The Paleomagnetics of the Green Pond Outlier

by Peter L. von Schondorf

A thesis submitted to the

Graduate School - New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate Program in Geological Sciences

Written under the direction of
Doctor Randall S. Forsythe
and approved by

Randall S. Forsythe

Richard K. Olssen

Michael J.Carr

Robert Sheridan

New Brunswick, New Jersey
April 1989

ABSTRACT

The paleomagnetics of the lower Paleozoic Green Pond Outlier of northern New Jersey were studied using principal component analysis and great circles of remagnetization techniques. Ninety seven samples from ten sampling sites were collected. Sampling sites were selected laterally across several minor folds within the Outlier's synclinal structure and vertically across the Shawangunk and Skunnemunk Formations. Sampling was conducted to define a primary magnetic vector representative of the Green Pond Outlier or Silurian/Devonian time, to test the stability of the vector by means of a fold test, to determine the age of remanence acquisition by comparing the Green Pond magnetic pole to the North American Apparent Polar Wander Path, and to discuss the significance of these results in light of previous studies and the tectonics of the Green Pond.

All specimens were thermally demagnetized in a program of step-wise demagnetization to a temperature of 780 degrees Celsius or to a magnetic intensity of less than 0.01 of the initial NRM intensity. All specimen NRM's were measured using a spinner magnetometer. Principle linear and planar components were obtained from sample Zijderveld diagram analysis. Each principal component was then rotated through a series of bedding tilt corrections to reduce the component population's directional scatter, and to define when during folding the

component's remanence was acquired. Planar component analysis was also conducted using Halls' great circles of remagnetization technique to define a characteristic remnant magnetic direction.

An analysis of the Green Pond's magnetic components indicate there is no single dominant population of stable magnetic vectors present, and that the samples analyzed were either partially or totally remagnetized. Analysis of planar components did identify three in situ and four tilt-corrected populations. Using Halls' technique, four magnetic pole positions were determined. Two of the four poles correlated closely with the latitude position of the North American Late Devonian apparent polar wander path. These post-folding poles were located at 37.6 degrees North, 91.7 degrees East, and 35.9 degrees South, 46.3 degrees East.

Table of Contents

Page

Abstract.................................... i

Table of Contents.............................iii

List of Tables............................... iv

List of Illustrations........................ v

Table of Appendices.......................... vi

Introduction................................. 1

Previous Work................................ 5

Site Geology................................. 7

Technical Approach........................... 13

Sampling and Sample Analysis................. 13

Data Analysis................................ 19

Results...................................... 29

Sample Demagnetization....................... 29

Planar Component Data........................ 30

Linear Component Data........................ 49

Component Analysis using Halls' Technique......... 54

Discussion................................... 57

Remanence Acquisition and Age Constraints......... 59

Tectonic Implications to the Paleopole Positions.. 68

Conclusions.................................. 74

Appendices................................... 78

References................................... 83

List of Tables

		Page
Table 1.	The Green Pond Stratigraphic Column	9
Table 2.	Intervals of Thermal Demagnetization in Degrees Celcius	16
Table 3.	Individiual Component Data	32
Table 4.	Component Statistics	37
Table 5.	Incremental Fold Test Parameters	61
Table 6.	Poles of the North American Apparent Polar Wander Path	64
Table 7.	Remagnetized Paleopoles from the Appalachians	71

List of Illustrations

		Page
Figure 1.	Study Area Location Map................	8
Figure 2.	Green Pond Structural Map..............	11
Figure 3.	NRM Intensity Delay During Demagnetization..........................	18
Figure 4.	Magnetic Component Forms................	22
Figure 5.	Halls' Construction of the CRMD........	24
Figure 6.	Fold Test Significance Curves..........	25
Figure 7.	Occurrences of Planar Component Directions within the Green Pond Outlier................................	31
Figure 8.	Green Pond Outlier Component Zijderveld Diagrams	
	Figure 8A...........................	38
	Figure 8B...........................	40
	Figure 8C...........................	42
	Figure 8D...........................	45
	Figure 8E...........................	47
	Figure 8F...........................	48
Figure 9.	Stereo Net Projection of Planar Components.............................	50
Figure 10.	Equatorial Projection of Planar Component Poles.........................	51
Figure 11.	Stereographic Projection of Green Pond Outlier Linear Components..............	52
Figure 12.	Halls' Construction of the CRMD........	55
Figure 13.	A Comparison of Linear Components and Planar Component Great Circles.........	58
Figure 14.	The Apparent Polar Wander Path of North America during the Silurian through Triassic...............................	66
Figure 15.	Error Analysis of the CRMD Positions...	68

Table of Appendices

Page

Appendix A: Descriptions of Sample Locations...... 78

INTRODUCTION

The Green Pond Outlier of northern New Jersey is one of the easternmost exposures of lower Paleozoic age sedimentary rocks found within the Mid-Atlantic States. The Outlier's geographic position is within the Precambrian Highlands province approximately twenty miles southeast of the Appalachian structural front, and approximately 10 miles northwest of the Piedmont province and the Triassic Lowlands. Ideally, because the area is east of the Applalachian structural front and within close proximity of the Piedmont province, many structural features of the Appalachian orogeny and Newark disturbance should be represented within the Outlier. For example, cleavage sets and tension gash arrays have been identified within the Outlier (Mitchell and Forsythe, 1988) as Alleghenian features. The normal faulting found within the Outlier closely mimics the faulting found in the Newark Basin and was possibly initiated or reactivated by the Newark disturbance (Drake, 1987). To date, little geologic investigation work has been done on the Green Pond, as many investigators prefer to study the lower Paleozoics in eastern Pennsylvania (Drake, 1960, 1987; Van der Voo, 1988; Miller and Kent, 1988, 1986; Kent and Opdyke, 1986, 1978) and to a limited extent New York and northwestern New Jersey (Drake, 1960; Spink, 1967; Kent and Opdyke, 1985, 1979, 1978). During the last ten years, many of these investigators began using paleomagnetic techniques to derive an age of deformation independent of fossils and stratigraphic relationships.

The increase of paleomagnetic studies in eastern Pennsylvania was partially begun by investigations of similar Paleozoic rocks in New England and Maritime Canada (Knowles and Opdyke, 1968; Kent and Opdyke, 1978; Morris and Roy, 1979; Van der Voo, 1979). These investigations indicated the existence of an apparently displaced terrane within this region, which was called Acadia by Kent and Opdyke (1978). The paleomagnetic data agreed with the theories of other disciplines that portions of New England and eastern Canada had structural and paleontological affinities for other continents (Van der Voo, 1988). The data indicated that Acadia and other land masses of the Central Mobile Belt (CMB) originated in southern latitudes compared to cratonic North America during the Devonian.

Continued investigations of the northeastern Appalachians have resulted in several additional theories about the existence of Acadia (Kent and Opdyke, 1979; Miller and Kent, 1986, 1988; Van der Voo, 1988). These studies have refuted the earlier theories and have proposed new theories which have scaled down the initially proposed extent of the Acadian land mass. The new theories have proposed a narrowing of the Acadian Sea between North America and the CMB during the Devonian, and called for the existence of a Devonian Super-Continent. After ten years of investigative work, a clear picture has still not developed concerning the existence of Acadia, the timing of deformation/drift which may have caused Acadia to migrate to its present position, or the position of the Silurian-Devonian magnetic pole.

The major problem with the cited paleomagnetic data has been the presence of a strong secondary magnetic component. This secondary component in most cases completely overprints the primary magnetic vector (Kent and Opdyke, 1983) and obscures the true magnetic field position. To some extent the existence of a strong secondary magnetization is common to most Silurian-Devonian aged rocks and specifically those that are associated with a more complex thermal and structural history (Miller and Kent, 1988).

The Green Pond area was chosen for a paleomagnetic investigation for several reasons. The rocks exposed within the Outlier are similar in age to those used in previous work. The Outlier's location and the deformation and thermal history of the area may offer a different remanence acquisition environment from other study areas. The structural features and lithologies present in the Green Pond section also offer many good sampling exposures to test and determine the direction of the Silurian-Devonian magnetic field.

The goals for this study are to:

1. Isolate a stable primary magnetic vector which can be said to represent the Green Pond Outlier or Silurian and/or Devonian time.

2. To test the stability of the vector by means of a fold test.

3. To determine the age of remanence acquisition by comparing the Green Pond Outlier pole position to the path of the North American Apparent Polar Wander Path (NAAPWP).

4. To discuss the significance of these results in light of previous studies and the tectonics of the Green Pond Outlier area.

PREVIOUS WORK

The Mid-Atlantic region of the Appalachian mountain chain has been of an area of geologic interest for nearly a century. Since the 1950's, interest in this area as well as the entire mountain chain, has been rejuvenated by the works of Bullard (1965), Rodgers (1970), and Dewey (1969) on the relationships between orogeny, continental drift, and plate tectonics. Because of these concepts, prior ideas of geologic space and time needed to be re-evaluated using an age dating technique independent of the stratigraphic and fossil record. Paleomagnetic dating techniques provided the needed data to validate earlier ideas.

During the last 20 years, the orogenic belts of the world have been the primary subject of paleomagnetic investigations. Investigators using background information from stable cratonic areas could now provide independent evidence of the large scale movements of the orogenic belts and could determine the origins of the isolated enigmatic areas that did not geologically fit their location.

Paleomagnetic interest in the Mid-Atlantic region has been augmented in recent years as a result of the emergence of evidence defining an apparently displaced terrane called Acadia. Acadia encompasses the coastal regions of New England and the Canadian Maritime Provinces (Kent and Opdyke, 1968, 1978; Roy and Morris, 1983; Van der Voo, 1979). Many of these studies have resulted in contradictory conclusions about the existence of Acadia as a true displaced terrane. This dilemma has caused several resamplings of the original Acadia study areas (Kent and Opdyke, 1985; Miller and Kent, 1986). The Mid-Atlantic region is important to these investigations because the age of the formations present are equivalent to those formations in the Acadia region, the formations exhibit the effects of several orogenic events, and the units are folded and thus provide samples which may be tested for their magnetic acquisition using paleomagnetic and statistical techniques.

The Green Pond Outlier has not been previously investigated using paleomagnetic techniques. Much of the recent geologic work has been done by Mitchell and Forsythe (1988) who studied the kinematics of the Outliers deformation history, by Toskos (1985) who conducted a gravity survey across much of the northern sections of the Outlier, by Barnett (1970, 1976) who mapped and wrote specifically about the Outlier's stratigraphy, and by Spink (1967) who studied the stratigraphy and structural relations of the Paleozoic rocks of Northern New Jersey including the Green Pond Outlier. This study is the first to investigate the deformation history of the Green Pond Outlier using paleomagnetic techniques.

SITE GEOLOGY

The Green Pond Outlier is an elongated northeast-southwest trending band of folded Paleozoic sedimentary rocks which is continuous in length for approximately 120 miles from Flanders, New Jersey to Cornwall, New York. At its widest location, the Outlier has a width of approximately 13 miles. The Outlier represents one of the easternmost outcrops of Paleozoic sediments in the Mid-Atlantic states and exhibits structures reflective of the cumulative crustal movements which have occurred in this site since its deposition.

The geology of the Outlier consists of Cambrian through Middle Devonian age strata resting unconformably on rocks of Proterozoic age. Throughout much of the study area (Figure 1) strata of Cambrian and Ordovician age are absent or deeply eroded, causing the Silurian strata to rest either directly upon the Precambrian or on the thin remnants of the Cambrian and Ordovician. The remainder of the section, the Silurian Shawangunk Formation through the Devonian Skunnemunk Formation, can be mapped continuously (Barnett 1976).

Table 1 lists and describes the stratigraphic section of the Green Pond Outlier (Barnett, 1976). The Cambrian and Ordovician systems are represented by three basic sequences; the Hardyston Quartzite Formation (Cambrian), the Kittatinny Formation carbonate sequence (Cambrian), and the Martinsburg Formation (Ordovician). The Silurian system is represented by

STUDY AREA LOCATION MAP

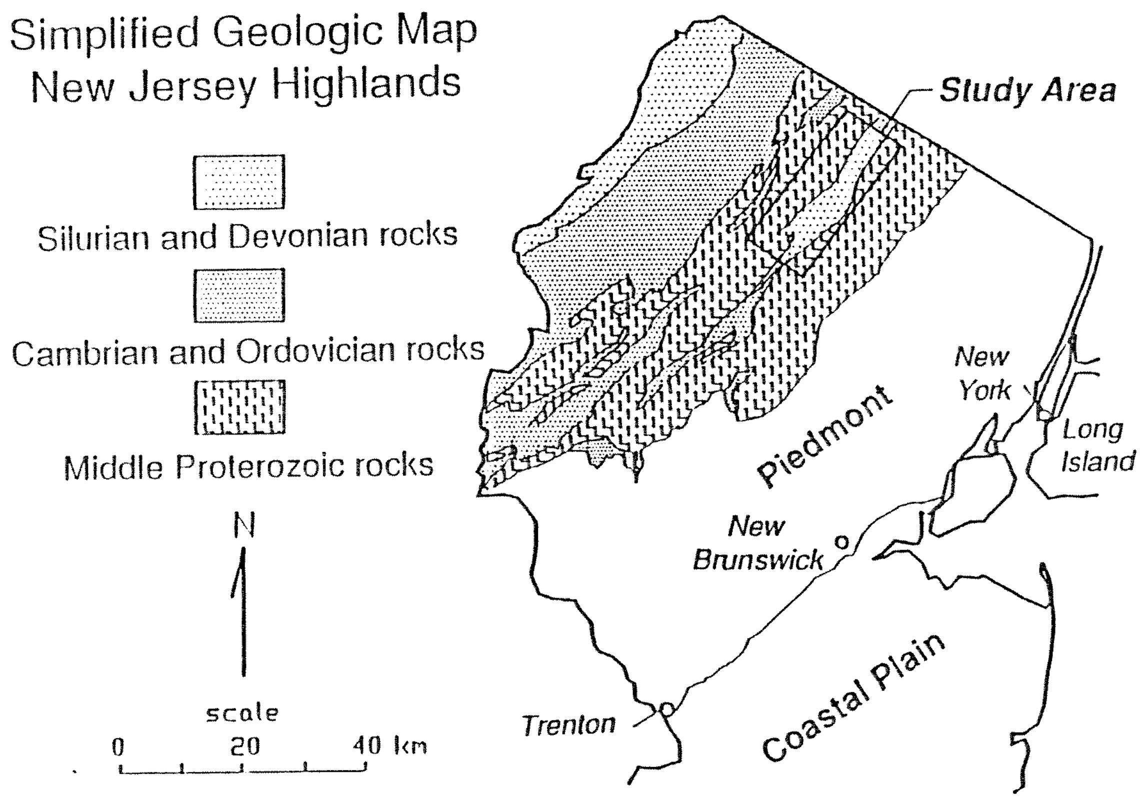
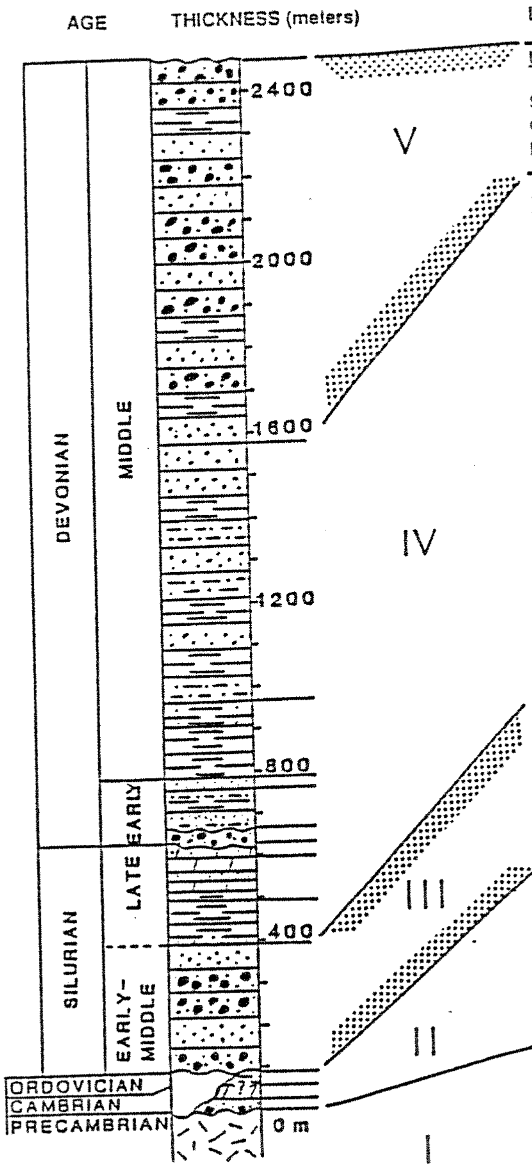


Figure 1. A simplified geologic map of northern New Jersey illustrating the New Jersey Highlands and the study area (From Mitchell and Forsythe, 1988).

TABLE 1

THE GREEN POND STRATIGRAPHIC COLUMN



LITHOSTRATIGRAPHIC UNITS

Unit V: Primarily conglomerate and sandstone.

Skunnemunk Conglomerate: reddish-purple conglomerate, red sandstone, and red shale; quartz cement; pebbles up to 15 cm, one-half are milky vein quartz.

Unit IV: Primarily shale, siltstone, and sandstone; some conglomerate and carbonate.

Bellvale Sandstone: black shale and siltstone and gray sandstone; shale and siltstone more abundant in lower part.
Cornwall Shale (also called Monroe Shale and Marcellus Shale): dark gray slightly silty shale; silt more abundant in upper part.
Kanouse Sandstone (previously Newfoundland Grit): gray sandstone and conglomerate; upper part mostly sandstone.
Esopus Formation: dark gray and black mudstone; also light to dark gray siltstone and sandstone.
Connelly Conglomerate: predominantly light colored quartz pebble conglomerate with abundant quartz sand.
Berkshire Valley Formation: mostly gray calcareous siltstone with lenses of gray silty dolomite; basal olive-gray shale.
Poxono Island Formation: predominantly gray dolomite with interbeds of green sandstone, green and purple silty shale, and green siltstone.
Longwood Shale (High Falls Formation of Barnett, 1976): purple-red silty shale; sandstone beds in lower part.

Unit III. Primarily conglomerate and sandstone.

Green Pond Conglomerate (correlative with Shawangunk Formation): purple-red conglomerate interbedded with and grading upward into purple-red sandstone; quartz cement; pebbles up to 8 cm and almost entirely white quartz, chert, red sandstone and shale.

Unit II: Variety of discontinuous sedimentary rocks.

Martinsburg Formation: dark gray shale with prominant slatey cleavage and orange-buff weathered siltstone.
Leithsville Formation: gray massive silty dolomite.
Hardyston Quartzite: white to blue-gray conglomeratic sandstone grading upwards into calcareous sandstone.

Unit I: Basement crystalline rocks.

A variety of gneisses, igneous intrusives and foliated granitoids; some amphibolites and marble.

FROM MITCHELL AND FORSYTHE, 1988

four formations; the Shawangunk Formation, the High Falls Formation, the Poxono Island Formation, and the Berkshire Valley Formation. The Devonian system is represented by six formations; the Connelly Conglomerate Formation, the Esopus Shale Formation, the Kanouse Sandstone Formation, the Marcellus Shale Formation, the Bellvale Sandstone Formation, and the Skunnemunk Conglomerate Formation. In general, the strata above the Proterozoic basement represents a number of depositional environments from deep marine to terrestrial delta. These strata indicate three cycles of progressive sediment coarsening which peak with the conglomeratic formations of the Shawangunk, the Connelly, and the Skunnemunk. These conglomeratic formations are likely to be associated with uplift in the sediment source area and may reflect tectonic pulses of the Taconic and Acadian orogenies.

The structure of the Outlier is that of a large northeast southwest trending synclinorium (Figure 2). Both limbs of the fold have been down faulted against older rocks along the margins of the Outlier. In the northeastern portion of the Outlier, north of the Clinton Reservoir, the structure is composed of a single syncline. In places the beds are tightly folded and asymmetrical with the beds of the eastern limb steeply dipping and in some locations overturned. In the southern regions of the Outlier a series of open folds have developed on the eastern limb of the synclinorium. Each fold is separated by a high angle fault that is nearly parallel to

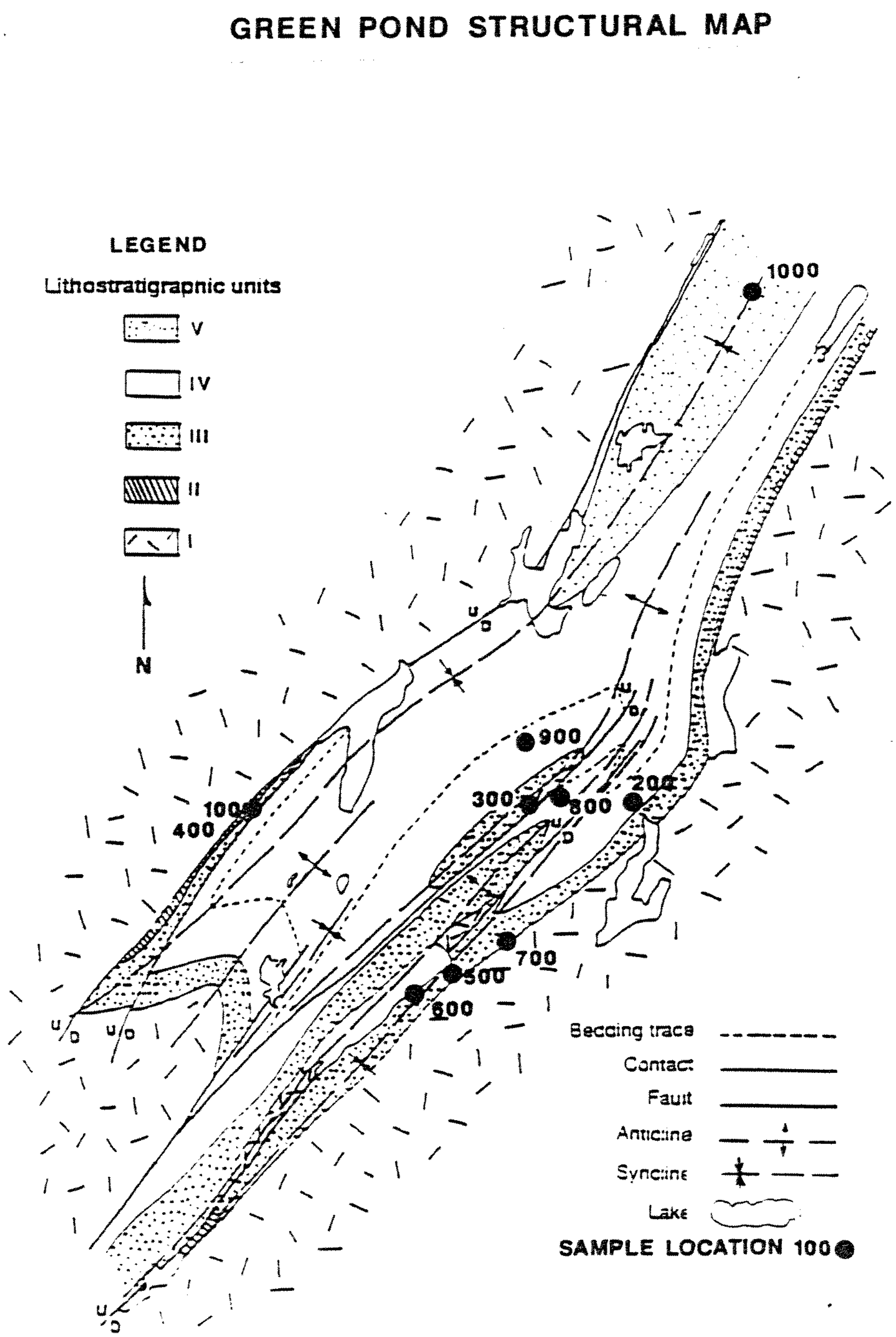


Figure 2. A simplified structural geology map of the study area with sample locations (From Mitchell and Forsythe, 1988).

the individual fold axes. The eastern block of each fault is down dropped relative to the western block (Barnett, 1976).

Cleavage surfaces are common and best developed in the finer grained units of Silurian and Devonian age. Two distinct cleavage groups have been observed, a slaty cleavage parallel to fold axial planes (N50E) and a locally developed space cleavage which strikes nearly east to west and dips at a high angle to the fold structure (Mitchell and Forsythe, 1988). The two different cleavage sets indicate two stages of non-coaxial deformation (Mitchell and Forsythe, 1988). The youngest rocks from which cleavage surfaces have been found are of Early to Middle Devonian age, thereby restricting the age of cleavage development to the Alleghenian events (Pennslyvanian and Permian, 320-225). Assuming the development of cleavage is not contemporaneous with the deposition of sediment (Skunnemunk), a Carboniferous age of deformation is reasonable.

TECHNICAL APPROACH

This section discusses the technical approach taken for this study. To simplify the discussion, the section will be discussed in two subsections; sampling and sample analysis, and data analysis.

Sampling and Sample Analysis

Ten locations were chosen for sampling from the Outlier's rock sequences. The number of locations were selected based on statistical practicality; many statistical references for paleomagnetic applications do not consider the statistical probabilities (P) for a particular result with locations or sample numbers (N) less than six to be acceptable (Tarling, 1971; McElhinny, 1964). This number of locations gives a greater coverage of the Outlier and allows for ambiguous results to be ignored while still retaining a statistically significant sample number.

Sampling was conducted on the Outlier's thickest exposed formations. These consisted of Silurian age Shawangunk and High Falls Formations, and the Skunnemunk Formation of Devonian age. Figure 2 illustrates the sampling locations within the Outlier structure.

Sample sites were selected based on three criteria. The criteria were chosen to reduce measuring errors and the possibility of chemically altered samples due to weathering, and to allow pole positions to be determined within the confines of a single stratigraphic sequence. These criteria include: the outcrop had to be in a condition where a fresh sample could be obtained; the sample could be accurately oriented and completely removed from the parent rock; and a reasonable thickness of the formation was available to be sampled to average out magnetic secular variation. In general, sampling sites were chosen on the eastern and western limbs of several minor folds within the Outlier's major synclinal structure. Appendix A details the geology and location of each sampling site.

At each site, samples were collected either as block samples or drilled cores. Block samples were the preferred method of sampling due to the hardness of the rock and the cumbersome drilling equipment.

Prior to sample collection, the rock was cleared of weathered veneers and given orientation marks. Orientation marks were measured by Brunton compass to identify the horizontal and vertical angles of each sample. After the samples were removed from the formation, the sample was refitted to confirm the initial orientation. Once the sample was labeled it was marked with an identification code and pertinent site information was recorded in a sample log.

In the laboratory, each specimen was cut into a cube to avoid magnetic anisotrophies related to shape. The size of the cube was defined by the shape of the magnetometers specimen holder. After cutting, each specimen was given a set of orientation marks which served to orient the specimen in the six positions required for measurement. The marks were measured from the field orientation markings according to the measurement convention of the magnetometer.

A MoleSpin Magnetometer, used in conjunction with a micro-computer, analyzed all specimens. The magnetometer was used in two modes of operation; to analyze the magnetic vectors and to measure the specimen's bulk susceptibility. The magnetometer's internal computer was used to calculate the orientation of the resultant magnetic vector component (RMVC). The micro-computer was also used to calculate the magnetic pole locations and to rotate the RMVC through various coordinate systems, or degrees of bedding tilt, for comparative analysis.

The demagnetization of a specimen's natural remanent magnetization (NRM) was completed using a Schoenstedt oven to achieve temperatures above the Curie point of hematite (675 degrees Celsius) in an environment free of magnetic fields. Demagnetization using an alternating field method proved to be ineffective after attempting the demagnetization of several samples, and was eliminated from the analysis program.

Thermal demagnetization was conducted in a program of increasing temperature which included twenty-two individual steps ranging from the NRM (ambient temperature) to an apparent temperature of 780 degrees Celsius (C). Table 2 provides a list of the individual temperatures used. Demagnetization

Table 2

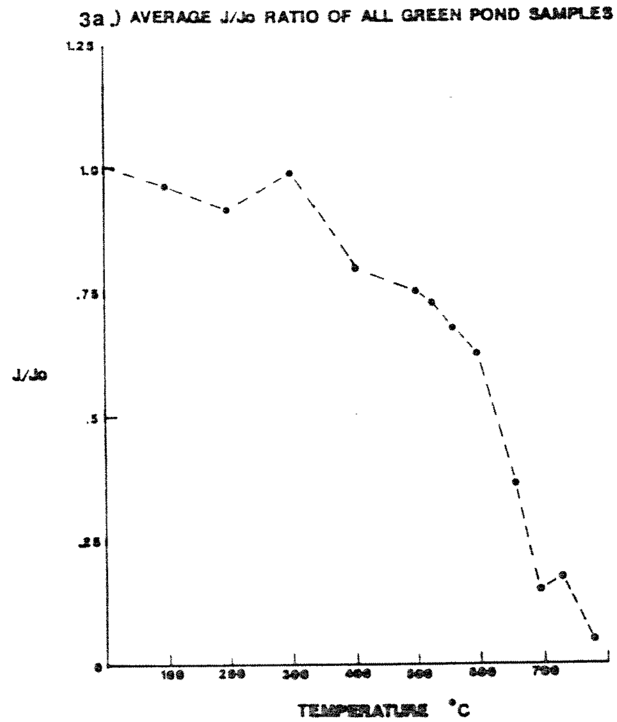
INTERVALS OF THERMAL DEMAGNETIZATION IN DEGREES CELSIUS

	APPARENT TEMPERATURE	ACTUAL TEMPERATURE
	NRM	NRM
	100	100
	200	200
	300	300
	400	400
	500	500
UNBLOCKING TEMP.	530	530
OF MAGNETITE	560	560
	600	600
	625	625
	650	650
	660	660
	670	670
	690	690
	700	700
	705	705
	710	710
	730	730
	740	740
	760	760
UNBLOCKING TEMP.	770	770
OF HEMATITE	780	780

temperatures greater than the Curie points of magnetite and hematite, 560 degrees and 675 degrees C respectively, were used for two reasons. The first reason being that remnant intensities of hematite rich samples were not decreasing as the temperature of demagnetization approached 675 degrees C. Figure 3 (Knowles and Opdyke, 1968) illustrates the typical intensity decay for hematitic rich samples. The second reason being that it was believed the actual temperature achieved by the oven was not accurately recorded by the oven's thermometer, and therefore provided misleading information on the actual temperature of demagnetization. A demagnetization temperature limit of 780 degrees Celsius (oven thermostat setting) was chosen to ensure that oven core temperature reached 675 degrees Celsius and to protect the oven's thermal and magnetic shielding from overheating. Samples were heated at temperature for 45 to 60 minutes and allowed to cool within the magnetic free atmosphere of the oven to room temperature. Between each heating the NRM of the specimens were measured on the magnetometer.

Prior to every measurement session, and at 30 to 40 minute intervals of specimen spinning, the magnetometer was calibrated to an intensity of approximately 850 x 10^{-6} gauss and a declination of 0 degrees +/- 0.5 degrees. This calibration frequency reduced the measurement error due to drift of the magnetometer calibration. To increase the sensitivity of the magnetometer measurements, the duration of measurement spinning

NRM INTENSITY DECAY DURING DEMAGNETIZATION



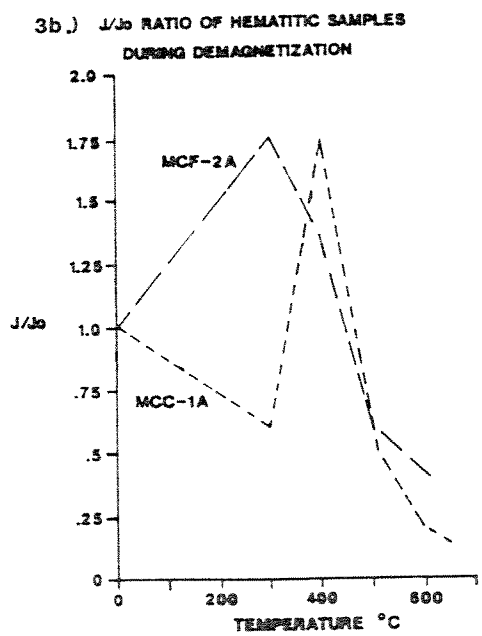


Figure 3 The average J/Jo ratio of all samples collected during demagnetization. Figure 3b. The J/Jo ratio of two hematitic rich samples during demagnetization (Knowles and Opdyke, 1968).

could be increased from six to twelve seconds. When the magnetic intensity of a specimen was reduced below 0.5 x 10^{-6} gauss, the duration of spin time was increased to twelve seconds. Demagnetization continued for each specimen until the magnetization intensity was less than 0.01 of the initial NRM, or the sample was demagnetized at the highest oven temperature.

Data Analysis

The program for data analysis proceeded in phases; the first phase was a general plotting of all data using the appropriate nets, graphs, and three dimensional projections; the second phase of the analysis consisted of a comparative analysis of the data and the determination of which additional procedures would be in order; and the third, and final phase, consisted of additional data manipulations of individual vectors. In general, plotting and statistical techniques were used to describe the path of vector demagnetization and the relative stability of common sample vector components. Once suitable components were defined, the location of their magnetic poles were calculated.

The first phase of data analysis consisted of drawing three basic diagrams; the drawing of in situ and tilt corrected Zijderveld diagrams for the demagnetization path of each specimen, and a plot of the ratio of specimen intensity to the initial NRM intensity (J/J_o) with increasing demagnetization temperature.

The analysis of data used during the second phase of the program was a comparative study of individual Zijderveld diagrams for the various samples. This analysis attempted to seek out similar components among vector demagnetization paths of different samples. For each component a consistent vector trajectory over the spectra of three or more demagnetization steps was needed. Identified vectors were noted for further analysis, but in many cases the data required further manipulation.

The analysis of sample J/J_o diagrams provided a means of identifying the carrier of magnetic remanence and the upper limit demagnetization temperature. In most cases demagnetization continued over the ideal temperature (the temperature at which the magnetic intensity approached zero) to ensure complete sample demagnetization. A problem with achieving the ideal demagnetization temperature in the sample oven was indicated during this study and rectified by using higher oven temperature settings.

Because there was lack of consistent and stable vectors between samples and sites, a technique was needed to salvage apparently meaningless data. Two techniques which proved applicable were a principal component analysis of least squares fitting lines and planes (Kirschvink, 1980), and a converging remagnetization circles technique (Halls, 1978). These techniques along with a classic fold test by McElhinny (1964) provided the basis for the last phase of data analysis.

As mentioned above, the third and final phase of analysis consisted of using three techniques of data manipulation; a least squares analysis, converging remagnetization circles, and a fold test. The least squares analysis was chosen because it could be used on all available vector data. This technique uses a multivariate analysis of selected principal vector components to determine the direction of lines and planes of best least squares fit. Eigenvalues from this analysis are the variance of the data along each principal axis and provide a relative measure of linearity or coplanarity (Kirschvink, 1980). Using this technique, the data was analyzed to determine how a series of consecutive vector endpoints fit; eigenvalves of $E_1 \neq 0$, $E_2 = E_3 = 0$ described a line, eigenvalues of E_1 & $E_2 \neq 0$, $E_3 = 0$ described a plane, eigenvalues of E_1 & E_2 & $E_3 \neq 0$ described a conic volume. Vector components describing conic volumes were eliminated from the analysis, as well as lines or planes which did not consist of at least four consecutive vector endpoints.

Principal component planes are the result of two or more superimposed components of magnetic remanence. If there exists a difference between the normalized coercivity, or blocking temperature (T_b) spectra of two components after successive demagnetization, the directions revealed at successive stages of demagnetization will form a great circle and describe a plane (Figure 4). When this technique is extended to other samples or sites, the dispersion between components results in

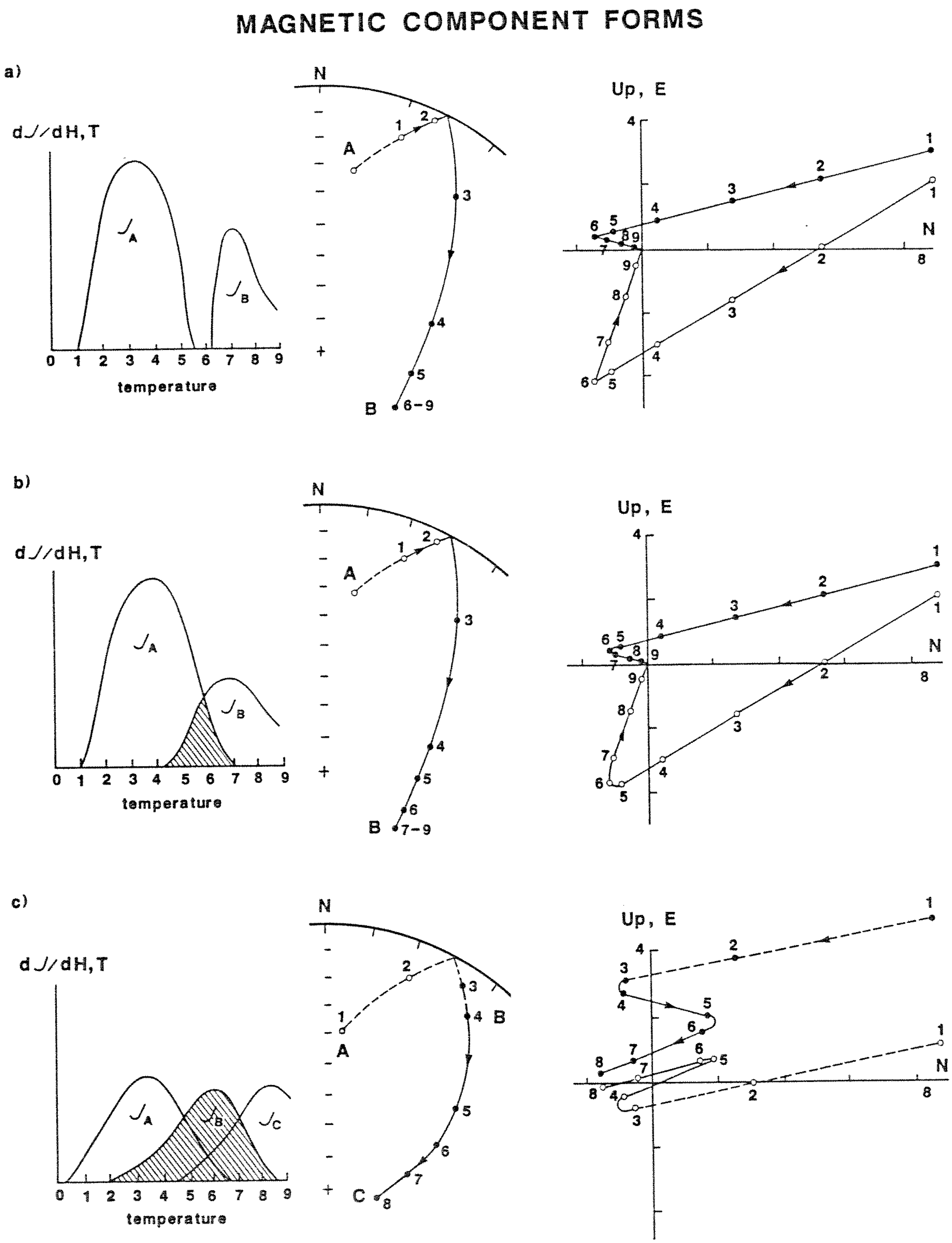


Figure 4. Examples of coercivity or blocking temperature spectra and resultant NRM behaviour during demagnetization illustrated on stereographic projection and Zijderveld diagram: (a) non-overlapping primary and secondary components; (b) partial overlap of components; (c) total overlap. (From Dunlop, 1979)

a convergence of great circle paths pointing in the direction of the least dispersed component (Figure 5). The direction of this component is the direction of the common remnant magnetization of all the samples used in the analysis.

The mean characteristic remanent magnetic directions (CRMD) were then subjected to incremental fold tests (McElhinny, 1964) to determine the stability of the magnetic direction. The stability of the magnetic direction (k_2/k_1) is given by the ratio of the sample precision about the mean vector direction for the tilt corrected population (k_2) to the precision of the in situ population (k_1). Where k_2 equals the population variance with 2(N-1) degrees of freedom before folding, k_1 equals the population variance after folding, also with 2(N-1) degrees of freedom, and N is the number of NRM directions. When the f distribution equals k_2/k_1, then the populations have different directional dispersions (population precision) for a given confidence limit and the fold test is significant within that limit. The stability of the pre-folding population direction is greatest with a significant fold test result. Figure 6 (McElhinny, 1964) illustrates the value of k_2/k_1 which must be exceeded for a given N if the difference in precision is to be significant at the 95% and 99% level of probability.

The precision value, k, may also be defined by $k=(N-1)/(N-R)$ for $k>3$ (Fisher, 1953), where k is the best estimate of the precision K, and R, is the length of mean

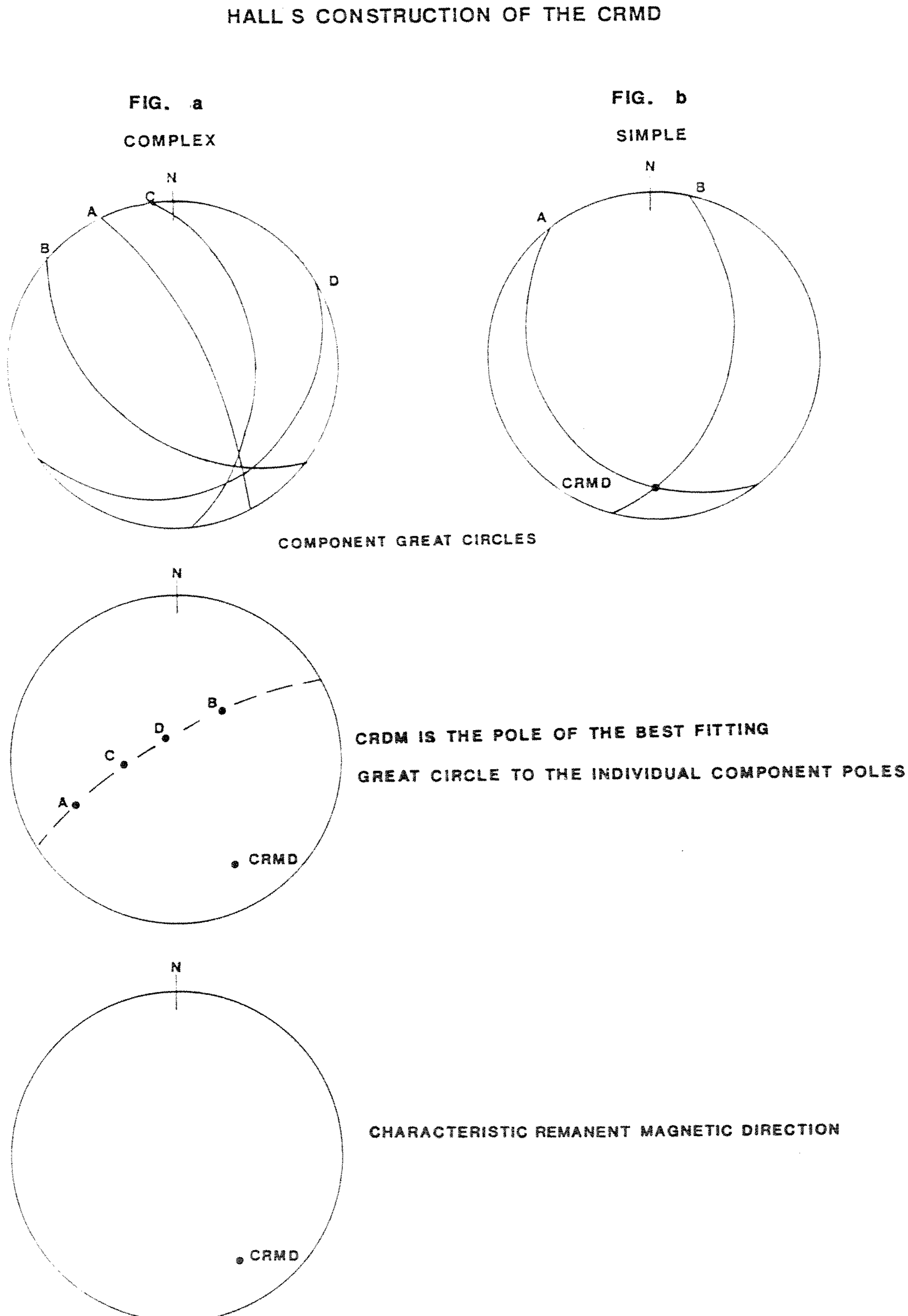


Figure 5. Examples using Halls' technique to find a characteristic remanent magnetic direction: (a) the complex form using three or more planar components (great circles); (b) the simple form where only two planar are used.

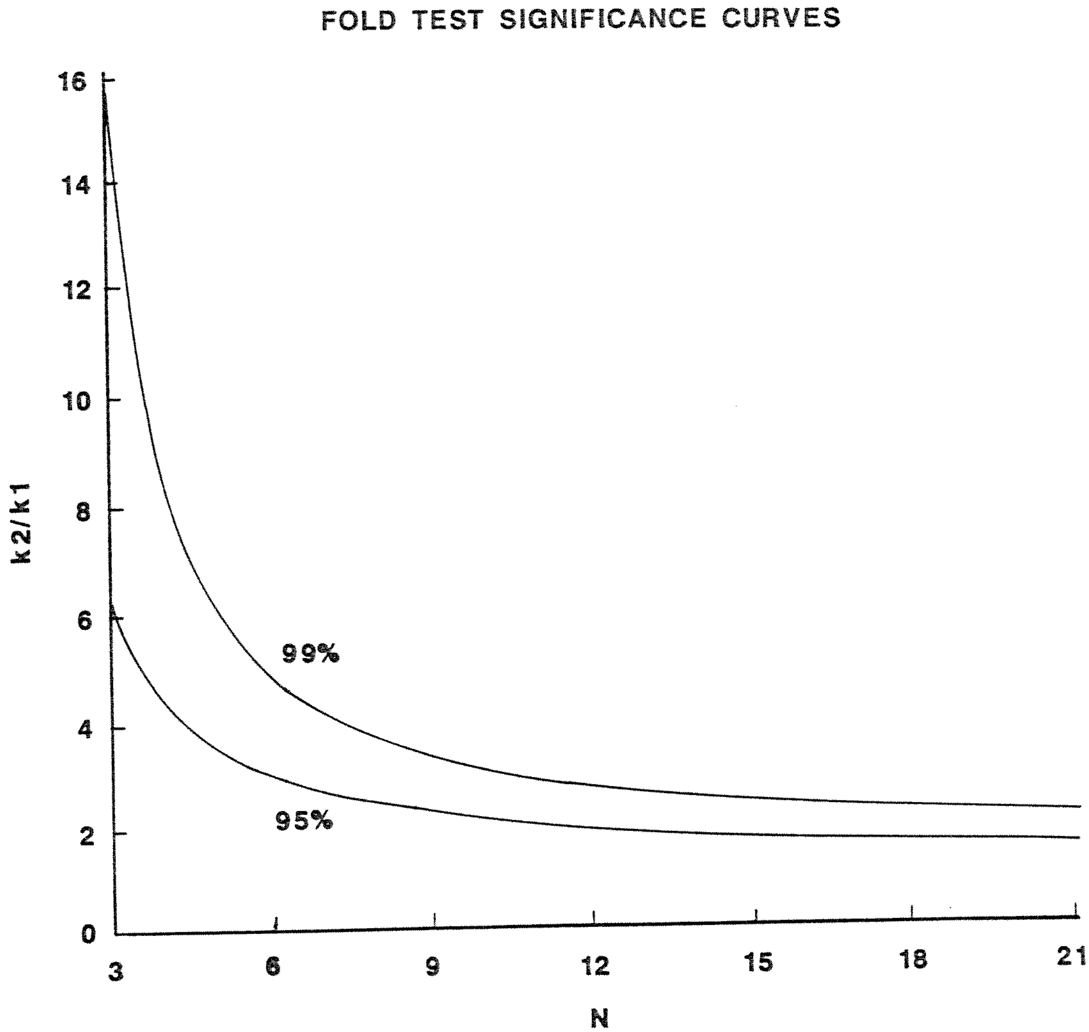


Figure 6. Examples of significance curves for the fold test. Values of k2/k1 plotted against N for the 95% and 99% probability level. (From McElhinny, 1964)

direction resultant vector about which the population of directions (N) is scattered. The precision value, k, is usually in the range of 10-1000, with the higher the value the more tightly the population is grouped about the mean direction. As K=0 or k approaches 1, a random or near random population of directions is implied. The probability (P) of the distribution as proposed by Fisher (1953) is determined by the angle, between the mean resultant vector (R) and one of the N directions and takes the form of

$$P = k/4\sin K \ \exp (k \cos\theta)$$

A quantity analogous to the standard deviation for a normal distribution is given by $81/k^{1/2}$ degrees. By describing the probability a direction exists within a given population, the acceptable limit of randomness is also defined. For this study, randomness is defined by $k<10$ with a probability of 95% that a given direction exists within a specified population.

Typically the fold test used only the in situ (k_1) and the tilt corrected (k_2) precision values (k) of the mean remanence direction. Previous investigators (Kent and Opdyke, 1978; Van der Voo, 1980; Miller and Kent 1986, 1988) have realized the utility of incremental fold tests in determining when the magnetic remanence was acquired. This is especially true for Silurian and Devonian age rocks which are plagued with secondary magnetizations acquired at different degrees of bedding tilt. The incremental fold test was conducted on four stages of tilt correction; 25%, 50%, 75% and 100%. The most stable direction was given by the greatest value of the fold test ratio (k_2/k_1). The timing of remanence acquisition was determined by the results of the fold test and described by the folding phase, prefolding, synfolding or postfolding. The age associated with remanence acquisition is determined by comparing the pole position for the most stable remanence direction to the North American Apparent Polar Wander Curve (NAAPWC).

The linear components developed by the principal component technique have a remanent magnetic direction that can be used as a characteristic remanent magnetic direction (CRMD) without any further manipulation. The linear component directions (LCD) were statistically treated using the same techniques as the CRMD's so the two results can be directly compared.

After an analysis of the isolated magnetic components, it was clear that the data did not follow patterns of previous Silurian and Devonian investigations. The levels of comparison used included; bedding dip direction, formation age, grain size and sample location. At this point of the analysis it was felt that the next prudent step would be to determine if the data was randomly distributed.

To test for randomness a test closely following a Chi Squared test was developed. The data was graphed using declination intervals of ten degrees between 0 and 180 degrees. For declinations greater than 180 degrees, the complementary angle was used. At this time the sign (+/-) of dip was waived. The null hypothesis of the test assumed that if the frequency of the interval is equally distributed then the data is random. The alternative is the negative; that if the data is not equally distributed then it is not random.

The test was conducted for in situ and tilt corrected data. The results of the test indicated the data was not random if the entire data set was compared. This analysis was continued for varying degrees of tilt correction; 25%, 50%, and 75% to see if a relationship existed between the amount of tilt correction and the frequency of the observations.

The success of this rather unorthodox method reduced the complexity of the data, and made it more appropriate for defining a CRMD, the stability of the remanence and the location of the pole.

RESULTS

This section will discuss the collected paleomagnetic data in two sections; the results of the sample demagnetization, and the results of Halls' analysis.

Sample Demagnetization

The results of sample demagnetization are characterized by three forms of magnetic components; lines, planes and conic volumes. In general, planar forms were the most common form of magnetic components observed, as they were found in sixty seven samples of the ninety four samples examined. This finding was very disturbing, as this type of component form indicates the remanence of two or more discrete magnetic components are being removed simultaneously at different rates. The effect of multiple component demagnetization was so varied that the resulting sample orientations (declination and inclination) observed often varied greatly between samples of the same site. Approximately 17 percent of the samples analyzed were composed of linear components.

To interpret the effects of multiple overlapping magnetic components, each remanence was divided into its simplest component forms; lines and planes. All conic volume components were eliminated from the data set because the direction of the remanence could not be solved. A similar rate of demagnetization between two or more components prohibits the isolation of simple component forms for which their orientation can be solved. The data was then sorted by declination according to the declination of the remanence. Earlier attempts to sort the data by location or by stratigraphy indicated the data was randomly scattered.

Planar Component Data

Figure 7 illustrates the planar data with both the in situ and tilt corrected positions as a frequency of the declinations observed; declinations are provided in ten degree increments, from 0 to 180 degrees. Components with declinations greater than 180 degrees were given their complementary declination less than 180 degrees with an opposite sign (+/-) of their inclination. The sign of the inclination for a given mean declination was determined by the majority of values for that particular population.

In situ orientations shown in Figure 7 is characterized by three general component directions A, B and C. Table 3 presents the individual component mean declination, inclination, and a precision value (k). It is assumed that because these component frequencies are greater than the remaining component frequencies, the magnetic remanence is biased in component A, B and C directions.

The bias observed in the in situ orientation (Figure 7) is only valid because of the increased dispersion of the component population with tilt correction (TC). Tilt corrected

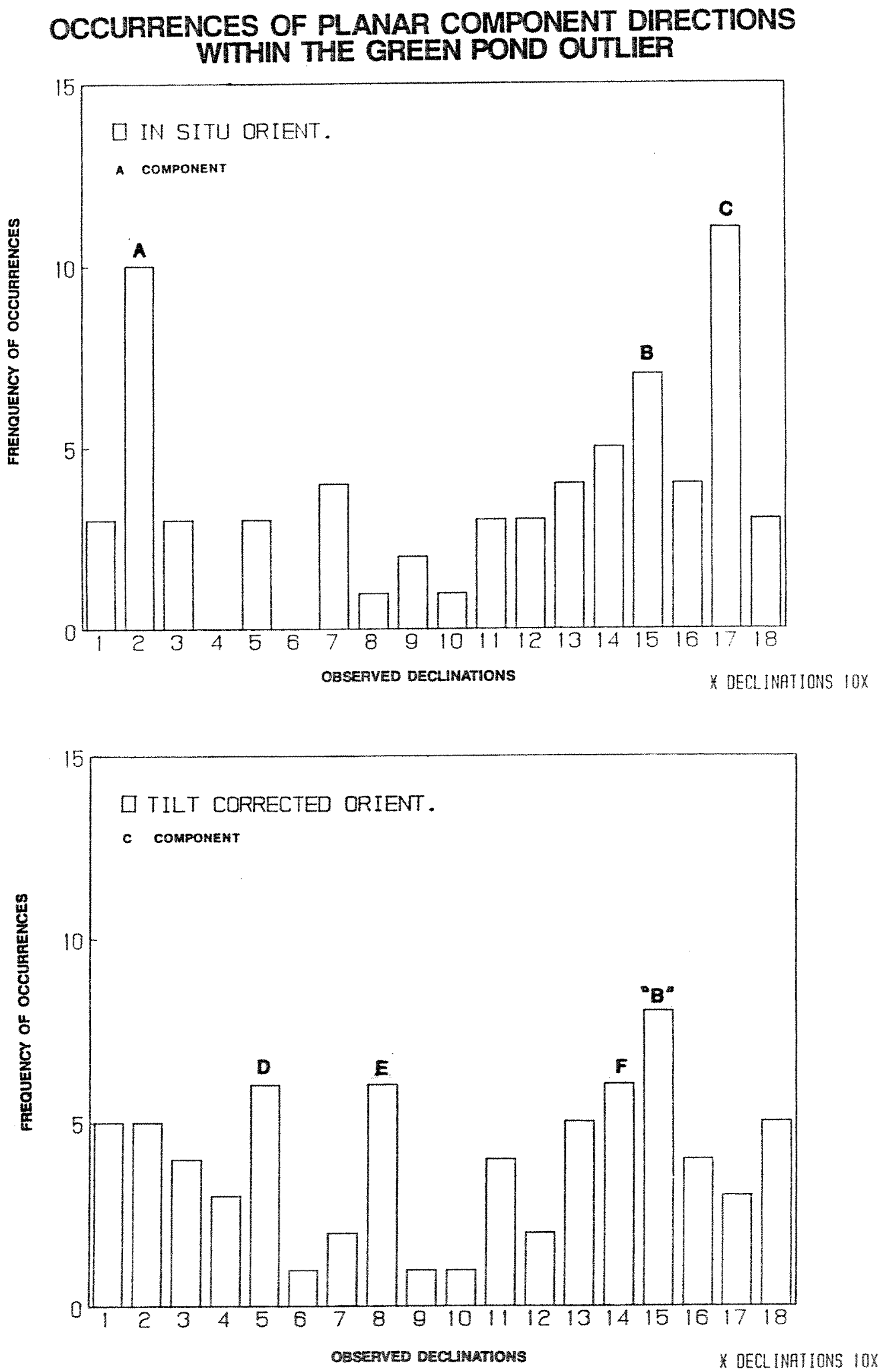


Figure 7. The occurrences of planar component directions within the Green Pond samples. Plots illustrate the frequency of observations for in situ and tilt-corrected sample orientations.

Table 3

Individual Component Data

Component A1
In Situ

Sample	Dec.	Inc.
502	15	+24
202	17	-23
230	14	-31
103	12	+10
801	17	+11
801a	17	+8
Mean	15.3	+17.8

k=71.7
N=6
alpha 95=7.9

Component A1
Tilt Corrected

Sample	Dec.	Inc.
502	43	+21
202	9	+79
230	12	+3.6
103	17	+2.8
801	40	+43
801a	43	+44
Mean	28.7	+32.4

k=6.6
N=6
alpha 95=27.9

Component A2
In Situ

Sample	Dec.	Inc.
240	17	+63
902	13	+68
701	18	+60
701b	10	-85
Mean	15.9	+69

k=52.4
N=4
alpha 95=12.8

Component A2
Tilt Corrected

Sample	Dec.	Inc.
240	157	+50
902	10	+55
701	14	+19
701b	148	+37.9
Mean	77.5	+68.0

k=2.3
N=4
alpha 95=78.6

All Samples (In Situ)

Mean	15.5	+38.0

k=8.54
N=10
alpha 95=17.5

All Samples (Tilt Corrected)

Mean	37.3	+46.0

k=3.4
N=10
alpha 95=30.3

Table 3 (cont.)

Individual Component Data

Component B
In Situ

Sample	Dec.	Inc.
503	140	+12
273	143	-33
274	144	-10
1500	145	-13
480	142	-22
704	140	-7
703	147	-36
Mean	142.9	-19

k=47.20
N=7
alpha 95=8.8

Component B
Tilt Corrected

Sample	Dec.	Inc.
503	140	+12.7
273	134	-71
274	141	-48
1500	202	-52
480	143	-39
704	134	-70
703	126	+80
Mean	128.5	+61.6

k=9.9
N=7
alpha 95=22.9

Component "B"
In Situ

Sample	Dec.	Inc.
503	140	+12
800b2	168	+68
274	38	+29
203	132	-66
210	152	-50
263	166	+24
701b	10	+85
480	103	+22
Mean	127.3	+53.5

k=4.1
N=8
alpha 95=30.9

Component "B"
Tilt Corrected

Sample	Dec.	Inc.
503	140	+12.7
800b2	143	+55
274	141	-48
203	145	+56
210	142	+80
263	142	-6
701b	148	+37.8
480	143	-39
Mean	142.9	+41.9

k=11.6
N=8
alpha 95=16.9

Component C1
In Situ

Sample	Dec.	Inc.
903	161	-64
800b2	168	-68
702a	169	-65
290b	160	-68
Mean	164.5	-66.0

k=847.3
N=4
alpha 95=3.1

Component C1
Tilt Corrected

Sample	Dec.	Inc.
903	171	-45
800b2	143	+55
702a	169.9	-65
290b	132	+63
Mean	155.2	+58

k=34.8
N=4
alpha 95=19.0

Table 3 (cont.)

Individual Component Data

Component C2
In Situ

Sample	Dec.	Inc.
201b	162	-13
1300	164	+8
263	166	+24
281	161	-23
501	168	+41
503	163	+0.5
Mean	163.8	+18.2

k=31.6
N=6
alpha 95=12.1

All Samples

Mean	164.0	-37.5

k=9.1
N=10
alpha 95=16.8

Component C2
Tilt Corrected

Sample	Dec.	Inc.
201b	9	+61
1300	173	-29
263	142	-6
281	36	+62
501	152	+2.5
503	11	-71
Mean	155.8	-45.9

k=3.6
N=6
alpha 95=28.0

All Samples

Mean	155.6	+51.5

k=6.0
N=10
alpha 95=21.4

Component D
In Situ

Sample	Dec.	Inc.
102	48	+0.6
801c	17	+8
801	17	+11
1600	20	-1
401	41	+25
502	15	-24
Mean	26.2	+11.9

k=21.2
N=6
alpha 95=14.8

Component D
Tilt Corrected

Sample	Dec.	Inc.
102	41	-25
1600e	42	+1.6
401	41	+25
502	43	+21
801c	43	+44
801	40	+43
Mean	41.7	+26.0

k=26
N=6
alpha 95=10.8

Table 3 (cont.)

Individual Component Data

Component E
In Situ

Sample	**Dec.**	**Inc.**
1700	178	-42
1400	4	+34
281	9	+45
275	62	+19
604	60	+7.4
250	109	-19
Mean	123.8	+42.7

k=2.5
N=6
alpha 95=50

Component E
Tilt Corrected

Sample	**Dec.**	**Inc.**
1700	76	+30
1400	71	+25
281	78	+41
275	70	+13
604	73	+.3
250	78	-50
Mean	73.9	+26.0

k=19.6
N=6
alpha 95=15.4

Component F
In Situ

Sample	**Dec.**	**Inc.**
704a	140	-7
705	139	-69
273	134	-10
290	160	-68
800b1	150	-27
1200	137	+37
Mean	141.7	-36.0

k=8.5
N=6
alpha 95=19.7

Component F
Tilt Corrected

Sample	**Dec.**	**Inc.**
704a	134	-70
705	133	+40
273	134	-71
290	132	+63
800b1	138	-82
1200	137	-12
Mean	134.6	-57.0

k=10.1
N=6
alpha 95=22.0

orientations illustrate the observed frequencies of sorted TC declination data. As the tilt corrected figure indicates, several other component directions appear to have gained significance (D, E, F) as a result of TC. Table 4 presents the statistical data for all of the components observed in Figure 7.

Figures 8A through 8F are examples of typical sample Zijderveld diagrams where major in situ or tilt corrected components could be identified. The individual magnetic signature of each of the samples illustrated is composed of several magnetic components. In most cases the major component was isolated from surrounding components and then analyzed using the Kirshvink's multivariate principal component analysis.

Component A was identified in ten samples of the in situ (0% TC) data with a mean declination of D=15.5 degrees, an inclination of I=+38.0 degrees, and a precision value k=8.54. Of the ten samples with component A characteristics; six samples (A1 population) had inclinations less than 40 degrees while the remaining samples (A2 population) had inclinations greater than 60 degrees. All but three of the samples of this population had positive (reversed) inclination polarities. The mean declination, inclination and k for subset A1 was D=15.3, I=+17.8, and k=71, and subset A2 was D=15.9, I=+69, and k=52.4. Figure 8A illustrates a Zijderveld diagram for sample 902 in the 0% TC position. Component A was developed between

Table 4

Major In Situ Component Statistics

Component	Declination	Inclination	k	N	Alpha 95
A(all samples)	15.5	+38.0	8.0	10	17.5
A1	15.3	+17.8	71.7	6	7.9
A2	15.9	+69.0	52.4	4	12.8
B	142.9	-19.0	47.2	7	8.8
"B"	127.3	+53.5	4.1	8	30.9
C(all samples)	164.0	-37.5	9.1	10	16.8
C1	164.5	-66.0	847.3	4	3.1
C2	163.8	+18.2	31.6	6	12.1
D	26.2	+11.9	21.2	6	14.8
E	123.8	+42.7	2.5	6	50.0
F	141.7	-36.0	8.5	6	19.7

Major Tilt Corrected Component Statisitics

Component	Declination	Inclination	k	N	Alpha 95
A(all samples)	37.3	+46.0	3.4	10	30.3
A1	28.7	+32.4	6.6	6	27.9
A2	77.5	+68.0	2.3	4	78.6
B	128.5	-60.0	9.9	7	22.9
"B"	142.9	+41.9	11.6	8	16.9
C(all samples)	155.6	+51.5	6.0	10	21.4
C1	155.2	+58.0	34.8	4	19.0
C2	155.8	-45.9	3.6	6	28.0
D	41.7	+26.0	26.0	6	10.8
E	73.9	+26.0	19.6	6	15.4
F	134.6	-57.0	10.1	6	22.0

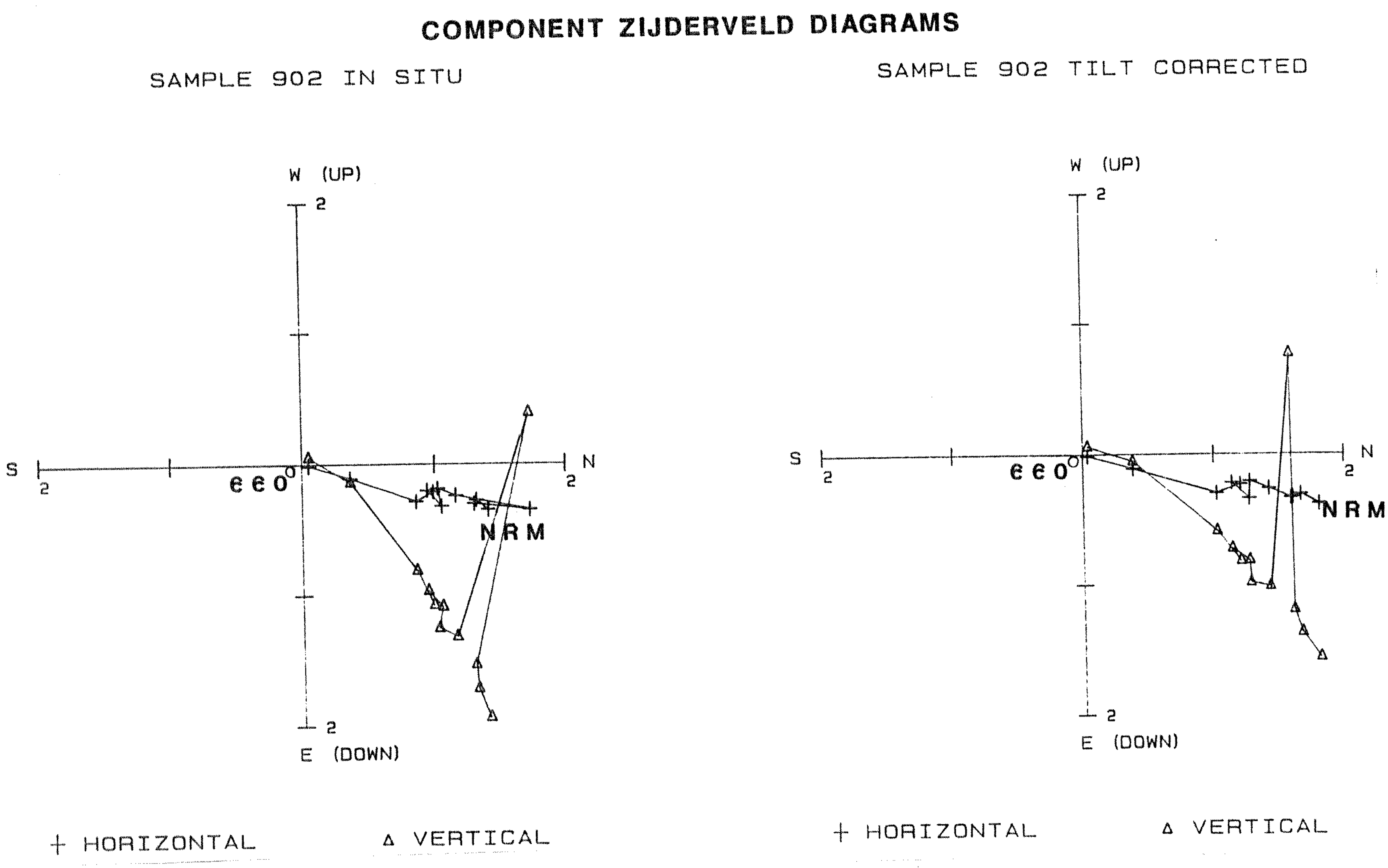


Figure 8a. Examples of a typical Zijderveld diagrams with the A component. All units equal x10^{-6} e.m.u. cm^{-3}

demagnetization step 1 through 12 which represented an apparent thermal interval of 0 to 660 degrees Celsius. As the population of the A component was rotated to 100% TC, the precision of the population mean deteriorated and approached randomness (D=37.3, I=46.0, and k=3.4). The subsets of the A component were also affected by tilt correction, as the precision of populations A1 and A2 equaled 6.6 and 2.3 respectively. The A component was therefore not considered a significant part of the tilt corrected magnetic field.

The polar positions determined from the component A data are located in the southern hemisphere. These positions for the in situ data are: A1 55.3 degrees south, 133.2 degrees east; A2 74.2 degrees south, 143.8 degrees east; and 66.3 degrees south, 144.3 degrees east for all component A data. The pole positions for the tilt-corrected data are: A1 56.0 degrees south, 161.0 degrees east; A2 37.8 degrees south, 156.9 degrees east; and for component A data 56.5 degrees south, 183.7 degrees east.

The B component was identified for seven samples of in situ data for which a mean declination of D=142.9, inclination of I=-19.0, and k= 47.20 was determined. Of the seven samples, six samples had negative (normal) inclination polarity. Figure 8B illustrates two typical Zijderveld diagrams from which the B component was isolated; sample 273 at 0% TC, and sample 210 at 100% TC. The B component was developed between demagnetization steps 1 and 11 in both

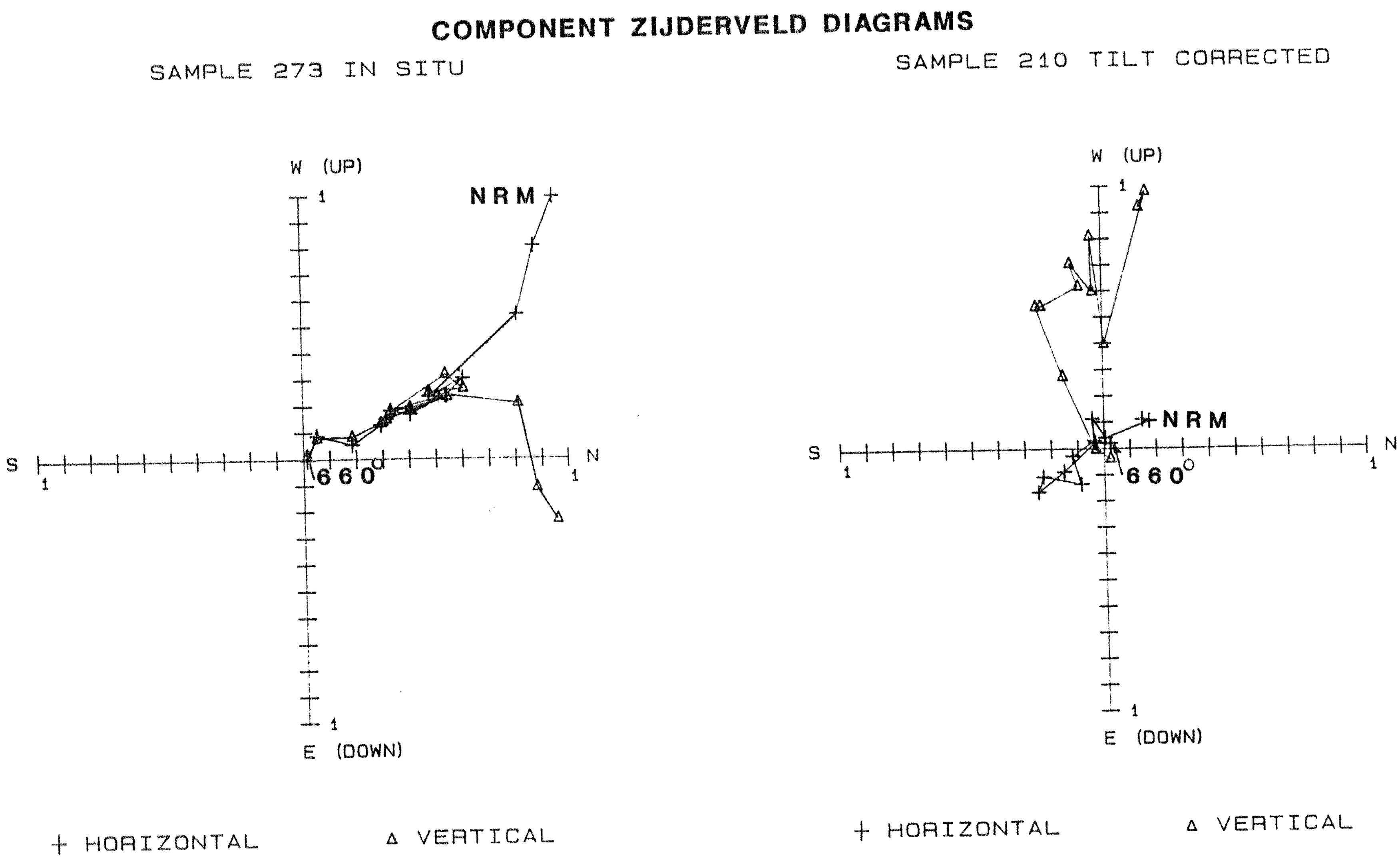


Figure 8b. Examples of typical Zijderveld diagrams with the B (in situ) and "B" (tilt corrected) components. All units equal $\times 10^{-6}$ e.m.u. cm^{-3}

diagrams which corresponded to an apparent thermal temperature range between 0 and 660 degree Celsius. As a result of the tilt correction rotation, the sample population forming the original in situ population (B) became more dispersed with k decreasing from 47.2 to 9.9 at 100% TC. As the figure illustrates, however, the "B" component declination at D=140 degrees was still a significant frequency observation after 100% TC. Using the sample declination data, resorted after tilt correction, eight samples are observed at the 140 degree interval. The declination, inclination, and k of the new population was D=142.9, I=+41.9 and k=11.6. The in situ orientation of the "B" population developed a mean about a declination of D=127.3 and an inclination of I=53.5 with a precision equal to k=4.1.

Polar positions determined from B and "B" component data are generally located in the northern hemisphere. There is however one exception, the B tilt-corrected position which is located in the southern hemisphere. The polar positions for the in situ data are; B 44.7 degrees north, 162.8 degrees south and for the "B" component, 0.66 degrees north, 147.2 degrees east. For the tilt-corrected data the positions are; B 4.2 degrees south, 142.3 degrees east and for the "B" component 16.3 degrees north, 140.9 degrees east.

The C component was identified in ten samples of in situ declination data. The component had a mean declination of D=164.0, inclination of I=-37.5 and k=9.1. Figure 8C

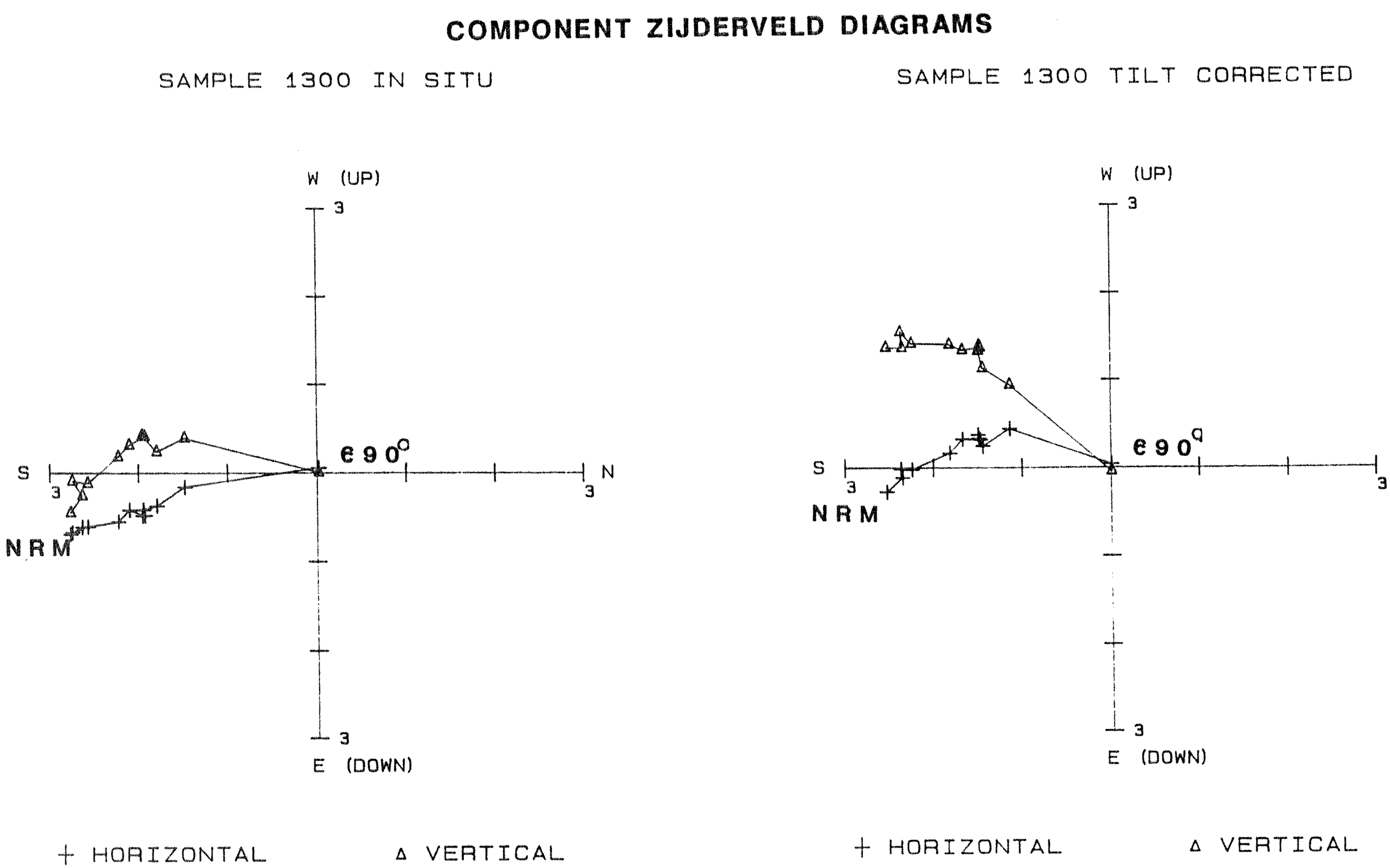


Figure 8c. Examples of typical Zijderveld diagrams with the C component. All units equal $\times 10^{-6}$ e.m.u. cm^{-3}

illustrates a typical sample Zijderveldt diagram of component C. The data was then divided into two subsets based on the angle of inclination, as was done with the A component. As a result the precision of the subset, means were greatly improved. One subset, C1 with inclinations greater than 60 degrees, had a mean D=164.5 degrees, I=-66.2 degrees, k=847.3, and N=4. The second subset, C2 with inclinations less than 60 degrees, had a mean D=163.8 degrees, I=+18.2 degrees, k=31.6, and N=6. The inclination data of the individual subsets was fairly consistent; the C1 subset had a negative polarity (4 of 4 samples) and was confined between the dip angles of 64 and 68 degrees. The C2 subset was not as precise, as four of six samples had a positive polarity and an angle of inclination between 0.5 and 41 degrees. As the original set of data was rotated to the 100% TC position, the population became randomly dispersed (k=6.0). The effect of tilt correction on the precision of the subset data was just as significant; for C1 k became 34.8, and for C2 k became 3.6.

Polar positions determined from the component C data are located in the northern hemisphere. Polar positions determined from the in situ data are as follows: C1 76.8 degrees north, 157.8 degrees east; C2 37.4 degrees north, 126.3 degrees east; and for all in situ component C data, 65.8 degrees north, 144.9 degrees east. For the tilt-corrected data the positions are: C1 7.1 degrees north, 125.2 degrees east; C2 65.8 degrees north, 168.9 degrees east; and for all component C data, 13.4 degrees north, 127.0 degrees east.

The three components D, E, and F were first observed as a result of the sorting of 100% tilt corrected declination data and the plotting of the frequency of declination observations against intervals of declination. The populations of a given component were then folded to determine if the sample population maintained its precision.

The D component was observed in six samples of tilt corrected data. From the data, a mean declination of 41.7 degrees, an inclination of I=+26 (5 of 6 samples indicated a positive polarity), and k=26 was determined. When the population was rotated to its in situ position, the mean declination and inclination maintained its precision, only decreasing slightly to k=21.2. The rotation however, shifted the orientation of the mean counter-clockwise to D=26.2 degrees and an I=11.9 degrees. Figure 8D illustrates a typical Zijderveld diagram with the D component. The component exists in a very narrow range of apparent demagnetization temperatures, between 400 and 560 degrees, and between 740 and 780 degrees Celsius.

Polar positions determined from the component D data are located in the southern hemiphere. Polar positions for in situ and tilt-corrected data are 47.9 degrees south, 146.9 degrees east, and 44.6 degrees south, 171.3 degrees east, respectively.

COMPONENT ZIJDERVELD DIAGRAMS

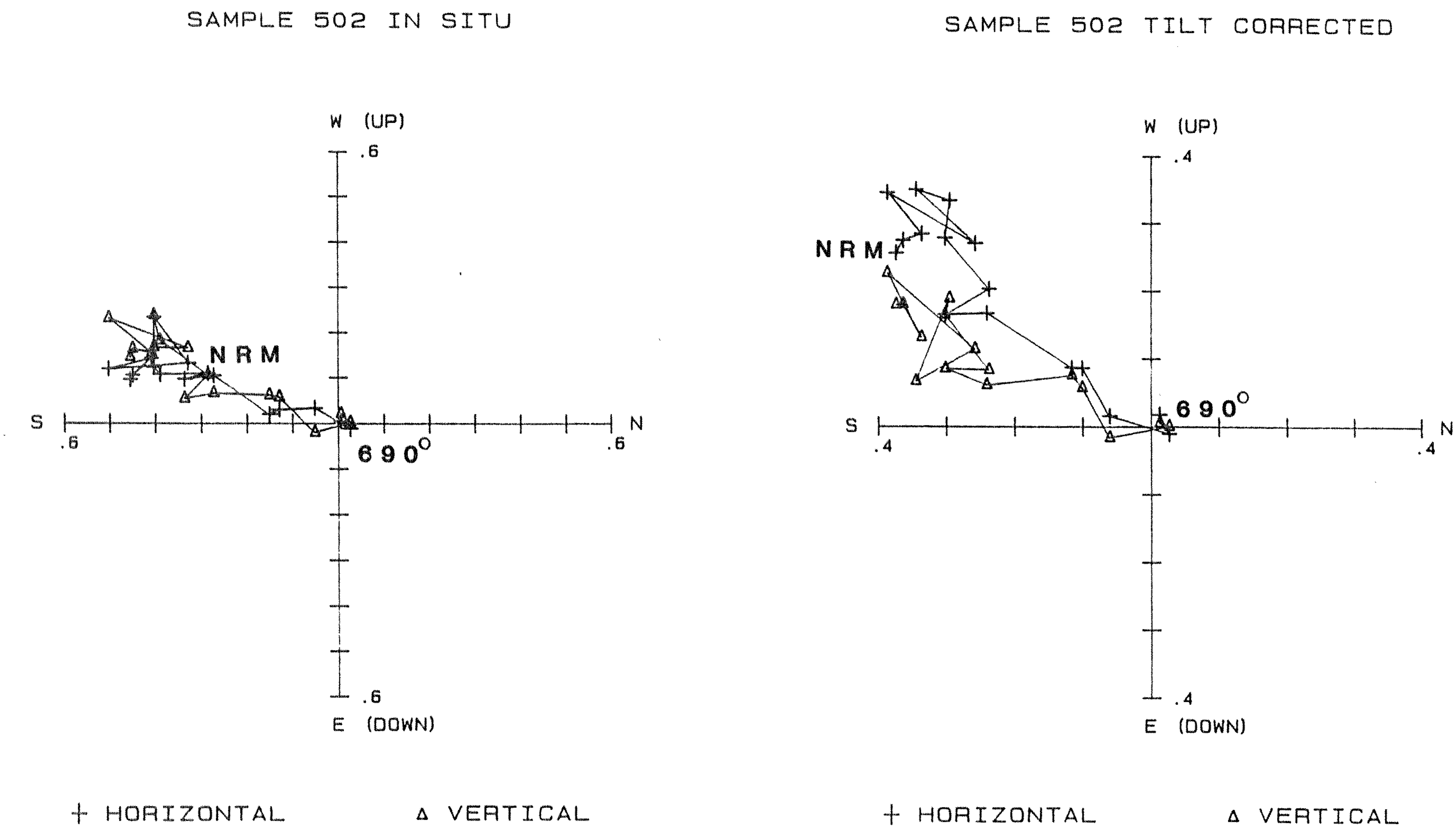


Figure 8d. Examples of typical Zijderveld diagrams with the D component. All units equal $\times 10^{-6}$ e.m.u. cm^{-3}

The E component was observed in six of the tilt corrected samples, for which a mean declination of D=73.9 degrees, an inclination of I=+26.0, and k=19.6 were determined. The polarity of the inclination TC data was predominately positive (5 of 6 samples). When the component population was rotated to its in situ position the precision of the mean was decreased (k=2.5). Figure 8E illustrates a typical sample Zijderveld diagram with the E component existing between apparent temperatures 200 and 690 degrees Celsius; demagnetization steps 1 through 12.

Polar positions determined from the component E data are located in both, the northern and southern hemispheres. Polar positions for both the in situ and tilt-corrected data are; 6.1 degrees north, 155.3 degrees east and 21.0 degrees south, 195.8 degrees east, respectively.

The F component was observed in six samples of the 100% TC data with a resulting mean declination of D=134.6 degrees, inclination of I=-57 degrees and k=10.1. The inclination of the TC population was dominantly negative (5 of 6 samples). When the component population was rotated back to the in situ position the precision of the mean only decreased slightly, k=8.5. The effect of folding on the mean declination was also very slight, a change of approximately seven degrees from 141.7 (0% TC) to 134.6 degrees (100% TC). The inclination however, changed more abruptly from -36 (0% TC) to -57 degrees (100% TC). Figure 8F illustrates a typical Zijderveld diagram

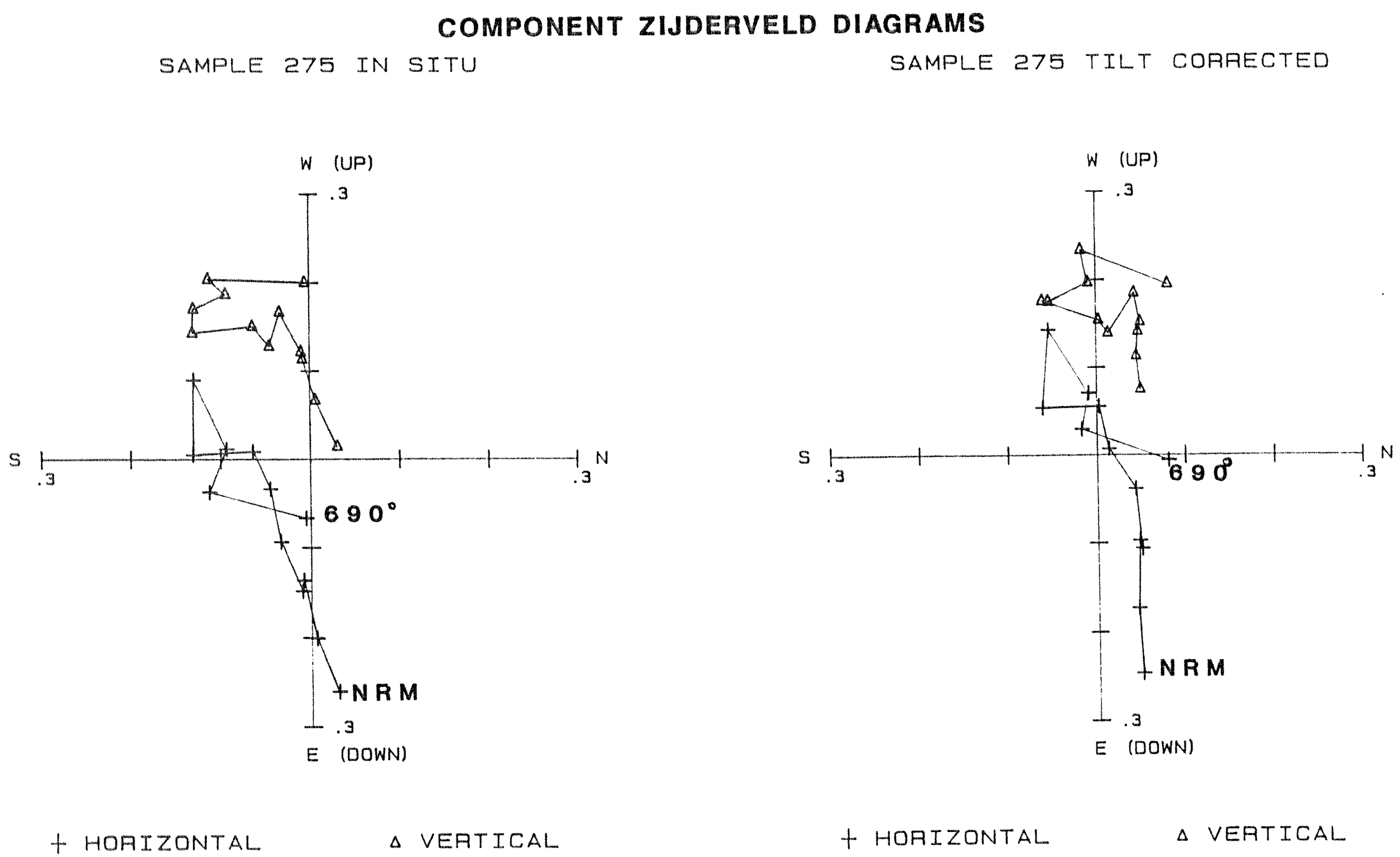


Figure 8e. Examples of typical Zijderveld diagrams with the E component. All units equal $x10^{-6}$ e.m.u. cm^{-3}

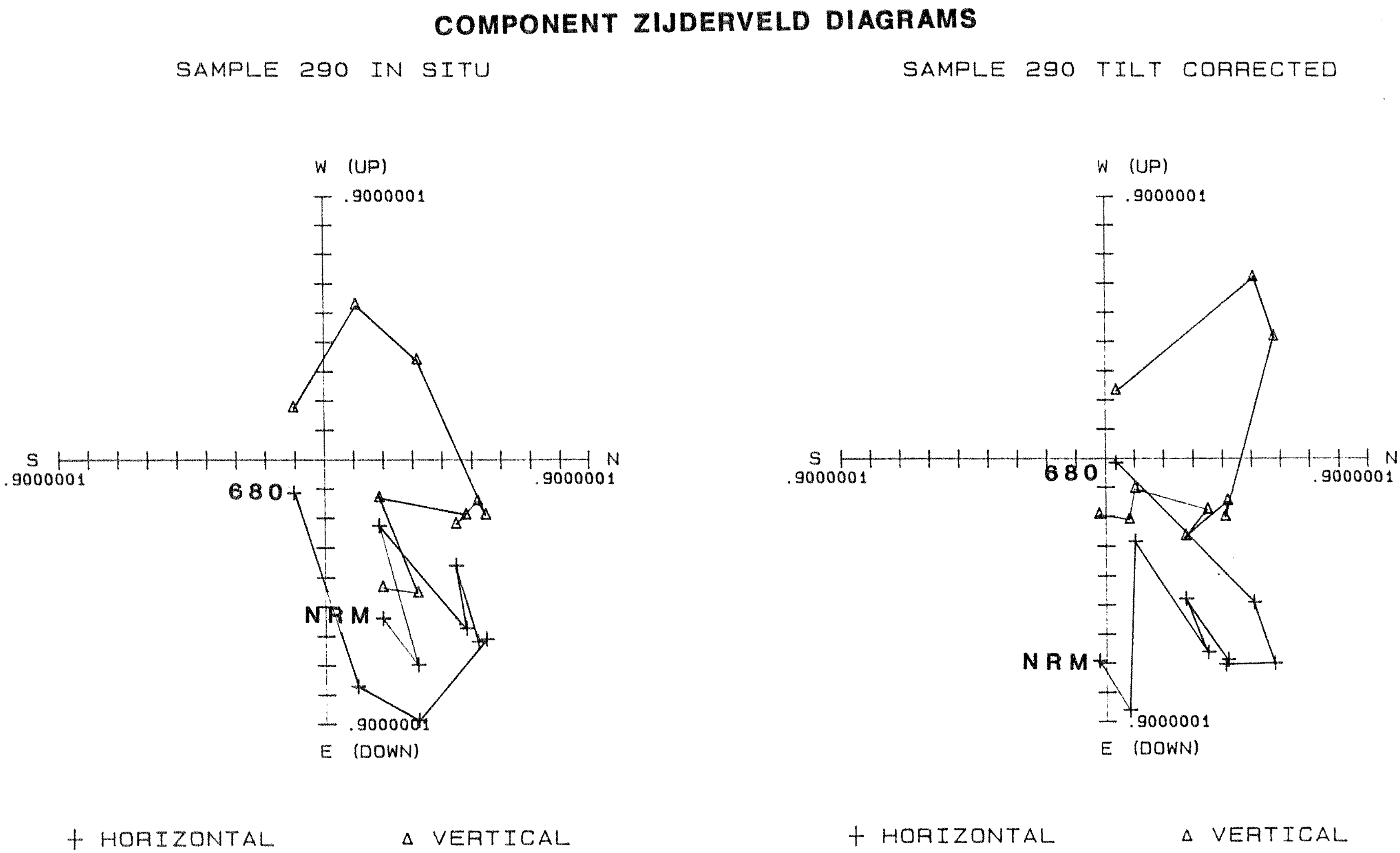


Figure 8 f. Examples of typical Zijderveld diagrams with the F component. All units equal $\times 10^{-6}$ e.m.u. cm^{-3}

composed of the F component. The component exists at an apparent temperature between 200 and 680 degrees Celsius which represents demagnetization steps 1 through 12.

Polar positions determined from component F data are located in the northern hemisphere. The polar positions for the in situ and tilt-corrected data are; 51.3 degrees north, 174.7 degrees east and 55.0 degrees north, 186.4 degrees east, respectively.

Figures 9 and 10 illustrate the positions of the individual planar components plotted on a stereo net and the polar positions of the planar components plotted on an equatorial net, respectively.

Linear Component Data

From the demagnetization of ninety four samples, seventeen samples indicated the presence of linear principal components. The positions of the linear components are illustrated on Figure 11. For a component to be considered linear, it should span at least four demagnetization steps with eigenvalues not exceeding $E_1>97.0$, $E_2<3.0$, and E_3 0. Two observations made from this data are the general declination and inclination of the components (vector endpoints) and their precision. The in situ component positions are, in general, scattered on the stereonet with the majority of the data (positive projection) found in the northern hemisphere of the net. The precision parameter (k=2.9) of the in situ data

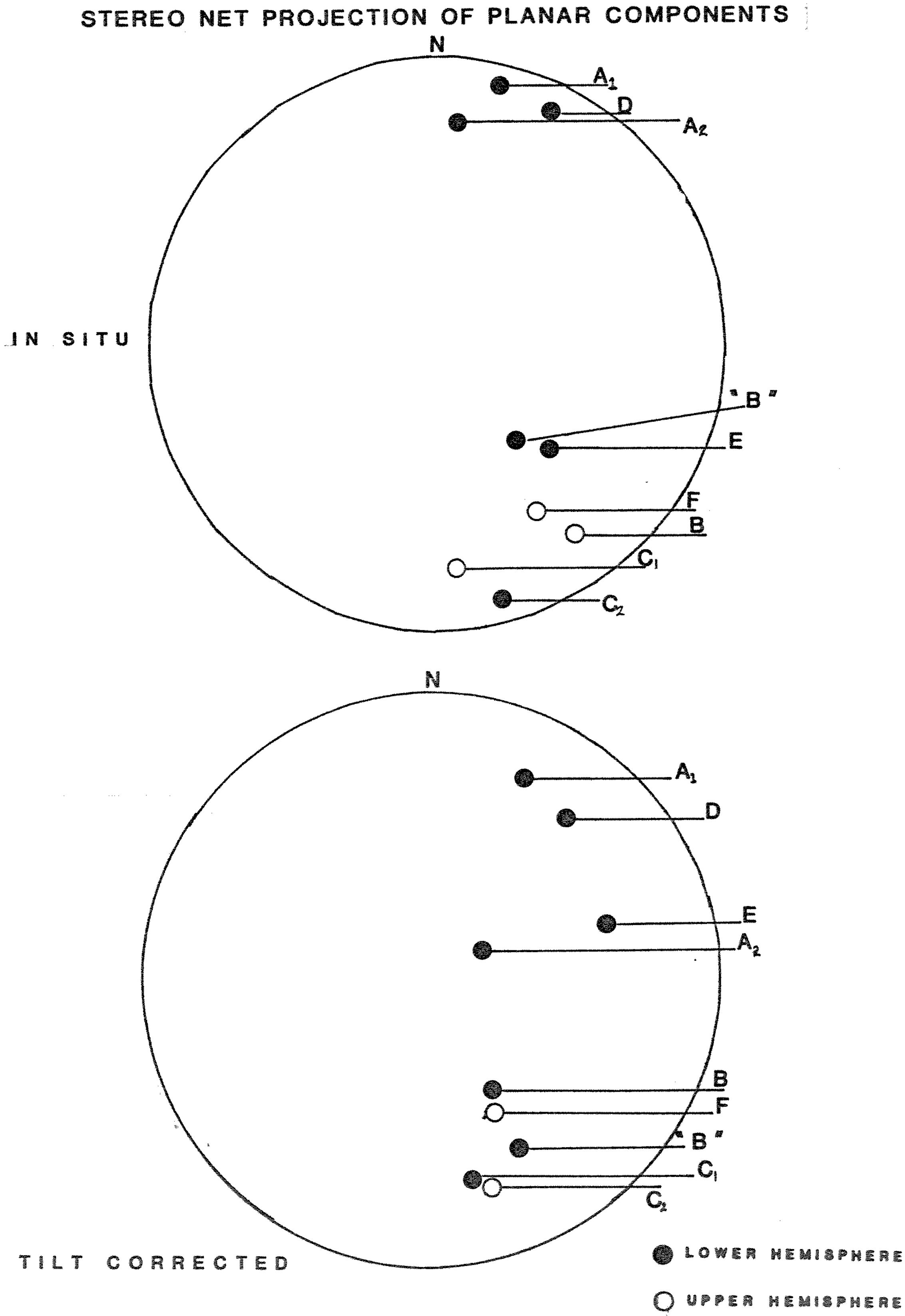


Figure 9. Stereo net projections of Green Pond planar component data.

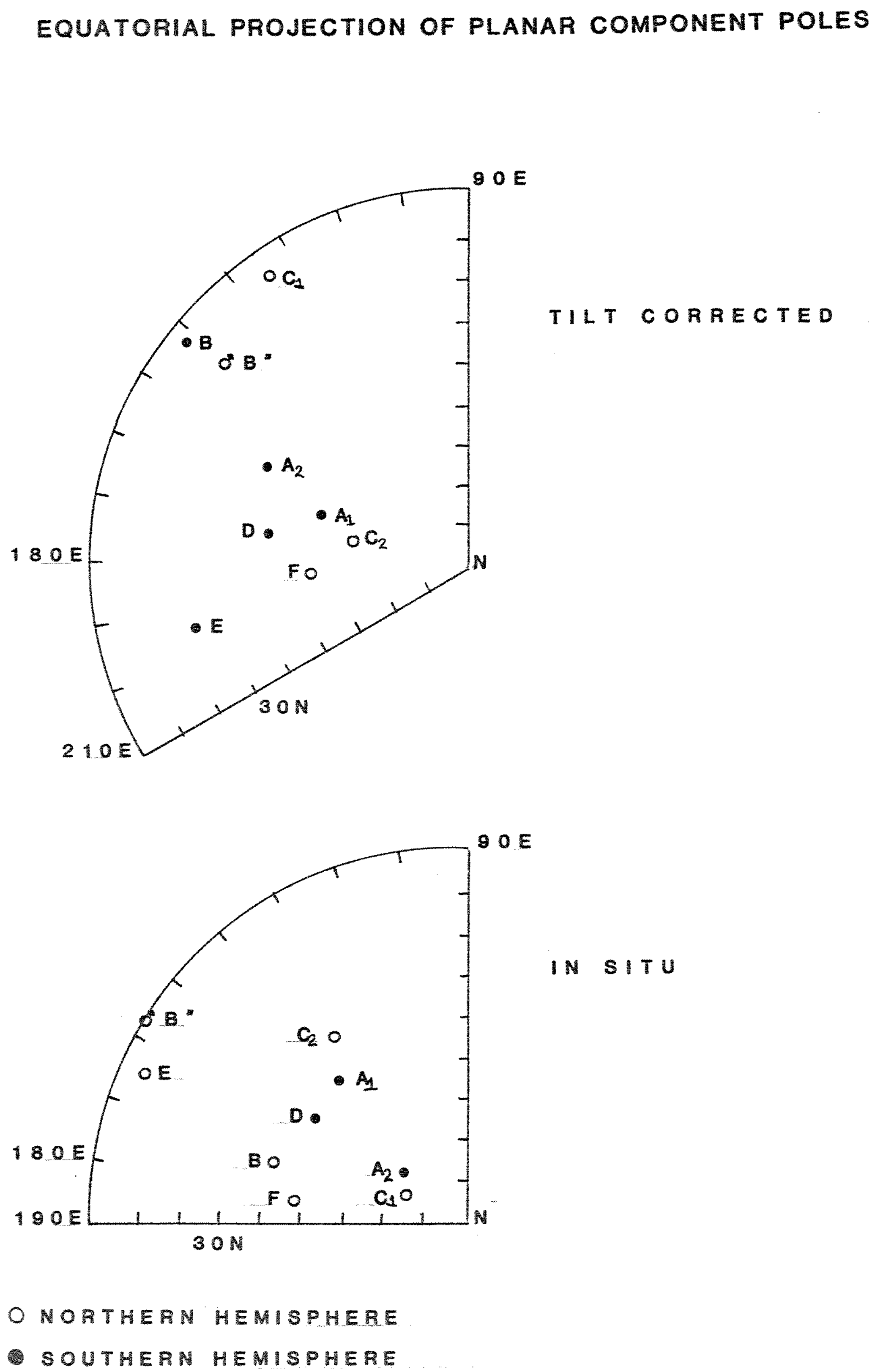


Figure 10. Equatorial projection of planar component poles of Green Pond data.

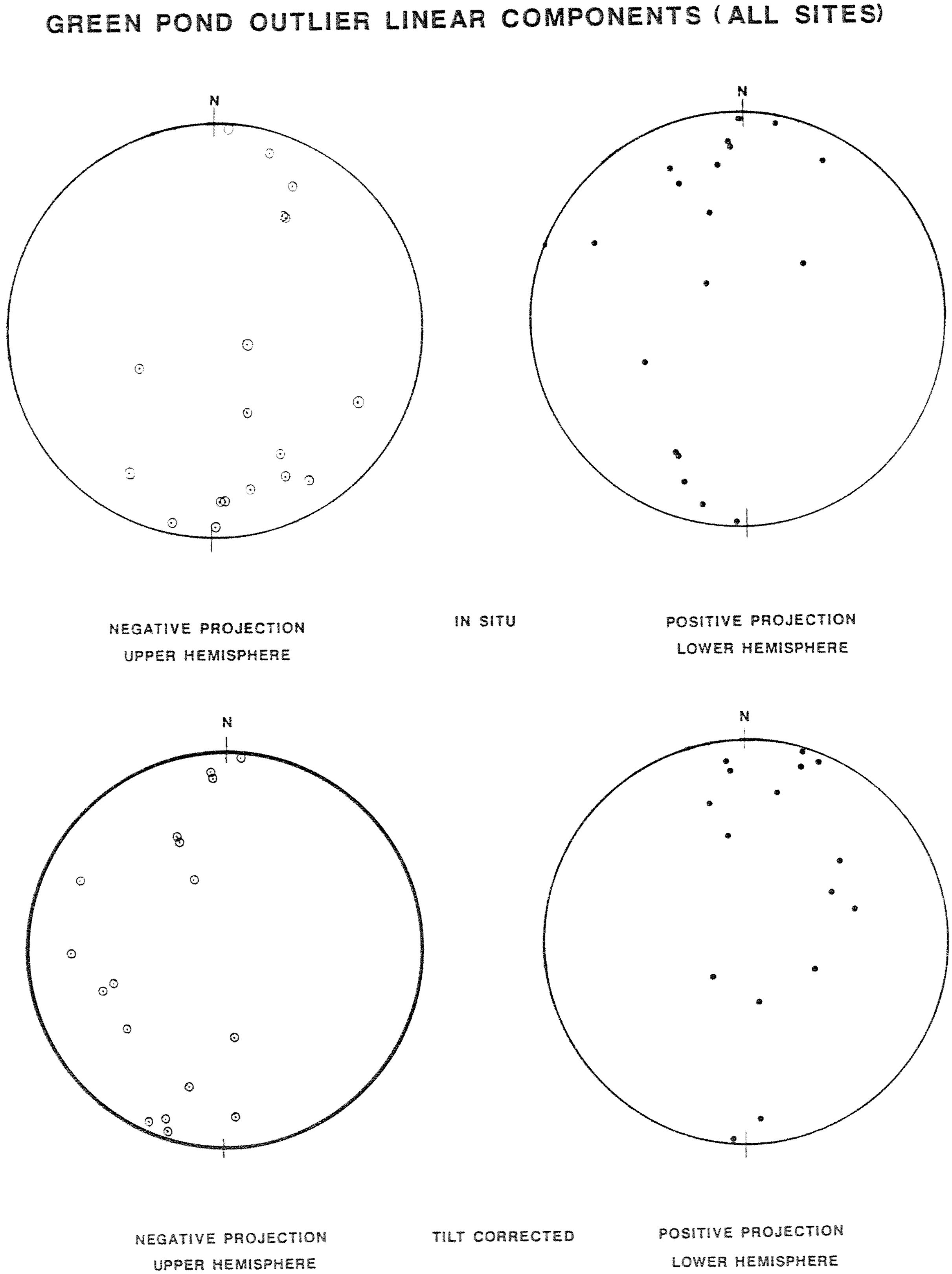


Figure 11. Stereographic projections of Green Pond linear component data, for the in situ and tilt-corrected sample orientation. All data are shown in both upper and lower hemisphere positions.

indicates that the components are randomly distributed about the mean direction. The inclination polarity for this data is generally negative. The component declinations after 100% TC are also scattered, but with a tendency for steep inclinations. There has been no improvement of the precision (k=3.1) of the data after rotation to the tilt corrected position. The sign of inclination for this data is mixed between positive and negative.

The analysis of individual planar components indicates that the majority of components are constructed of vector endpoints from a wide range of thermal demagnetization temperatures. These temperatures are generally found in the interval from 200 to 680 degrees Celsius. The decay of the remnant magnetic intensity, plotted as J/J_o (the observed intensity versus the initial NRM intensity) versus the demagnetization temperature, Figure 3, indicates the primary mineral for remanence is hematite. Hematite mineralization is indicated by the high temperature of demagnetization required to decrease the magnetic intensity and the high temperature at which the J/J_o curve approaches zero intensity (unblocking temperature). The unblocking temperature observed in the Green Pond Outlier samples is comparable to other studies (Knowles and Opdyke, 1968) where the sample remanence was acquired by hematite.

Component Analysis Using Halls' Technique

Component analysis using Halls' technique was conducted on the components that had k (precision value) greater than random (k>10) for the in situ (0%) and 100% tilt corrected (TC) positions. The analysis consists of the construction of two diagrams per TC position; a plot of component great circles and corresponding poles, and a plot of the best fit "pole" great circle and the characteristic remanent magnetic direction (CRMD). The CRMD is the pole of the best fit "pole" great circle. Figure 5 illustrates the Halls' construction. Two situations are usually encountered constructing the Halls' diagrams, simple and complex. A simple construction produces a diagram where the component great circles intersect at a common point. Here the CRMD is obvious and no further diagrams are needed to define the CRMD. The complex construction is the opposite situation. The component great circles do not intersect at a common point and the pole diagrams must be constructed to define the CRMD. These construction types are illustrated in the figure.

Figure 12 illustrates the Halls' great circle diagrams for the 0% TC position using components A (subsets A1=I<40 and A2=I>60 degrees), B and C (subsets C1=I>60 and C2=I<60 degrees). The technique indicates the CRMD for components B and C1 is at a declination of D=167 degrees and an inclination of I=-34 degrees and will be referred to as SEa. One other CRMD was also located in the in situ position using components

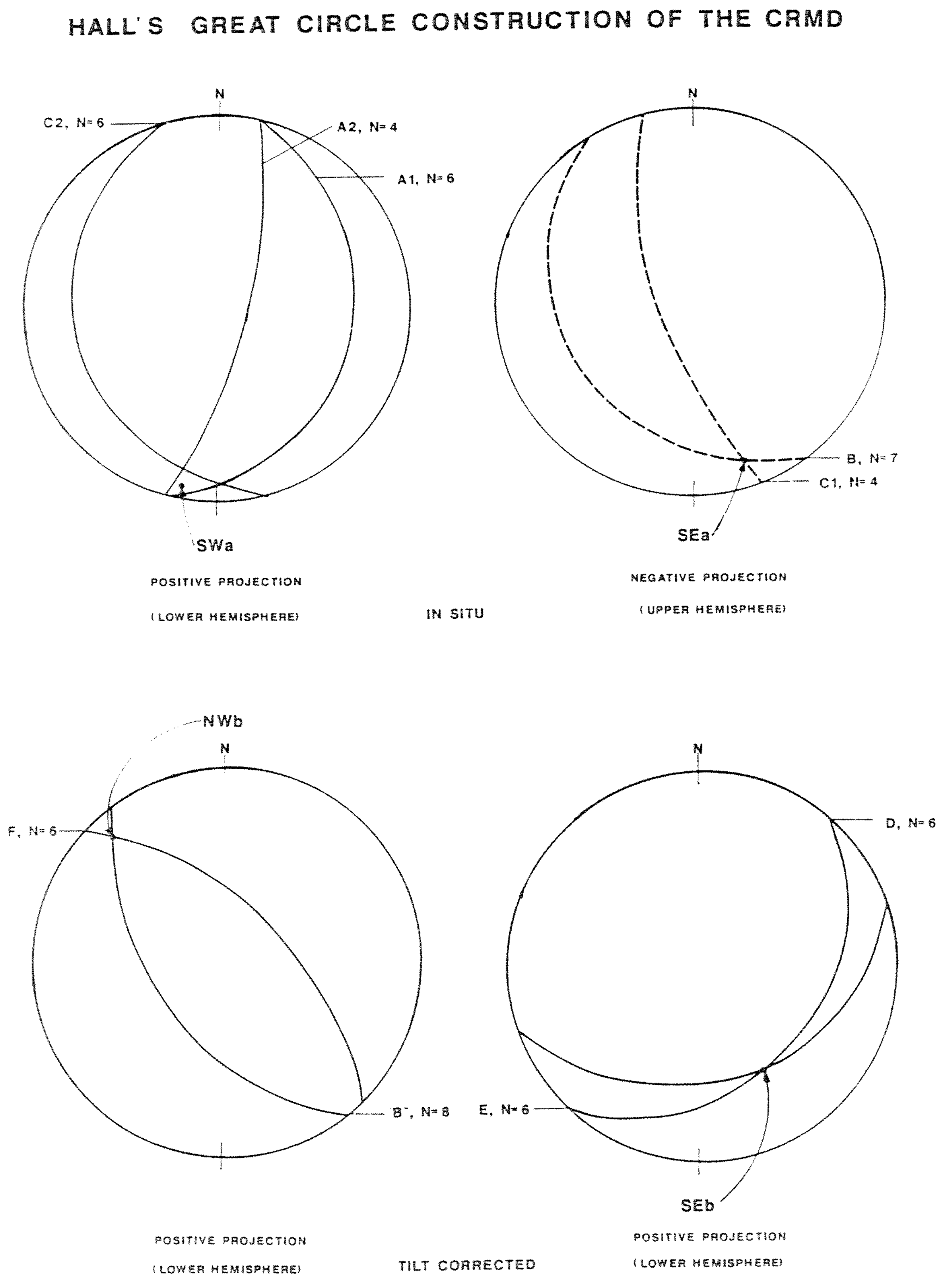


Figure 12. The use of the Halls' Technique on Green Pond planar component data and the construction of four characteristic remnant magnetic directioncs; SWa, SEa, NWb, and SEb.

A1, A2 and C2. The CRMD described by these components was located at D=191, and I=20 degrees and will be referred to as SWa. Figure 12 also illustrates the Halls' great circle diagrams for the 100% TC positions for components "B", D, E and F. From the figure, two CRMD's were plotted; components "B" and F intersecting at D=316, I=+8 (NWb); and D and E intersecting at D=139, I=40 (SEb).

Polar positions determined from the CRMD data are primarily located in the northern hemisphere. There is however one exception, the NWb direction which is located in the southern hemiphere. The polar positions for the CRMD data are: SEa 64 degrees north, 140.3 degrees east; SWa 37.6 degrees north, 91.7 degrees east; SEb 5.7 degrees north, 144.9 degrees east; and NWb 35.9 degrees south, 46.3 degrees east.

The principal component and Halls' methods have provided a means of analyzing scattered paleomagnetic data. The characteristic remanent magnetic directions SEa, SWa, SWb, and NWb provided by these methods are the basis for calculating the Green Pond Outlier's paleopole positions.

DISCUSSION

The results of the component great circle analysis produced four characteristic remanent magnetic directions; SEa D=165, I=-34, SWa D=191, I=20, SEb D=139, I=40 and NWb D=316, I=+8. These directions represent magnetic field directions found in both the in situ and bedding tilt-corrected positions. Unlike the multiple component vector data, the linear vector endpoint data was not able to define a dominant magnetic field direction. This data, when compared to the mean population direction, was completely scattered (k=3.1 at N=16).

There was, however, a relationship between the individual characteristic remanent magnetic direction (CRMD) data and the vector endpoints. This relationship was determined diagramatically and based on the assumption that if a common field direction existed between the data sets then one of two situations should prevail. One, identical magnetic fields will co-exist at the same location on the stereo net, and two, fields common to the same plane will intersect the same great circle. If the endpoints cluster at the CRMD position, then it is presumed the CRMD represents a significant field. If the endpoints are dispersed along the great circle trace, it is presumed that common magnetic components do exist, but directions of the CRMD are intermediate or mixed.

The interrelationship between the linear vector endpoint data, the CRMD and its individual components is illustrated in Figure 13. As the figure indicates, there is some correlation

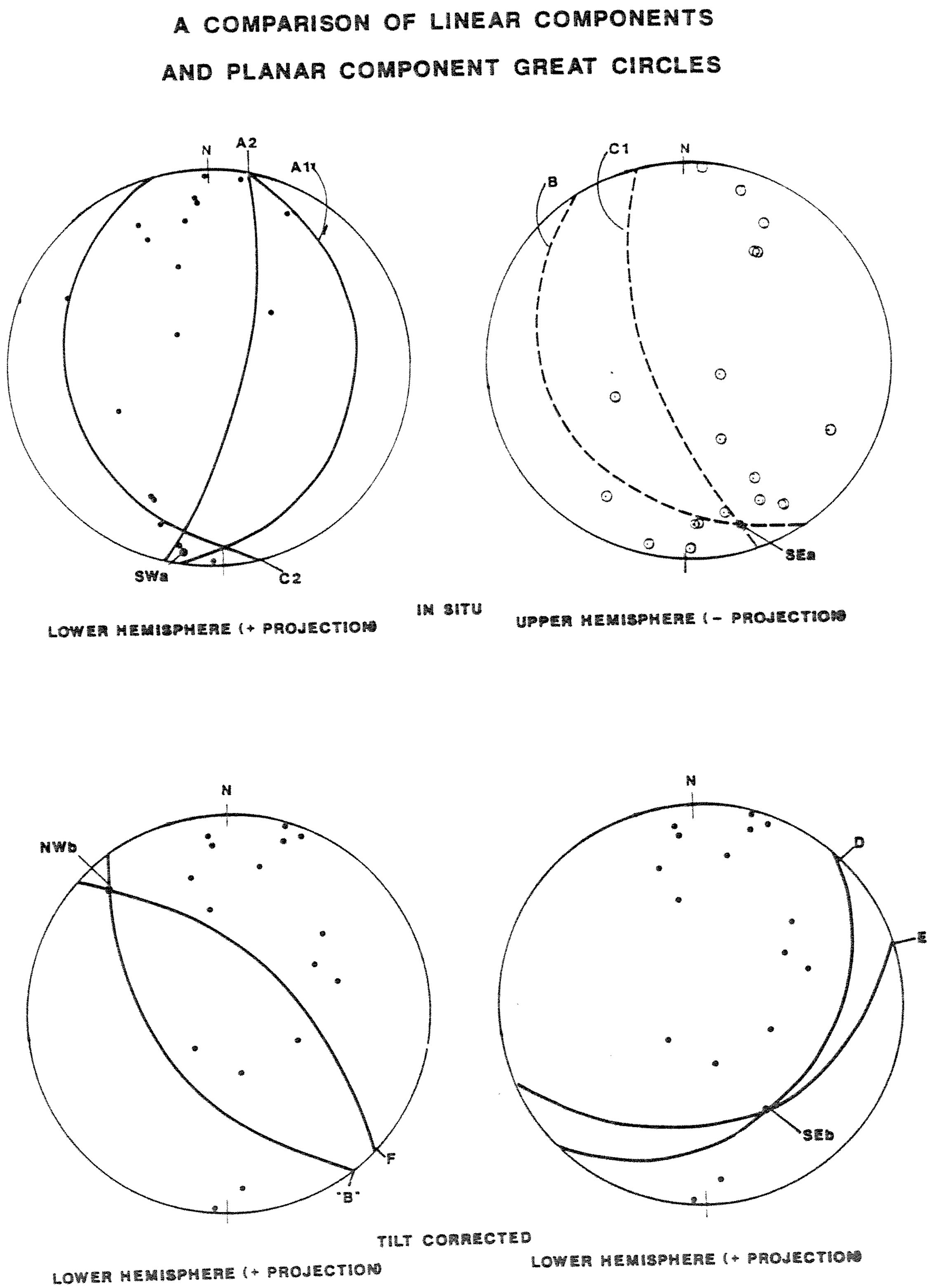


Figure 13. A comparative analysis of Green Pond linear and planar component data using stereographic projections.

between the data sets. This is especially true in the case of the in situ components B, C1 and C2. Eleven linear components align themselves closely with the great circle traces. The position of the vectors along the great circle are in most cases only separated from the CRMD by 10 to 15 degrees. This indicates the vector endpoints are heavily influenced by a field direction which is approximated by the CRMD. It appears that a common component is shared and there is a similar time of remanence acquisition.

Unfortunately there does not appear to be any correlation between the tilt-corrected endpoint data and the corrected CRMD data, where only one vector endpoint of seventeen aligns itself with the great circle trace.

Remanence Acquisition and Age Constraints

The interpretation of the age of magnetization is not a straight forward process due to the complexity of the magnetizations observed in Green Pond Outlier's samples. First, a determination must be made as to when the remanence was acquired; during prefolding, synfolding or postfolding. This is typically done with a fold test (McElhinny, 1964) and should resolve when the remanence was acquired in relation to the folding event. To quantify an age of acquisition, the location of paleo-poles of the individual CRMD's were then compared to the North American Apparent Polar Wander Path (NAAPWP) (Irving and Irving, 1982). The best fit between the

Green Pond Outlier pole and the NAAPWP will determine the age of the remanence.

Table 4 provides a listing of all component great circles and their respective mean declinations, inclinations, and precision values (k). Component precision was calculated at four different positions of tilt correction (unfolding); in situ, 25 percent of tilt correction, 50 percent, 75 percent, and 100 tilt correction and are shown on Table 5. A fold test was performed on only those components which showed an increase in k with incremental unfolding.

As Table 5 indicates, only one component, E, passes the fold test at the 99 percent confidence limit. Components B, D and F also pass the fold test, but below the 95 percent confidence limit. The failure of the components B, D and F to pass the fold test at the 95 percent confidence suggests the remanence was not acquired prior to folding. The acquisition could still be prefolding, but the certainty of the result is questionable. Two CRMD's were then determined using these components, and yielded the following directions; SEb declination (D) equals 139 degrees, inclination (I) equals 40 degrees, and NWb D=316 degrees and I=8 degrees. Components with lesser amounts of precision were combined with the E component to determine the CRMD's due to two component requirement of the Halls' method.

The remaining components A1, A2, B, C1, and C2 showed no increase in k and therefore indicate a postfolding acquisition.

Table 5

Incremental Fold Test Parameters (k_2/k_1)

Component	In Situ k_1	25%	50%	75%	Tilt Corrected k_2
A	8.0				3.4
A1	71.7	3.1	2.9	3.0	6.6
A2	52.4	1.6	1.9	2.8	2.3
B	47.2	3.6	2.9	2.8	9.9
"B"	4.1	4.1	4.9	3.9	11.6
C	9.1				6.0
C1	847.3	4.2	7.7	3.8	34.8
C2	31.6	27.0	16.9	28.5	3.6
D	21.2	3.3	2.6	3.1	26.0
E	2.5	3.3	3.5	3.2	19.6
F	8.5	4.2	4.6	5.3	10.1

The CRMD's determined from these components yielded the following directions; SEa D=165, I=-34, and SWa D=191, and I=20.

Having a pre and post folding remanence acquisition is a troubling issue. This is especially so considering the data (sample population) was manipulated as a single population instead of individual site populations. The ambiguity may be a result of data analysis, or further evidence of random data.

If the data was indeed random, the simplified Chi Squared test would have indicated this. The ambiguity of the results may therefore be an artifact of the individual vectors composing each least squares plane. The presence of pre and post folding vectors within the least squares plane would drive the great circle trace away from an expected pre/post folding orientation. As a result, a great circle component would provide an incorrect CRMD orientation. Unfortunately, this assumption does not satisfactorily resolve the question of when acquisition occurred.

Additional insights to the timing of acquisition may be provided by the linear vector endpoint data. As discussed earlier, the correlation between endpoint data and great circle component data was only significant for the in situ position. This indicates the post folding orientations are dominant among the linear vectors. Since the individual linear vectors and the individual great circles were developed with multiple vector endpoints spanning a wide range of demagnetization temperatures, it appears the remanence in most cases is dominated by post folding magnetic acquisitions. Remanences associated with component E and possibly components B, D and F are dominated by prefolding acquisitions.

To determine the age of remanence acquisition, paleopoles were calculated from the CRMD's. These poles were then compared to the NAAPWP and are presented with other significant poles on Table 6. Figure 14 illustrates on an equatorial projection, the polar locations of the poles listed on Table 6. As table indicates, only two CRMD's are in agreement with the paleolatitudes of the accepted NAAPWP data. This is especially true for poles SWa (37.6 degrees North, 91.7 degrees East - Green Pond this study) and the Catskill Formation (32.8 degrees North, 91.1 degrees East - Miller and Kent, 1986), and the NWb pole (35.6 degrees South, 46.3 degrees East - Green Pond this study) and the St. Lawrence Granite (35 degrees South - Irving and Strong, 1983).

There is a reliable correlation between the SWa pole and the Catskill Formation when comparing the formation ages and their polar positions, however, there is a discrepancy regarding when during folding the remanences were acquired. The Green Pond pole is clearly a postfolding acquisition while the remanence acquisition for the Catkill Formation has been proven by Miller and Kent to be prefolding. The difference is puzzling for several reasons; the nearly identical polar positions, and the similar present day geographic position of

Table 6

DATA FOR THE APPARENT POLAR WANDER PATH OF NORTH AMERICA DURING THE SILURIAN AND TRASSIC

Rock Formation (Reference)	Pole Position
1. Triassic Newark Group (Opdyke, 1961)	63N,108E
2. Permian Dunkard (Helsley, 1965)	43N,123E
3. Permian Prince Edward Island (Roy, 1966)	42N,133E
4. U. Mississippian Maringouin (Roy-Robertson, 1968)	34N,117E
5a. M. Mississippian Barnet Shale (Martinez-Howell, 1956)	41N,135E
5b. M. Mississippian Barnett Shale (Kent-Opdyke, 1979)	49N,119E
6. L. Mississippian St.Joe Limestone (Scott)	39N,132E
7. U. Pennsylvanian Murley Creek (Roy, 1968)	39N,125E
8. U. Pennslyvanian Mauch Chunk (Knowles-Opdyke, 1968)	43N,127E
9. U. Pennslyvanian Mauch Chunk (Kent-Opdyke, 1983)	31N,124.6E
10. L. Pennsylvanian Casper (Diehl-Shive)	46N,129E
11. L. Pennsylvanian Brush Creek (Payne)	36N,124E

DATA FOR THE APPARENT POLAR WANDER PATH OF NORTH AMERICA DURINGTHE SILURIAN AND TRASSIC (cont.)

Rock Formation (Reference)	Pole Position
12. U. Devonian Catskill (Miller-Kent, 1986)	32.8N,90E
13. U. Devonian Catskill (van der Voo-French-French, 1979)	43.5N,124.2E
14. U. Devonian St. Lawrence Granite (Irving-Strong, 1985)	35S
15. U. Devonian Wesleyville Dykes (Murthy, 1985)	42S
16. U. Devonian Terrenceville (Kent, 1982)	27.4N,123.5E
17. M. Devonian Compton (Seguin, 1982)	28N,77E
18. M. Devonian-Carboniferous Austell Gneiss (Ellwood-Abrams)	34N,126E
19. Devonian Enrage (Roy-Park)	32N,117E
20. Devonian Perry New Brunswick (Black, 1964)	26N,109E
21. Devonian Perry Maine (Phillips-Heroy, 1966)	24N,128E
22. Devonian Perry New Brunswick (Robertson, 1968)	32N,118E
23. L. Devonian Traveler (Spariousu-Kent, 1983)	25N,99E
24. U. Silurian Bloomsburg (Roy, 1967)	32N,102E
25. Green Pond SWa Pole (This Study)	37.8N,91.7E
26. Green Pond SEa Pole (This Study)	65N,135.32E
27. Green Pond SEb Pole (This Study)	15.75N,143.94E
28. Green Pond NWb Pole (This Study)	35.9N,46.3E

THE APPARENT POLAR WANDER PATH OF NORTH AMERICA DURING THE SILURIAN THROUGH THE TRIASSIC

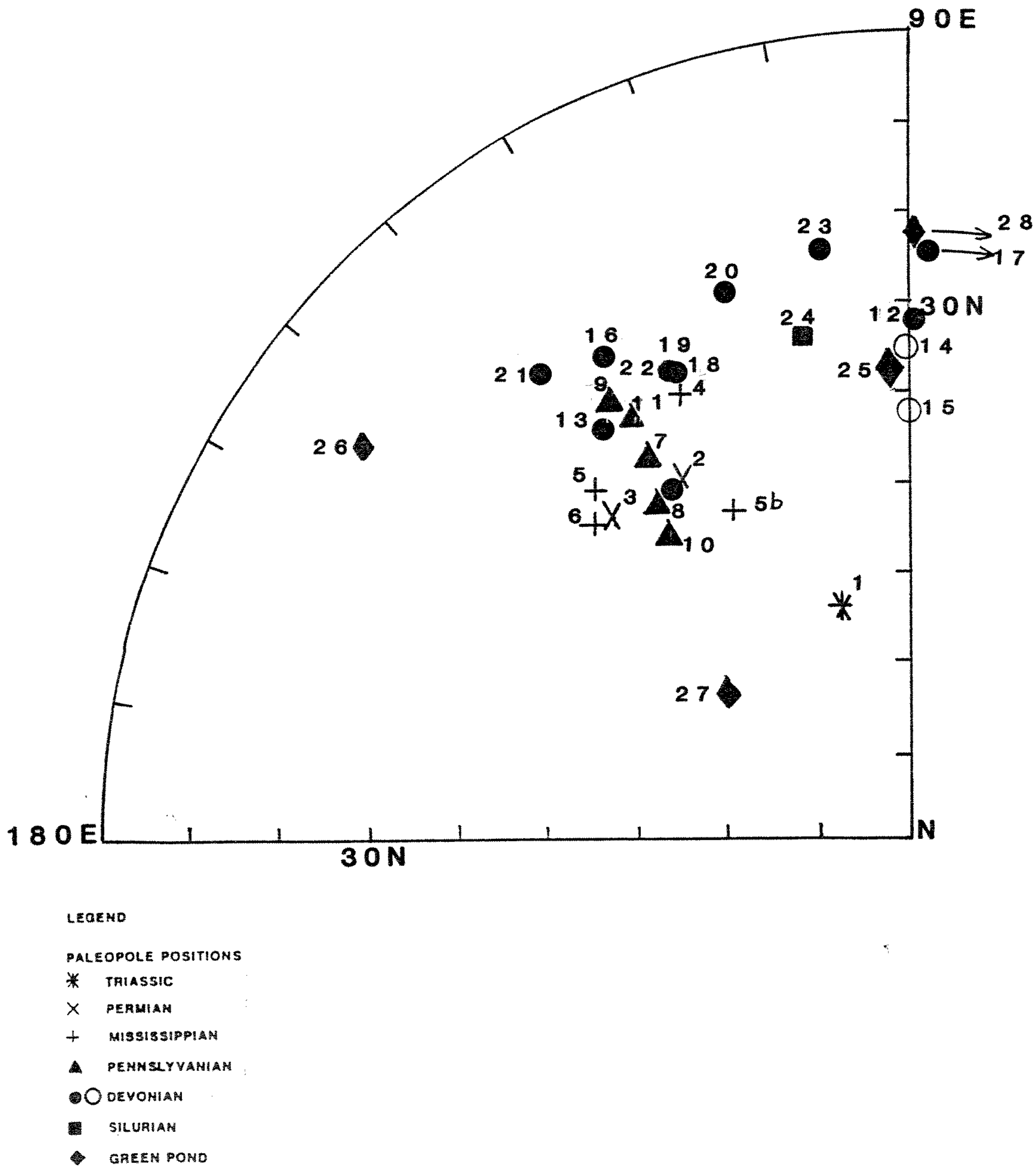


Figure 14. Equatorial projection of the Apparent polar wander path of North America during the Silurian through the Triassic.

the study areas (Green Pond 41.0 degrees North, 74.5 degrees West and Catskill 41.0 degrees North, 76 degrees West).

The nearly identical polar positions and the opposing acquisition timing may be explained by examining the statistical error of each result. Since the CRMD is a diagrammatic construction, the amount of error attributable to any given CRMD is not easily calculated, but easily visualized. Figure 15 illustrates the CRMD position with its individual components. If the error associated with each component is plotted, an area of error can be determined by the boundaries of the individual component error bands. The area is shown in Figure 15 as a shaded area. Also indicated in the figure is the 95 percent circle of confidence (alpha=7.2 degrees) for the Catskill pole. As the figure illustrates, the statistical confidence areas overlap. This indicates the two positions are statistically the same within the area of the overlap. Therefore, it is reasonable that the two poles could co-exist with the presented data. The result also suggests that either the remanence was acquired over a very short period of time, or the North American craton was stable over the same time period. The position of the NAAPWP and the Green Pond Outlier pole indicates a Late Devonian age.

There also exists a correlation between the paleolatitudes of the NWb pole (35.9 degrees South) and the St. Lawrence Granite Formation pole (35 degrees South). Both poles represent Upper Devonian formations as well as pretilting

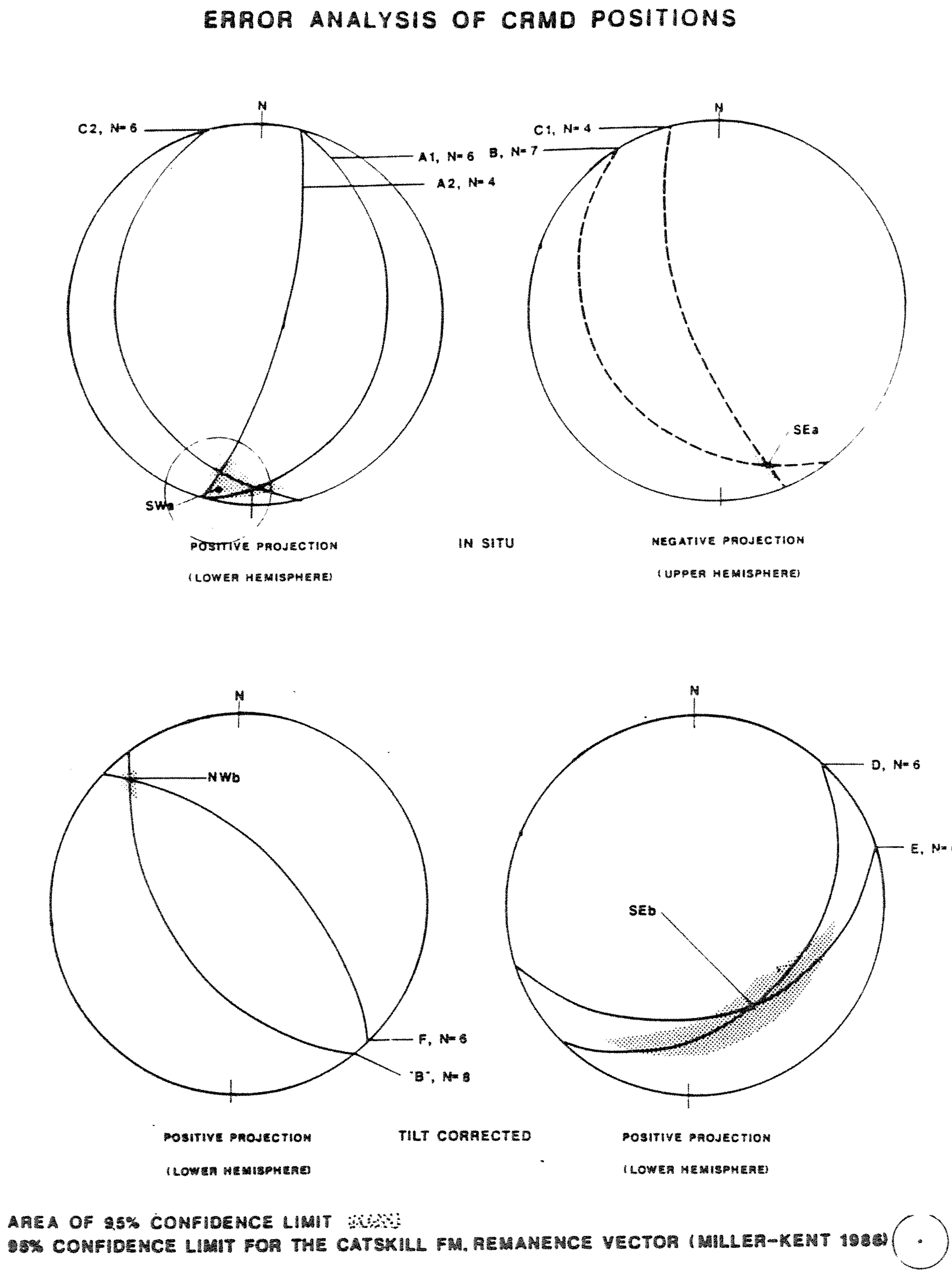


Figure 15. An error analysis of the Green Pond planar data using a probability of 95% confidence.

acquisitions. Unfortunately, the NWb CRMD is defined by the minimum number of great circles required by Halls' method and as a result the direction is only tentative. The position of the NWb pole with respect to the NAAPWP indicates Late Devonian age.

In most situations only the paleolatitudes have been used for comparison purposes with the NAAPWP. This is because only the site paleolatitude can be determined through calculations using the measured inclination of the sample. The site's longitude is based on the subjective position of the Greenwich meridian. The paleolatitude is also significant in the determination of landmass drift between hemispheres for paleo-reconstructions. The declination and paleolongitude of a sample is sometimes ignored in paleo-reconstructions because of the small regional rotations which may occur in tectonically active areas.

Tectonic Implications to the Paleopole Positions

The paleopole positions determined from the CRMD's, NWb and SWa appear consistent with the data from previous studies, but are contradictory to one another considering their tectonic implications. Therefore, a minimum of two tectonic solutions can be implied from the poles.

If the SWa pole position (35 degrees North) is a true post folding remanence of the Green Pond Outlier, then the pole should be considered with other synfolding and postfolding results. As Table 7 indicates, the SWa pole is at a southerly latitude compared to the other synfolding and postfolding acquisition poles and is more comparable to the prefolding result of Miller-Kent (1986). This would indicate that folding of the North American craton started during the Late Devonian and continued until Late Carboniferous or Permian time.

Deformation during the Late Devonian may have resulted from the collisions between North America and the land masses of the Central Mobile Belt (CMB). Again returning to Table 6 and to Figure 14, poles from the Lower Devonian Traveler Felsite (29 degrees North - Spariousu and Kent, 1983), the Upper Devonian Compton (28 degrees North - Segiun et al, 1982) and the Upper Devonian Dockendorff Group (20 degrees North - Brown and Kelly, 1980) indicate a northernly drift of the CMB land masses during the Devonian and possibly into the Carboniferous and Permian. Recent results from the Upper Devonian St. Lawrence and Wesleyville Dykes (35 degrees South, Strong-Irving 1985; and 42 degrees South - Murthy, 1983), which are other land masses associated with the CMB, remained at more southerly latitudes during this time. This land mass configuration is typical of Late Devonian Gondwana, where the North American craton is located in the northern hemisphere Gondwana is in the south and the drifting masses of the CMB are scattered in between. By the Late Carboniferous, the remaining CMB land masses and Gondwana have entered the northern latitudes and initiated deformation with North America. This

Table 7

REMAGNETIZED PALEOPOLES FROM THE APPALACHIANS

ROCK UNIT	ROCK AGE	POLE	FOLD TEST RESULT
MAUCH CHUNK	E.CARBONIFEROUS	112E,50N	SYNFOLDING
MAUCH CHUNK	E.CARBONIFEROUS	130E,52N	SYNFOLDING
GREENBRIER	E.CARBONIFEROUS	131E,43N	POSTFOLDING
CATSKILL	L.DEVONIAN	124E,48N	SYNFOLDING
CATSKILL	L.DEVONIAN	127E,43N	SYNFOLDING
CATSKILL	L.DEVONIAN	117E,47N	INCONCLUSIVE
COLUMBUS	M.DEVONIAN	120E,46N	INCONCLUSIVE
HELD.-ONONDAGA	SIL.-DEVONIAN	129E,50N	POSTFOLDING
HELDERBERG	SIL.-DEVONIAN	115E,49N	SYNFOLDING
ANDREAS	SIL.-DEVONIAN	122E,58N	SYNFOLDING
BLOOMSBURG	L.SILURIAN	103E,51N	SYNFOLDING
BLOOMSBURG	L.SILURIAN	118E,43N	SYNFOLDING
ROSE HILL	M.SILURIAN	117E,45N	INCONCLUSIVE
JUNIATA	L.ORDOVICIAN	129E,47N	INCONCLUSIVE
TRENTON	M.ORDOVICIAN	127E,53N	INCONCLUSIVE

FROM MILLER AND KENT, 1988

phase of continental drift would be typical of a Pangea continental configuration. This stage of deformation, the largest since the Acadian, indicates the start of the Alleghenian-Hercynian Orogeny and is well defined paleomagnetically by wide spread remagnetizations of the Silurian-Devonian sediments.

The multi-phased deformation suggested by the paleomagnetics is clearly exhibited in the structural fabrics of the Green Pond Outlier. Throughout the Outlier's Silurian-Devonian stratigraphic section, two sets of non-aligned cleavages and tension gashes can be observed. These features have been analyzed by Mitchell and Forsythe (1988) and identified as being related to a non-coaxial strain. The nature of this strain is consistent with the notion of a phased deformation as suggested by the paleomagnetic model.

The second tectonic model suggested by the data proposes that the NWb polar position is representative of the Upper Devonian Green Pond. Since the NWb pole (35 degrees South) is consistent with the Upper Devonian St. Lawrence Granite (35 degrees South - Irving and Strong, 1985) and the Wesleyville Dykes (42 degrees South - Murthy, 1985) a Devonian-Carboniferous tectonic model should include these poles. The St. Lawrence Granite and Wesleyville Dykes are found in Maritime Canada in an area which is considered part of the former CMB.

The data suggests a model which positions the North American craton in a southerly latitude during Late Devonian time. At this time and latitude, the North American craton and the CMB would be in very close proximity to one another with a slight lateral offset. This Late Devonian configuration is very similar to the Super-Continent configuration suggested by Van der Voo (1988). The North American craton and the CMB would then drift in unison with Gondwana, in a pseudo Pangea configuration, into the northern hemisphere by Late Carboniferous time. Deformation would occur as a result of drift and rotations of the land masses about a unique continental axis. This model could still satisfy the observed SWa and Miller-Kent pole by having these remanences acquired during the Carboniferous with their deformation occurring shortly thereafter.

CONCLUSIONS

This study was conducted to investigate the paleomagnetics of the Green Pond Outlier. The following were used as the objectives of this study.

To isolate stable magnetic remanence vectors from the samples of the Green Pond Outlier formations.

To test the stability of the vectors and to determine when during folding the remanence was acquired by means of a fold test.

To determine the age of remanence acquisition by comparing the Green Pond Outlier poles (as determined from the remanence vector direction) to the North American Apparent Polar Wander Path (NAAPWP).

To compare the results to previous paleomagnetic studies and to discuss the significance of the results as they refer to the tectonics of the North American craton.

From the data, and in light of the study's objectives, the following conclusions have been made:

1. There is no single population of dominant stable magnetic vectors identified in the data; although five multiple vector planar component directions were identified using a principal component analysis. The principal component population directions were randomly distributed on the site, formation and fold level of comparison. When the data were analyzed as a single population, three subset populations with in situ directions could be isolated and shown statistically significant about a mean declination.

2. During fold test analysis none of the in situ components remained clustered about a mean direction. The component populations remained unstable during incremental unfolding. These components were therefore identified as a post folding remanence.

A further analysis was conducted at the 100 percent tilt corrected position to determine if the sample population clustered about some new mean declination direction. From this analysis four significant direction populations were identified. During incremental fold testing, three of four prefolding populations were shown to be statistically insignificant. One component was clearly prefolding, and as a result the component was insufficient for the Hall's method.

In order to determine an apparent prefolding characteristic remnant magnetic direction, all four remanences were used during Halls' analysis.

3. The poles for the Green Pond were determined through Halls' analysis using the mean principal component data. From this data base four poles were determined. Two of the four poles correlated closely with the latitude position of the Late Devonian, North American Apparent Polar Wander Path (NAAPWP). These poles were the post folding SWa 37.6 degrees North, 91.7 degrees East, and the apparent prefolding NWb 35.9 degrees South, 46.3 degrees East. The age indicated by the NAAPWP correlates well with the stratigraphic and paleontological age of the Outlier's youngest formation.

4. The poles determined for the Green Pond Outlier imply two tectonic scenarios, however, the data most closely supports the scenario provided by the post folding pole. This tectonic model indicates that folding occurred initially during the Late Devonian. This age is constrained by the deposition of the Skunnemuck and the Catskill Formations which are both Late Devonian in age and the prefolding pole of Miller-Kent (32.8 degrees North, 90.0 degrees East). The correlation between paleomagnetic data sets of separate locations support the Late Devonian age of folding and the position of the craton at this time. The position of North America in the northern hemisphere

and Gondwana in the south separated by an open Theic Ocean (Sheridan personnal communication) is supported as opposed to Van der Voo's (1988) Late Devonian Super-Continent.

The closure of the Atlantic was initiated during the Late Devonian and evidenced by the deformation caused by the collisions of the CMB with the North American craton. The isolated areas of deformation provide a mechanism for the observance of suspect terranes and variable ages of folding and remagnetization. It was not until the Late Carboniferous that the major phase of the Alleghenian Orogeny takes place and the closure of the Theic Ocean occurs.

APPENDIX A

Sample Locations

Following are details of the locations of sample collection and general descriptions of the sample location geology.

Location 100

Sample location 100 is found on the west side of Milton Dover Road 0.6 miles north of its intersection with Milton Road in the Town of Milton. The High Falls Shale at this site is poorly exposed in beds of less than six inches in thickness, dips approximately 33 degrees east, and strikes approximately north. The beds are heavily fractured, but two distinct cleavage directions are recognized, 49 degrees northeast and 41 degrees northwest. This exposure represents the western most limb of the Outlier syncline. The fissile nature of the rock allowed the successful removal of 6 samples.

Location 200

Sample location 200 is a large road-cut of the Shawangunk Formation located along Route 23 approximately 2.0 miles south of the Town of Newfoundland. Twenty-five samples were collected from this location. The major features of the road-cut are three small open folds. The formation at this site is composed of beds of shale, fine to coarse sandstones and pebble conglomerate. Beds range in thickness from less then six inches to approximately two feet, and strike from 30 to 60 degrees northeast, with dips from 19 to 63 degrees in the northwest to southeast direction. Two cleavage directions were observed, with general azimuths of 32 degrees northwest and 56 degrees northeast. Both cleavage sets were nearly vertical.

Location 300

Sample location 300 is located adjacent to Greenpond Road 1.5 miles south of Route 23. Eight samples were collected from the High Falls Shale at this location. The formation is thinly bedded and severely fractured by a slaty cleavage which made the identification of the bedding plane and the collection of samples nearly impossible. The orientation of the bedding plane was measured to be a strike of 30 to 45 degrees northeast with a dip of approximately 40 to 49 degrees southeast. The orientation of the slaty cleavage was measured to be 58 to 70 degrees northeast and vertical to subvertical. This outcrop appeared to represent the western limb of a minor syncline within the Outlier.

Location 400

Sample location 400 is located approximately 50 feet up section from sample location 100 and consists of an outcrop of the Poxono Island Formation. The formation is well exposed, but hidden from view by dense brush. The beds are composed of gray, fine grained dolomitic sandstone and siltstone that have a direction of strike of 0 to 10 degrees northwest, and a corresponding dip of 25 degrees in a northeast direction. The formation was free of cleavage, but did have two sets of quartz filled tension gashes. These gashes had bearings of 35 to 42 degrees northeast and 55 to 74 degrees northeast. Six samples were collected from this location.

Location 500

Sample location 500 is located adjacent to Green Pond Road approximately 0.25 miles south of the intersection of Green Pond Road and East Shore Road. Three samples were collected from the Shawangunk Conglomerate at this site. The formation consists of beds of coarse to medium sandstone and pebble conglomerate varying in thickness from one to three feet. The average strike and dip direction of the bedding surface was a strike of 45 degrees northeast and a dip of 62 degrees in a northwest direction. These beds represent the eastern most limb of the Outlier syncline.

Location 600

Sample location 600 is located south of East Shore Road, 0.6 miles west of the intersection of East Shore Road and Green Pond Road. Four samples were collected at this location to represent the uppermost units of the Shawangunk Formation. The formation here consisted of one half to one foot thick beds of a fine to medium grained sandstone lying with a strike of 46 degrees northeast and a dip of 75 degrees in a southeast direction.

Location 700

Sample location 700 is located on Jacobs Road, 1.25 miles south of the intersection of Jacobs Road and Green Pond Road. Six samples were collected at this location from the lower units of the Shawangunk Formation. These samples were collected at a lower stratigraphic interval than those collected at location 500 and approximately 200 feet above the Precambrian contact. The formation at this location consists of beds of pebble conglomerate alternating with beds of sandstone and shale. The general direction of strike of these beds is approximately 53 degrees northeast with a dip of 43 degrees in a northwest direction.

Location 800

Sample location 800 is located on Green Pond Road opposite Craigmier Ski Area. Three samples were collected from a poorly exposed outcrop of the High Falls Shale. Bedding planes were oriented at a strike of 64 degrees in a northeast direction and a dip of 54 degrees in a northwest direction. The exposure did not reveal any other structural fabrics, but was thought to represent the eastern limb of a small syncline whose opposing limb was sampled at location 300. If this correlation is correct then the outcrop should exhibit a well defined slaty cleavage in better exposures.

Location 900

Sample location 900 is located adjacent to Old Route 23, 0.10 miles south of the intersection of Old Route 23 and Route 23. Four samples were collected at this location from an exposure of the Shawangunk Formation. The formation exposes one to two foot thick beds of pebble conglomerate which strike 77 degrees northeast and dip 20 degrees in a northwest direction.

Location 1000

Sample location 1000 is located approximately 2000 feet east of Clinton Road and approximately 0.10 miles south of the intersection of Clinton and Goldfinch Roads. All locations are located adjacent to an existing underground petroleum gas pipeline. Ten samples were collected from the Skunnemunk Formation in beds of sandstone and shale on opposing limbs of a slightly overturned and down-faulted syncline. The strike of the bedding surface was measured to be between 18 and 52 degrees in a northeast direction with corresponding dip angles of 47 and 55 degrees in a southeast direction and 78 to 96 degrees in a northwest direction. The northwest dipping beds were slightly overturned between samples 1400 and 1600. Beds frequently contained quartz filled fractures and two sets of cleavage planes; one set was oriented parallel to strike and dip, while the other was parallel to strike and dipping at an angle of 60 degrees in a southwest direction. The cleavage planes were commonly found within the finer grained beds of the overturned limb.

REFERENCES

Barnett, S.G., 1970, Upper Cayugan and Helderbergian stratigraphy of southeastern New York and northern New Jersey, Geologic Society of America Bulletin, v.81, p.2400.

Barnett, S.G., 1976, Geology of the paleozoic rocks of the Green Pond Outlier, Geologic Report Series No. 11, New Jersey Department of Environmental Protection, New Jersey Geologic Survey.

Briden, J.C., 1972, A stability index of remnant magnetism, Journal of Geophysical Research, v.77, p.1401- 1405.

Brown, L.L., Kelly, W.M., 1980, Paleomagnetic results from northern Maine-Reinterpretations, Geophysical Research Letters, v.7, p.1109-1111.

Bullard, E.C., 1965, A symposium on continental drift IV: The fit of the continents around the Atlantic, Royal Society of London Philosophical Transactions, Series A, v.258, p.41-51.

Cook, F.A., Albaugh, D.S., Brown, L. D., Kaufman, S., Oliver, J.E., Hatcher, R.D., 1979, Thin-skinned tectonic in the crystalline southern Appalachians, Geology, v.7, p.563.

Dewey, J.F., 1969, Evolution of the Appalachian/Caledonian orogen, Nature, v.222, p.124-129.

Doell, R.R., Cox, A., 1967, Analysis of paleomagnetic data, in "Developments in Solid Earth Geophysics", Collison, Creer, and Runcorn, editors, 307pp.

Drake, A.A., Davis, R.E., Alvord, D.C., 1960, Taconic and post-taconic folds in eastern Pennsylvania and western New Jersey, United States Geologic Survey, Professional Paper 400-B, p.B180-B181.

Epstein, A.G., 1967, Upper Silurian and Lower Devonian stratigraphy of northeastern Pennsylvania, New Jersey, and southeastern New York, United States Geologic Survey Bulletin 1243, 74pp.

Fisher, R.A., 1953, Dispersion on a sphere, Proceedings of the Royal Society of London Philosophical Transactions, Series A, v.217, p.295-305.

Halls, H.C., 1979, Separation of multicomponent NRM: combined use of difference and resultant magnetization vectors, Earth and Planetary Science Letters, v.4, p.303- 308.

Halls, H.C., 1978, The use of converging remagnetization circles in palaeomagnetism, Physics of the Earth and Planetary Interiors, v.16, p.1-11.

Halls, H.C., 1976, A least-squares method to find a remanence direction from converging remagnetization circles, Geophysical Journal of the Royal Astronomical Society, v.45, p.297-304.

Hospers, J., Van Andel, S.I., 1968, Paleomagnetic data from Europe and North America and their bearing on the origin of the North Atlantic Ocean, Tectonophysics, v.6, no.6, p.475-490.

Ingram, J.A., 1974, Introductory Statistics, Cummings Publishing Company, Menlo Park, New Jersey, 203pp.

Irving, E., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, Geophysical Survey, v.5, p.141-188.

Irving, E., 1977, Drift of the major continental blocks since the Devonian, Nature, v.270, p.304-309.

Kent, D.V., Opdyke, N.D., 1985, Multicomponent magnetizations from the Mississippian Mauch Chunk Formation of the central Appalachians and their tectonic implications, Journal of Geophysical Research, v.90, no.B7, p.5371-5383.

Kent, D.V., Opdyke, N.D., 1979, The early Carboniferous paleomagnetic field of North America and its bearing on tectonics of the northern Appalachians, Earth and Planetary Science Letters, v.44, p.365-372.

Kent, D.V., Opdyke, N.D., 1978, Paleomagnetism of the Devonian Catskill Red Beds: Evidence for motion of the Coastal New England-Canadian Maritime Region relative to Cratonic North America, Journal of Geophysical Research, v.83, no.89, p.4441-4450.

Kent, J.T., Briden, J.C., Mardia, K.V., 1983, Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of paleomagnetic remanence, Geophysical Journal of the Royal Astronomic Society, v.75, p.593-621.

Kirschvink, J.L., 1980, The least-squares line and plane and the analysis of palaeomagnetic data, Geophysical Journal of the Royal Astronomic Society, v.62, p.699-718.

Kligfield, R., Owens, W.H., Lowrie, W., 1981, Magnetic susceptibility anisotropy, strain, and progressive deformation in Permian sediments from the Maritime Alps (France), v.55, p.181-189.

Kligfield, R., Lowrie, W., Dalziel, I.W.D., 1977, Magnetic susceptibility anisotrophy as a strain indicator in the Sudbury Basin, Ontario, Tectonophysics, v.40, p.287-308.

Knowles, R.R., Opdyke, N.D., 1968, Paleomagnetic results from the Mauch Chunk Formation: A test of the origin of curvature in the folded Appalachians of Pennsylvania, Journal of Geophysical Research, v.73, no.20, p.6515-6526.

Larson, E.E., LaFountain, L., 1970, Timing of the breakup of the continents around the Atlantic as determined by paleomagnetism, Earth and Planetary Science Letters, v.8, p.341-351.

MacDonald, W.D., 1980, Net tectonic rotation, apparent tectonic rotation, and the structural tilt correction in paleomagnetic studies, Journal of Geophysical Research, v.85, no.B7, p.3659-3669.

McClelland Brown, E., 1983, Paleomagnetic studies of fold development and propagation in the Pembrokeshire Old Red Sandstone, In "Paleomagnetism of orogenic belts", E. McClelland Brown and J. VandenBerg, editors, v.98, p.131-149.

McElhinny, M.W., 1964, Statistical significance of the fold test in palaeomagnetism, The Geophysical Journal of the Royal Astronomical Society, v.8, p.338-340.

McFadden, P.L., Schmidt, P.W., 1986, The accumulation of palaeomagnetic results from multicomponent analyses, Geophysical Journal of the Royal Astronomic Society, v.86, p.965-979.

McFadden, P.L., Reid, A.B., 1982, Analysis of palaeomagnetic inclination data, Geophysical Journal of the Royal Astronomic Society, v.69, p.307-319.

McFadden, P.L., Jones, D.L., 1981, The fold test in palaeomagnetism, The Geophysical Journal of the Royal Astronomic Society, v.67, p.53-58.

McFadden, P.L., 1977, Comments on 'A least-squares method to find a remanence direction from converging remagnetization circles' by H.C. Halls, The Geophysical Journal of the Royal Astronomic Society, v.48, p.549-550.

Miller, J.D., Kent, D.V., 1988, Regional trends in the timing of Alleghenian remagnetization in the Appalachians, Geology, v.16, p.588-591.

Miller, J.D., Kent, D.V., 1988, Paleomagnetism of the Silurian-Devonian Andreas red beds: Evidence for an Early Devonian supercontinent?, Geology, v.16, p.195-198.

Miller, J.D., Kent, D.V., 1986, Synfolding and prefolding magnetizations in the Upper Devonian Catskill Formation of eastern Pennsylvania: Implications for the tectonic history of Acadia, Journal of Geophysical Research, v.91, no.B12, p.12,791-12,803.

Mitchell, J.P., Forsythe, R.D., 1888, Late Paleozoic noncoaxial deformation in the Green Pond outlier, New Jersey Highlands, Geological Society of America Bulletin, v.100, p.45-59.

Morris, W.A., 1976, Transcurrent motion determined paleomagnetically in the Northern Appalachians and Caledonides and the Acadian Orogeny, Canadian Journal of Earth Sciences, v.13, p.1236-1243.

Murthy, G.S., 1983, Paleomagnetism of diabase dykes from the Bonavista Bay area of Newfoundland, Canadian Journal of Earth Sciences, v.20, p.206-216.

Noel, J.R., Spariosu, D.J., Dailmeyer, R.D., 1988, Paleomagnetism and 40Ar/39Ar ages from the Carolina slate belt, Albemarle, North Carolina: Implications for terrane amalgamation with North America, Geology, v.16, p.64-68.

Rodgers, J., 1970, The Tectonics of the Appalachians, Wiley Publishers, New York, 70pp.

Roy, J.L., LaPointe, P.L., 1978, Multiphase magnetizations: Problems and implications, Physics of the Earth and Planetary Interiors, v.16, p.20-37.

Roy, J.L., Morris, W.A., 1983, A review of paleomagnetic results from the Carboniferous of North America; the concept of Carboniferous geomagnetic field horizon markers, Earth and Planetary Science Letters, v.65, p.167-181.

Roy, J.L., Tanczy, E., and Lapointe, P., 1983, The paleomagnetic record of the Appalachians, in "Regional Trends in the Geology of the Appalachian-Hercynian-Maurintanide Orogen", P.E. Schenk, editor, 11pp.

Spink, W.J., 1967, Stratigraphy and structure of the Paleozoic rocks of northwestern New Jersey, PhD thesis, Rutgers University.

Stupavsky, M., Symons, D.T.A., 1978, Separation of magnetic components from AF step demagnetization data by least squares analysis, Journal of Geophysical Research, v.83, no.B10, p.4925-4931.

Tarling, D.H., 1971, The magnetization of rocks and its physical analysis, in "Principles and Applications of Paleomagnetism", 32pp.

Uyeda, S., Fuller, M.D., Belshe, J.C., Girdler, R.W., 1963, Anisotrophy of magnetic susceptibility of rocks and minerals, Journal of Geophysical Research, v.68, no.1, p.279-291.

Van Alstine, D.R., de Boer, J., 1978, A new technique for constructing apparent polar wander paths and the revised Phanerozoic path for North America, Geology, v.6, p.137-139.

van der Pluijm, B.A., 1987, Grain-scale deformation and the fold test - Evaluation of syn-folding remagnetization, Geophysical Research Letters, v.14, no.2, p.155-157.

Van der Voo, R., 1988, Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes: Comparisons of paleomagnetism with paleoclimatology and biogeographical patterns, Geological Society of America Bulletin, v.100, p.311-324.

Van der Voo, R., 1980, Paleomagnetism in orogenic belts, Reviews of Geophysics and Space Physics, v.18, no.2, p.455-481.

Van der Voo, R., 1979, Age of the Alleghenian folding in the central Appalachians, Geology, v.7, p.297.

Van der Voo, R., French, R.B., 1974, Apparent polar wandering for the Atlantic-bordering continents: Late Carboniferous to Eocene, Earth Science Reviews, v.10, p.99-119.

Van der Voo, R., French, A.N., French, R.B., 19??, A paleomagnetic pole position from the folded Upper Devonian Catskill red beds, and its tectonic implications, Geology, v.7, p.345-348.

Van der Voo, R., Henry, S.G., Pollack, H.N., 1978, On the significance and utilization of secondary magnetizations in red beds, Physics of Earth and Planetary Interiors, v.16, p.12-19.

Williams, H., 1984, Miogeoclines and suspect terranes of the Caledonian-Appalachian Orogen: tectonic patterns in the North Atlantic region, Canadian Journal of Earth Sciences, v.21, p.887-901.

Woodward, H.P., 1957, Structural elements of Northeastern Appalachians, Bulletin of the American Association of Petroleum Geologists, v.41, no.7, p.1429-1440.

Zijderveld, J.D.A., 1967, A.C. demagnetization of rocks: Analysis of results, in "Developments in Solid Earth Geophysics", Collison, Creer, Runcorn editors, 245pp.