks will be calculated from inclination.
data and compared. This method is less precise in determining the relative positions of the
two blocks but can be used to determine their latitudinal separation. Even this method of
comparison may be difficult since unknown large-scale rotations about a vertical axis may
prevent the determination of southern or northern hemisphere. All of the paleomagnetic
results of this study are presented in Table 7.1.

THE YANGTZE BLOCK

Results from the early and middle Triassic Daye and Jianlingjiang Formations presents
evidence that these sites have been rotated in a manner similar to two formations studied by
Steiner and others (1989). Both sites pass a fold test and this data appears to have
implications for large scale rotations in the region.

The sites sampled by Steiner and others were from southeastern Sichuan Province. Poles
for the Daye and Jianlingjiang Formations fall nearly on top of the poles of Steiner and others
but were sampled from northwest Hunan Province. This indicates that this section of the
APWP for this region in northwest Hunan is rotated in a similar sense and by a similar
amount (Figure 7.4).

This being the case, it seems that a fairly large region of the Yangtze Block has been
affected by this rotation. This area must include the area sampled by Steiner and others and
probably extends east into parts of northeastern Guizhou and western Huanan Provinces.
Such large scale rotations may explain the discrepancies in pole positions for the Permian and
Triassic reported by McElhinney and others (1981) and Zhao and Coe (1987) since it is
believed that the Emeishan Mountain region (from which those samples were taken) has been
rotated as well (Lin, personal communication, McElhinney, 1985).

THE HUANAN BLOCK

Devonian

Data obtained from one site in the early Devonian Xikuangshan Formation places this site
at approximately 27° latitude during this time and the results pass an attitude test. As
mentioned above, it may sometimes be difficult to determine in which hemisphere the site
was magnetized. For example, a group of samples with a mean declination of 60° and
negative inclinations would appear to have acquired it's magnetization in the southern
hemisphere and was subsequently rotated 60°. If, however, the samples have been rotated
120° about a vertical axis this statement is not true. In the latter case, the samples acquired
their magnetization in the northern hemisphere and the rotation makes the samples appeare to
have been magnetized in the opposite hemishpere. Since there does not appear to be any
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**TABLE 7.1** Table of all paleomagnetic results from this study. *In situ* = in geographic coordinates, B.C. = bedding corrected, k = Fischer’s Precision Parameter, $\alpha_{95}$ = the 95% circle of confidence, (Y) = Yangtze Block, (H) = Huanan Block, (R) = Remagnetized direction.
FIGURE 7.4 Composite APWP for the Yangtze Block after Lin and Fuller (1990) and the location of the rotated Early and Middle Triassic poles from this study (Tr1-D and Tr2-D) and Steiner and others (1989) (Tr1-S).
geologic evidence for large scale rotations of greater than 90° (Zhao and Coe, 1987; Steiner et al., 1989; Hsu and Chen, personal communication), the scenario requiring the least amount of rotation was considered in the following evaluations. At the end of this section, however, both scenarios will be summarized together and compared to the geologic evidence.

Comparing the corrected mean from this site to the middle Devonian and Silurian results of Fang and others (1989) and Lin and others (1985), and Fang and others (1989), it is seen that the Yangtze Block is thought to be at equatorial latitudes at this time. The least amount of rotation would place the site from this study in the northern hemisphere indicating a separation of nearly 30° of latitude between the two blocks and implying a southern direction of motion for the Huanan block. It is difficult to determine if these results are primary or remagnetized as little is known about the position of either the Yangtze or Huanan Blocks during the early Paleozoic. Hsu and others postulate, based on the geologic evidence, that the Huanan Block was part of Gondwanaland during this time (Hsu et al., in press). If the results from this study are considered to be from the southern hemisphere, the paleolatitude for this site is in close agreement with Gondwanaland — specifically Australian — data (Van der Voo, 1988). This would require more rotation but seems a more likely scenario when the geological data is considered. The paleobotanical data also suggest an Australian affinity further supporting a southern hemisphere position for the block (Hsü, personal communication).

**Carboniferous**

Results from the unremagnetized lower Carboniferous Gelaohe Formation which appear to have escaped Jurassic remagnetization indicate that these sites were at about 9°S latitude during this time if the least amount of rotation is assumed. Thus far there is little reliable paleomagnetic data from the Carboniferous of the Yangtze Block with which to compare these results. The only pole reported for the lower Carboniferous for the Yangtze Block (Lin et al., 1985) yields a paleolatitude for that block of 15.7°S, however the $\alpha_{95}$ is very large at 28.2. Therefore, while the paleolatitudes argue for a separation of the two blocks during this time, the evidence is far from conclusive.

When compared with the Devonian results, a southward motion of the block seems to be loosely confirmed. The results from these two formations would imply a movement of more than 30° of latitude from the middle Devonian to the lower Carboniferous. This motion, however, is based on mean directions with large $\alpha_{95}$s and may, in fact, be considerably less.

**Lower Permian**

It is also difficult to determine the validity of the results from the siltstones of the lower Permian Wenbinshan as no fold test is available and there are few reliable results from the Yangtze Block with which to compare them. The mean direction, however, does not appear
to be related to any of the previously discussed remagnetization events. The corrected mean places the sites at 40° latitude during the early Permian. Assuming that the sites were in the southern hemisphere at this time a rotation of about 77° is still required. This large amount of rotation makes a determination of the north or south hemisphere more difficult.

These results may be compared with upper Carboniferous results from Lin and others (1985) which are reported to pass a fold test and place the Yangtze Block at about 15°S, again, however, with a large \( \alpha_{95} \) of 17.8. Lower Permian data from Zhou and others (1986) also places the block at 14°S latitude. These comparisons would support the notion that the two blocks were separated during the lower Permian.

**Upper Permian**

Results from the upper Permian Cuipingshan Formation, though scant, appear useful. The biggest problem with these results is the possibility that the ChRM direction may actually be a Brunhes overprint. In view of the difficulties in determining the origin of this magnetization it is especially important that this data should be examined closely in the context of the geologic evidence. The -20.2° inclination would put the site at 10.4°S latitude during the upper Permian and only 10° of rotation is seen in the data. Most reliable paleomagnetic data (Opdyke et al., 1986; Steiner et al., 1990) would put a site from this latitude from the Yangtze Block at approximately 50°N during the Permian - Triassic. This indicates that the two blocks would have been separated during the upper Permian by about 15° of latitude and the block is moving northward during this time.

If it is assumed that the data from this formation and the Wenbinshan are correct, this would require a movement of the Huanan Block of 30° of latitude - about 3000 km - during the Permian. This movement corresponds to a sea-floor spreading rate of more than 5 cm/yr. This is a high rate of spreading but certainly within reasonable limits.

As no reliable indicator of the age of remanence is available, the question must then be asked: is this consistent with what is seen in the geologic record and other paleomagnetic evidence? According to the geologic evidence, the answer must be - yes. The geologic evidence supporting this has been discussed in detail in Chapter I. It has already been widely accepted that the deformation in the region is Mesozoic. A separation of the two blocks during the Permian is consistent with an early Mesozoic collision and deformation. While the paleomagnetic data from these formations do not prove the blocks are separated during the Permian, they do, together with the geologic evidence, support that contention. As for the question of the paleomagnetic evidence - let us examine further the results from this study.

**Lower Triassic**

Five sites from the early Triassic Xikou Formation pass a fold test at the 99% confidence level. The paleolatitude obtained from these sites is 10°S - similar to the paleolatitude just
calculated for the Cuipingshan sediments. Again, when compared to the Yangtze, data this indicates a separation of the two blocks of about 12° to 15° and is consistent with a collision of the two blocks in the late Triassic to early Jurassic.

The fact that these results pass a fold test is strong evidence that the magnetization is primary. If they had been remagnetized during the collision prior to the folding - as was seen in the Gelaohe, Dalong, and Huanglong Formations - these sediments would have a similar mean direction more in agreement with a Jurassic paleolatitude of about 20°N. These results then strongly support a separation of the two blocks during the early Triassic and are in good agreement with the data from the Cuipingshan and Wenbinshan Formations.

The separation of the two blocks may be illustrated in a paleolatitude graph (Figure 7.5). Scenarios presenting both a northward and a southward motion for the Huanan Block are presented. Both scenarios are consistent with a separation of the two blocks during the late Paleozoic. A northward motion for the block, however, requires far less rotation and is more consistent with the geologic data presented by Hsu and others (1989, 1990, and in press). It is also consistent with data that indicates the Yangtze Block moved northward during the late Paleozoic until it's collision with North China (Lin et al., 1985, 1989; Chan et al., 1984; Opdyke et al., 1986; Steiner et al., 1989). It is important to point out here that both scenarios support the assertion by Hsu and others that the Yangtze and Huanan Blocks were separated during the upper Paleozoic.

In addition, new data has recently been obtained by Chen Haihong working on early Triassic samples from Guangdong Province on the Huanan Block (Chen, personal communication). These results also place the Huanan Block at shallow southern latitudes during this time though no fold test is available.

THE DAYE PROBLEM

The results from the Daye sediments which were sampled on the Huanan Block present some difficulties for interpretation. These results are in agreement with the early Triassic results from the Daye of the Yangtze Block if site three is excluded based on bedding orientation difficulties. Admittedly, the simplest interpretation is that the results are primary and indicate that the Yangtze and Huanan Blocks were already sutured in the early Triassic. This interpretation is, however, in direct disagreement with all other paleomagnetic results from the Huanan Block. Also, no fold test is available to determine if the mean direction obtained from this formation is primary.

If it is assumed that the direction is a Jurassic overprint, other difficulties arise. The Gelaohe Formation was sampled from the flanks of the same syncline from a continuous stratigraphic sequence of which the Daye Formation is a part. If the Daye was remagnetized during the Jurassic it must be assumed that these sediments were rotated approximately 30°
FIGURE 7.5  (a) Paleolatitudes of the Yangtze and Huanan Blocks since the Carboniferous. The two curves for the Huanan Block represent both a north to south movement and a south to north movement. (b) The amount of rotation required for the Huanan Block to be in the northern or southern hemisphere based on the formation mean directions.

<table>
<thead>
<tr>
<th>FORMATION (AGE)</th>
<th>SOUTH HEM. DEGREES OF ROT.</th>
<th>NORTH HEM. DEGREES OF ROT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gelaoh (C1)</td>
<td>30.2</td>
<td>148.8</td>
</tr>
<tr>
<td>Wenbinshan (P1)</td>
<td>76.4</td>
<td>103.6</td>
</tr>
<tr>
<td>Cuipingshan (P2)</td>
<td>10.3</td>
<td>169.7</td>
</tr>
<tr>
<td>Xikou (Tr1)</td>
<td>57.7</td>
<td>122.3</td>
</tr>
</tbody>
</table>
relative to the Gelaohe Formation. This is possible since, from geologic maps, it can be seen that the syncline itself is kinked in the middle and the sediments at the core - the Daye sediments - appear to be rotated more that those on the flanks - the Gelaohe sediments.

The third possibility is that the samples from site three preserve a primary magnetization which indicates that these sediments are part of the Huanan Block and places the location in the southern hemisphere during the early Triassic. This is consistent with other Permian and Triassic paleomagnetic results which were presented earlier. It is also consistent with the geologic evidence which indicates that this sedimentary sequence is distinctly of Huanan origin. This would imply that site three escaped remagnetization while the other sites were remagnetized during the Jurassic. It has been seen in other early Triassic Formations of south China that the more marly beds - similar to those from site three - preserve a primary remanence while the thin-bedded limestones - similar to those from the other sites - are remagnetized (Chen, personal communication). It is difficult to determine which of these three possibilities is more likely and this area might be interesting for further investigation.

HAINAN ISLAND

Though all of the data from the upper Paleozoic granites of Hainan Island are remagnetized or unstable, some interesting results have come from the Permian sediments sampled near Nanlong. While it is obvious that these sediments possess a well-defined magnetic fabric it is not clear the effect this fabric has had on deflecting the NRM directions. Though the ChRM directions obtained from these sediments are spread out along a small circle, all of the inclinations indicate that the sites were in the southern hemisphere at shallow latitudes during the Permian. Deformation which has resulted in the magnetic fabric, however, may well have deflected the inclinations. Since the orientation of the fabric is not related to bedding it seems that simple compaction of the beds is not the likely cause. In view of these facts it would not be appropriate to use these results to test Yu's theory of a Gondwana origin for these sediments.

CONCLUDING REMARKS

This study has shown that widespread remagnetization in these south China sediments may be related to tectonic activity. The age of the overprint is well correlated with the onset of collision and suturing of the Huanan and Yangtze Blocks during the early Mesozoic and several mechanisms for remagnetization have been proposed. The magnetic mineralogies of many of these sediments, however, appear to vary a great deal and present difficulties for interpretation. Such widespread remagnetization and complex mineralogies provide a wealth of topics for future research. Investigations of the magnetic mineralogies by direct
observation with SEM and TEM techniques as well as single crystal x-ray and x-ray flourescence methods may provide greater insight into the specific mechanisms of remagnetization.

Results from south China which appear to have escaped remagnetization tend to support a separation of the Huanan and Yangtze Blocks during the Permian and early Triassic. It should be noted here, however, that in most cases only one polarity is seen. This could indicate that some of these formations may be remagnetized though the paleomagnetic data is consistent with the geologic evidence and positive fold tests are reported. Correlation of results from older rocks from these two blocks is difficult, in part due to the paucity of reliable data. Together with the Jurassic remagnetization information, however, these results support an early Mesozoic collision and suturing of the two blocks.
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CURRICULUM VITAE

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