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**Paleomagnetism of the Catoctin Volcanic Province: A new Eocambrian-
Cambrian Apparent Polar Wander Path for North America**

Joseph G. Meert and Rob Van der Voo (University of Michigan, Department
of Geological Sciences, Ann Arbor, MI)

Troy W. Payne (University of Virginia, Department of Environmental
Studies, Charlottesville, VA)

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ABSTRACT

The Eocambrian/Cambrian segment of the Laurentian apparent polar wander path (APWP) has been poorly constrained and the subject of some controversy. The controversy was highlighted by Symons and Chiasson (1991) after their study of the 577 Ma Callander Complex (Ontario, Canada). The principal involved in this controversy is a high-latitude Eocambrian position of Laurentia versus a low-latitude position. The Catoctin volcanic province in central Virginia has been well-dated at 570 ± 35 Ma (Rb-Sr) and 597 ± 18 Ma (U-Pb) and thus presents an ideal paleomagnetic target for resolving the Eocambrian/Cambrian APWP. A total of 206 samples from 32 sites were collected from the Catoctin basalts, feeder dikes and sills. The study reveals three ancient components of magnetization. The youngest component (C-component) fails the fold test and yields a characteristic *in-situ* direction $D=147^\circ$ $I=+44^\circ$ ($K=21$ $A95=9^\circ$). The corresponding paleopole falls on the Middle Ordovician segment of the North American APWP and we consider this component to be the result of a Taconic remagnetization. The second component (B-component) is carried by hematite, exhibits dual-polarities and passes a fold test. The tilt-corrected B-component characteristic direction is $D=92^\circ$ $I=+17^\circ$ ($K=16$ $A95=13^\circ$). The corresponding paleopole at 4° S 193° E falls near a well-established Late Cambrian (505 Ma) pole for North America and we consider this component to be a remagnetization during a Late Cambrian tectonic event in the central Appalachians (collision of the Carolina terrane). The third component isolated in the Catoctin basalts (A-component) yields a tilt-corrected mean of $D=68^\circ$ $I=+84^\circ$ ($K=59$ $A95=9^\circ$). This component passes a fold test and reversal test. A suite of samples was collected from two Catoctin feeder dike and surrounding country rock and yield a positive baked contact test. Samples of the country rock taken near the contact with the dike show a steeply-down direction identical to the direction found in the dike whereas, samples of country rock further away from the contact show shallow-intermediate up directions. The A-pole at 43° S 128° E falls significantly away from previously proposed Eocambrian paths for North America. The A-pole does however, resemble the pole for the Callander Complex. A re-evaluation of previous paleomagnetic studies from coeval rock units reveals similarly steep directions and lead us to propose a new APWP. This new APW track indicates that Laurentia was located near the south pole at 615-580 Ma and drifted rapidly (16 cm yr^{-1}) toward its Late Cambrian equatorial position.

INTRODUCTION

The Wilson-Cycle of continental assembly and dispersal (*Wilson*, 1966) is one of the fundamental tenets of plate tectonic theory. The assembly of Pangea in the late Paleozoic and its subsequent Mesozoic dispersal is the best example of global-scale, Wilson-cycle, tectonism. It has long been suspected that an earlier aggregation of continental landmasses occurred during the late Proterozoic (*Dalziel*, 1992; *Hoffman*, 1991; *Piper*, 1987; *Bond et al.*, 1984; *Piper*, 1982). The assembly and dispersal of this supercontinent, recently called Rodinia (*Hoffman*, 1992), coincided with major changes in biological evolution, sea water chemistry and, by inference, paleoclimate. Most of the arguments favoring Rodinia were based on geologic evidence because the paleomagnetic evidence was considered of insufficient quality to provide rigorous tests of continental configurations (*Van der Voo and Meert*, 1991). Nevertheless, paleomagnetism offers the only quantitative tool for determining past plate motions and plate configurations. Laurentia occupied the central portion of Rodinia and detailed knowledge of its Eocambrian paleogeography will provide the initial framework for the paleogeography of the surrounding landmasses.

The late Proterozoic-Early Cambrian portion of the Laurentian apparent polar wander path (APWP) has been poorly constrained and is the subject of some controversy. The problem in interpreting this segment of the APWP arises from inconsistencies in placing the exact Precambrian/Cambrian boundary in a radiometrically calibrated time scale and from interpreting disparate poles of similar age. The controversy was highlighted by *Symons and Chiasson* (1991) after their study of the 577 Ma Callander Complex (Ontario, Canada). This well-dated pole falls at 46° S 121° E, away from any previously proposed segment of the Laurentian path (e.g. path of *Van der Voo*, 1990). The Catoctin volcanic province in Virginia was dated at 573 ± 35 Ma by *Badger and Sinha* (1988) and a later study of interbedded rhyolites produced a U-Pb zircon age of 597 ± 18 (*Aleinikoff et al.*, 1991). Thus, the Catoctin basalts presented an ideal target for further resolution of the Eocambrian/Cambrian apparent polar wander path. We sampled 32 sites of Catoctin basalts, feeder dikes and sills from sites along the Blue Ridge in central Virginia.

GEOLOGY

The Catoctin volcanic province is a series of predominately subaerial basalt flows that flanks both limbs of the Blue Ridge anticlinorium (Figure 1). This major flood basalt province in the Eastern United States is associated with the 600-550 Ma breakup of a late Proterozoic supercontinent and opening of the Iapetus ocean (*Bond et al.*, 1984; *Dalziel*, 1991). The basalts vary in metamorphic grade from amphibolite facies in Maryland and Pennsylvania, to lowest greenschist facies in NW-Virginia, and increases again to uppermost greenschist in SW-Virginia (*Reed and Morgan*, 1971; *Badger and Sinha*, 1988). The metamorphic grade also varies within individual massive flows. The central portion of any single flow is of lower metamorphic grade than the top or bottom of the flow (*Badger and Sinha*, 1988). *Badger and Sinha* (1988) estimated the age of this metamorphism at 450 Ma (Rb-Sr) in agreement with the estimates provided by *Pettingill et al.* (1984); *Reed and Morgan* (1971) and *Cloos* (1968). *Mose and Nagel* (1984) obtained a Rb-Sr whole rock age for the Catoctin basalts of 470 ± 77 Ma that they considered to date the metamorphism.

The basement rocks in the area (Pedlar Granite and Old Rag Granite) are cut by numerous diabase and metadiabase dikes. These dikes are thought to be feeders to the Catoctin lavas based on their spatial relationship, metamorphic grade, petrographic similarities, absence in younger rocks and bulk chemistry (*Reed and Morgan*, 1971; *Mose and Nagel*, 1984; *Reed and Clarke*, 1989). The dikes range in thickness from a few centimeters to 20 meters (*Reed and Morgan*, 1971; *Reed*, 1955).

TECTONIC HISTORY

Recent geologic evidence suggests that Laurentia was the interior portion of a supercontinent that experienced two rifting events in Late Proterozoic time (Figure 2; *Hoffman*, 1991; *Dalziel*, 1992). The first rifting event (750-680 Ma) was successful along the western margin of Laurentia but failed along the eastern margin (*Bond et al.*, 1984; *Hoffman*, 1991). There is considerable evidence of this failed rift event in the study area represented by the Mt. Rogers and Grandfather Mountain volcanic rocks (N. Carolina-S. Virginia) and the Crossnore plutonic suite (Virginia). Glacial deposits in eastern North America that are

estimated at c. 650 Ma (*Glover, 1989*) fill the hiatus between rifting events. A second rifting event began at 615 Ma and continued until about 560 Ma (*Glover, 1989*). Plutonic-volcanic events of this age are found along the eastern margin of North America (e.g., see Figure 3 for those units that have been studied paleomagnetically) and include the Long Range dikes (615 Ma, Labrador) at the northern end to the Unicoi basalts at the southern terminus (560 Ma, Tennessee). This second rifting event is manifested by the massive flood basalts of the Catoclin volcanic province (570-600 Ma).

The Lower Cambrian rift-drift sequence includes the basal Chilhowee sequence of non-marine feldspathic sandstones and conglomerates followed by the deposition of the Middle Cambrian, red-clastic, Rome-Waynesboro Formations and finally the Middle Cambrian Shady and Tomstown dolomites. Subsequently, a pre-Taconic event in the Appalachians is well substantiated by *Glover (1989)* and is ascribed to a collision of the Carolinia (Piedmont) terrane between 510-490 Ma. *Pavrides (1989)* identified a Cambrian arc in the Piedmont of Virginia, which he considered indicative of an early (505 Ma) collisional event. A similar Late Cambrian event is called the Penobscottian in Maine (*Neuman, 1967; Boone and Boudette, 1989*).

The Taconic orogeny is responsible for the formation of the ancestral Blue Ridge. This portion of the Laurentian margin was thrust westward during the early phases of the Taconic orogeny (*Glover, 1989; Wehr and Glover, 1985*). Many of the Taconic structural features were overprinted during the later Alleghenian Orogeny; however, as mentioned above, there is good isotopic-age evidence for the Taconic event in the Blue Ridge. Deformation of the Catoclin volcanic province is variable. Dips of individual fold limbs range from 8° (northern section of study area) to 125° (overturned limbs near Charlottesville, Virginia). In general, deformation increases from north to south in the study region.

SAMPLING

A total of 206 samples from 32 sites of Catoclin basalts, dikes and sills were collected along a 125 mile transect on both flanks of the Blue Ridge anticlinorium in western Virginia for paleomagnetic investigation (see Figure 1 for sampling locations). Of these 32 sites, 4 sites were sampled from Catoclin feeder dikes, sills and country rock (Pedlar Massif) for a baked contact test. Most samples were drilled using a conventional gasoline powered drill with the exception of two sites for which specimens were

drilled in the laboratory from oriented hand samples. Drilled samples were oriented using magnetic compass and inclinometer with care taken to ensure that compass readings were not affected by strong local magnetic effects. The transect included samples of all metamorphic grades, with higher grade (upper greenschist) samples generally found near the southern terminus of Skyline Drive in Shenandoah National Park (near Charlottesville, Virginia).

The intensities of the natural remanent magnetization (NRM) range between 10^{-5} and 10 A/m as measured on either a ScT cryogenic magnetometer or Schonstedt spinner magnetometer. Thermal and alternating (AF) demagnetization carried out on a pilot selection of samples for each site were used to determine the optimum method of demagnetization. In general, both treatments yielded similar results; nevertheless, most samples were treated thermally because complete decay of the NRM could be achieved. Demagnetization results were plotted in orthogonal vector diagrams (*Zijderveld*, 1967), and linear trajectories were used to determine directions of magnetic components, through vector subtraction comprising three measurements or more (*Kirschvink*, 1980). Occasionally, linear components were not isolated, due to overlapping coercivity or unblocking temperature spectra; for such results, great-circle analysis was combined with stable endpoint data to determine site means (following the methods of *Bailey and Halls*, 1984 and *Halls*, 1978). At least three distinct, ancient components were found in the samples and will be discussed sequentially below. A fourth and common, low-temperature component was found at 12 sites yielding a mean $D=15^\circ$ $I=+61^\circ$ ($k=74$ $A95=7$) that matches the expected value for the present-day Earth's field at this locality.

Component C

The results for sites containing Component C are given in Table I. This component has a characteristic unblocking temperature between 400° and 580° C and is the most common component observed in the Catoctin samples (from 15 sites 84 samples show this direction). Figures 4a-4f show typical orthogonal vector and stereo plots for these samples. Both the unblocking temperature spectra (Figure 4g) and response of these rocks to isothermal remanence acquisition (Figure 4h) indicate that the carrier of this direction to be magnetite. Only a single-polarity was observed in samples carrying this direction. The characteristic in-situ direction for the sites carrying this component is $D=147^\circ$ and $I=$

+44° (K=21 A95=9°). The tilt-corrected mean for these sites is D= 143° and I= +24° (K=3 A95=26°). The fold test for this component is clearly negative (Figure 5). Sites containing the C component were of higher metamorphic grade and more deformed (usually steeply-dipping and overturned limbs often showing strong cleavage) than sites containing the A component. No individual sample contained both the A and C components; however, two samples from sites characterized by the C-component carried only the A-component. The B component was observed in samples also containing the C component as will be discussed below. The corresponding paleomagnetic pole for the in-situ C component is 19° N 143° E.

Component B

This component was observed in 50 samples from 9 sites. The characteristic unblocking temperature for the B-component was between 640° and 690° C (Figure 6a-6d) and could not be isolated by alternating field methods. The unblocking temperature spectra (Figure 6e) and the response of the samples to IRM acquisition (Figure 6f) indicate that hematite is the carrier of remanence in these samples. Component B was observed in samples that also carried component C (e.g. in Figure 6a between 200° C and 585° C) but never in samples carrying component A. Table I gives the site mean results for Component B. In several cases, the final direction was estimated using great circle intersections. The mean of the site directions for component B is D= 91° I= +29° (in-situ K= 8 A95= 20°) and D= 92° I= +17° (tilt-corrected K= 16 A95= 13°). Both polarities were observed in the samples from these 9 sites (Figure 7). A fold test conducted for component B using the *McFadden* (1990) test demonstrates that the hypothesis that assumes the magnetization was acquired in-situ can be rejected at the 99% confidence level (ξ -in-situ =4.997 and ξ_{99} =4.85). This B magnetization is therefore older than the folding. The paleomagnetic pole for this component is 4° S 193° E (dp= 7° dm= 14° ;tilt-corrected).

Component A

The final component isolated in the Catoctin samples was found in 30 samples from 8 sites. These samples include eight Pedlar Granite samples from the contact zones next to Catoctin feeder dikes. The A-direction was not observed in samples carrying the B component. Two samples (least metamorphosed interior portion of the flows) from sites dominated by the C-component, carried only the A-component. Table I gives the site mean results for component A and Figures 8a-8c show typical

orthogonal vector diagrams for these samples. The magnetic carrier of remanence A is magnetite (in most samples) as indicated by unblocking temperatures between 500° and 585° C (Figure 8d) and isothermal remanence acquisition studies (Figure 8e). The A-component remanence at Site 2 (porphyritic basalt) is carried by hematite. A contact test was conducted on samples from site 8 where a 4 meter wide dike intruded the Pedlar granite. Orthogonal vector plots are shown for the dike (Figure 9a & 9b); the country rock 6 centimeters away from the dike contact (Figure 9c); the country rock 2 meters away from the dike (Figure 9d) and the country rock 5 kilometers from the dike (Figure 9e). Granite samples away from the dike did not group well, but the inclinations were shallow-intermediate (less than 35 degrees). On the other hand, the directions of the dike and contact are steep. Collectively, this suggests a positive baked contact test. A second positive contact test was derived from Site 28 where the granite was intruded by an 8 meter wide sill.

The mean direction for A-component sites is $D=346^\circ$ $I=+81^\circ$ ($K=23$ $A95=14^\circ$ in-situ) and $D=68^\circ$ $I=+84^\circ$ ($K=59$ $A95=9^\circ$ tilt-corrected). This direction is dual-polarity and significantly different from both the B and C directions. The fold test (outlier-test using Site 3 as the outlier ; *McFadden*, 1990) for the site mean directions (Figure 10) is significant above the 95% confidence level (probability $\gamma_m > 39^\circ = .023$). If individual sample directions are used, the *McFadden* (1990) fold test indicates that the hypothesis which states the magnetization was acquired in-situ can be rejected at the 92% confidence level (ξ -in-situ =5.23). These fold tests indicate that the A remanence is pre-folding. The *McFadden and McElhinny* (1990) reversals test is inconclusive for the in-situ directions, but is positive for the tilt-corrected directions and is rated C-class. We consider the evidence to favor a primary origin for the A remanence. The tilt-corrected paleomagnetic pole is 43° S 128° E ($dp=17^\circ$ $dm=17^\circ$; Figure 11).

DISCUSSION

We conclude that both the Catoclin B and C remanences are remagnetizations due to the Taconic (C-component) and Carolinian-Penobscottian (B-component) events. The Catoclin C pole (19° N 143° E) falls on the Laurentian apparent polar wander path of *Van der Voo* (1990) near the mid-late Ordovician (450 Ma) mean pole at 16° N 144° E (Figure 11). This age, as estimated from the APWP, corresponds to the isotopically determined ages of 450–470 Ma (*Badger and Sinha*, 1988; *Mose and Nagel*, 1989) and the

peak of greenschist metamorphism in the Blue Ridge (*Glover, 1989*). This pole is therefore considered to be the result of a thermal or chemical resetting of the original remanence. The C-component direction was also detected by *Brown and Van der Voo (1982)* in the similar-age Unicoi basalts in Tennessee. Those authors concluded, as we have, that this direction is the result of a Taconic remagnetization.

The B-component passes a fold test and is carried by hematite. This hematite-carried remanence was able to survive the later greenschist-grade Taconic overprint. Its direction is similar to the hematite direction found in the Unicoi basalts in Tennessee (*Brown and Van der Voo, 1982*) that yielded a paleomagnetic pole at 0.4° S 178° E. These authors concluded that the hematite-bearing remanence in the Unicoi was the result of high-temperature oxidation of the basalts at the time of cooling. The combined pole for the Catoctin B-component (4° S 193° E) and Unicoi basalts is 2° S 186° E. This combined mean pole falls near a late Cambrian mean pole for Laurentia (3° S 164° E; $A95=12^{\circ}$). We consider that the B-component is best interpreted as the result of a remagnetization during a late Cambrian (505-515 Ma) orogenic event in the central Appalachians such as that proposed for the collision of the Carolina terrane (*Glover, 1989*).

The A-component is interpreted as the oldest magnetization acquired by the rocks in the Catoctin volcanic province. This component passes a fold and reversals test and may well be a primary remanence given the positive baked contact test with the older Pedlar Granite. We therefore consider the age of this pole (43° S 123° E) to lie between 570-600 Ma.

The Eocambrian Laurentian APWP

The Eocambrian-Early Cambrian portion of the Laurentian apparent polar wander path is the subject of recent discussion (*Symons and Chiasson, 1991; Murthy et al., 1992; Park, 1992*) due to uncertainties in both the paleomagnetic data and in placing the exact boundary between the late Precambrian and earliest Cambrian in a radiometrically calibrated time scale. Laurentia is included in all recent models of a late Precambrian supercontinent (*Hoffman, 1991; Piper, 1987; Dalziel, 1991*), but these models do not specifically agree on either its position relative to other continents nor on its paleolatitude. Results from this study were combined with previous studies (Table II) to define the 615 to 505 Ma portion of the Laurentian APWP.

Symons and Chiasson (1991) recently suggested that Laurentia was located at the south pole instead and challenged an equatorial latest Precambrian position for Laurentia (e.g. *Van der Voo et al.*, 1984) based on their paleomagnetic investigation of the Callander Complex (Ontario). The pole calculated for the Callander Complex (46° S 121° E) falls near the Catoctin A-pole (see Figure 11). The Callander Complex is dated at 577 Ma (U-Pb, *Kamo et al.*, 1991) and is therefore coeval with the Catoctin Formation. *Symons and Chiasson* (1991) also pointed out that the Sept-Îsles B-pole (*Tanczyk et al.*, 1987), when corrected for a small regional tilt also falls near the Callander and Catoctin poles at 44° S 134° E. The Sept-Îsles Complex is not as well dated as the Callander Complex and Catoctin Formation. Its suggested age is c. 580 Ma (*Higgins and Doig*, 1981). Our late Precambrian pole (570-600 Ma) for Laurentia is computed as the average pole from the Callander, Sept-Îsles B-pole and Catoctin A-pole at 45.5° S 126° E ($A95 = 8^{\circ}$) and places the Callander Complex at $72^{\circ} \pm 8^{\circ}$ S, the Catoctin Formation at $78^{\circ} \pm 8^{\circ}$ S and the Sept-Îsles intrusion at $83^{\circ} \pm 8^{\circ}$ S.

In a recent study of the Long Range dikes, *Murthy et al.* (1992) reported "anomalous results" from three sites in one of the dikes. This anomalous result was derived from a dike that was dated at 615 Ma (U-Pb, *Kamo et al.*, 1989). Although it is possible that secular variation was not averaged in the results from these three sites, the pole (69° S 170° E) appears to give a reasonable approximation of the 615 Ma pole for Laurentia (Figure 11).

The remaining portion of the Laurentian APWP is represented by the Buckingham flows (Quebec) and Long Range Dikes "characteristic" pole. The Buckingham flows of Quebec are imprecisely dated at 572 ± 32 Ma (whole rock K-Ar by *LaFleur and Hogarth*, 1981) and the paleopoles for this unit were originally reported as three separate (in-situ) poles by *Dankers and Lapointe* (1981). A tilt-correction for this unit was not performed because the dip of the flows was considered primary. However, tilt-correction of all sites (according to bedding data in *Dankers and Lapointe*, 1981) yields a mean pole for the Buckingham volcanics at 16° S 165° E. Results from *Murthy et al.* (1992) taken from the dike with a K-Ar age of 553 ± 22 (Biotite age from *Wanless et al.*, 1970) yields a paleomagnetic pole at 11° S 164° E, nearly identical to the tilt-corrected Buckingham pole. We consider these K-Ar ages to be representative of a late Precambrian/Early Cambrian age; moreover, their mean pole (13.5° S 164.5° E,

A95= 11°) indicates an intermediate position (at c. 550 Ma) of Laurentia between the high-latitude position at 580 Ma and the equatorial position at 505 Ma. The paleolatitude of Laurentia at 550 Ma is approximately 15° S. The Catoctin B-pole falls near a well-established late Cambrian (505 Ma) mean pole for Laurentia at 3° S 164° E. The late Cambrian mean pole places Laurentia at equatorial paleolatitudes (6° S).

Our new apparent polar wander path of Figure 11 indicates that the latest Precambrian rifting event along the eastern margin of Laurentia took place at high southerly latitudes. The "breakout" of Laurentia included rapid drift of the continent toward the equator. The rate of drift with respect to the pole calculated for this motion is 16 cm yr^{-1} during the interval 600-550 Ma. This minimum drift rate is high compared to modern-day drift rates, but not unparalleled in Phanerozoic geologic history (Klootwijk *et al.*, 1991; Meert *et al.*, in press; Chen *et al.*, in press). The high latitude position of Laurentia at 615 Ma may explain the 650 Ma glacial event in eastern North America if Laurentia had drifted over the south pole as suggested earlier by Park (1992) and Piper (1982).

Inclusion of Laurentia as part of a late Proterozoic supercontinent, centered at the south pole, was also proposed by Bond *et al.* (1984). Later reconstructions placed Laurentia at the equator (Dalziel 1991) or the south pole (Dalziel, 1992). We support the south polar reconstruction of Dalziel (1992) for Laurentia with the 600 Ma rifting event responsible for the breakout of Laurentia from western Gondwana. Figures 12a-c show the drift and tectonic history for Laurentia based, in part, on the paleomagnetic data given in Table II. Figure 12a shows Laurentia at c. 650 Ma following the initial rifting of E. Gondwana away from the western North American margin (supercontinent shown in Figure 2). Figure 12b shows Laurentia following the second rifting phase with a passive margin along the present-day east coast at c. 550 Ma. Dalziel (1992) has suggested that this 600-550 Ma rifting phase was preceded by a second supercontinental assemblage because E. Gondwana had collided with W. Gondwana prior to the 600 Ma rifting event. Figure 12c shows the drift history of Laurentia from 615-505 Ma, based on paleomagnetic data, demonstrating a period of rapid drift away from the south pole between 580 and 550 Ma.

CONCLUSIONS

The Catoctin volcanic province in eastern North America (Virginia) yielded three paleomagnetic poles that correlate with a sequence of tectonic events at 570-600 Ma, 505-510 Ma and 450 Ma. The 570-600 Ma Catoctin A pole amplifies the late Precambrian apparent polar wander path for Laurentia suggested by *Symons and Chiasson (1991)* and *Park (1992)*. These new data indicate that Laurentia was located at the south pole at c. 615 Ma and drifted rapidly toward the equator during the latest Proterozoic to Early Cambrian interval (580-550 Ma). Plate velocities calculated for North America during the Cambrian are at least 16 cm yr^{-1} during the Early Cambrian suggesting that large continents may travel at fast rates for short periods of time.

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TABLE 1

COMPONENT C								COMPONENT B																				
Site	n/N	Ds	Is	k	α95	Plt	Plg	n/N	Ds	Is	Dc	Ic	k	α95	Plts	Plgs	Pltc	Plgc										
1	3/6	150	+72	55	13	9 N	308 E	5/6	100	+43	102	+28	87	08	8 S	176 E	0 S	183 E										
2	0/5						0/5																					
3	0/6						0/6																					
4	3/6	152	+34	24	25	27 N	140 E	6/6	103	+29	94	+31	13	19	1 S	182 E	7 S	186 E										
5	0/5						0/5																					
6	4/6						0/6																					
7	0/9	111	+55	33	17	8 N	342 E	0/9																				
8	0/9						0/9																					
9	0/6						0/6																					
10	3/5	150	+31	70	10	28 N	144 E	0/5																				
11	8/8		164	+28	51	07	35 N	131 E											0/8									
12	0/5							5/5											070	+29	79	+18	65	12	26 S	202 E	15 S	202 E
13	4/8	131	+59	53	24	0 N	147 E	0/8																				
14	0/7						0/7																					
15	0/6						0/6																					
16	3/5	137	+55	36	21	6 N	146 E	0/5																				
17	0/5						4/5	107											-04	106	-16	20	25	14 S	013 E	17 S	018 E	
18	0/6						6/6	251											-08	252	-06	100	08	18 S	211 E	16 S	211 E	
19	4/5	157	+29	154	09	32 N	138 E	0/5	102	-03	101	+16	20	22	11 S	015 E	3 S	009 E										
20	0/5						4/5																					
21	3/3		146	+30	21	26	27 N	148 E											0/3									
22	17/17	143	+58	27	07	6 N	141 E	0/17																				
23	8/8	155	+44	50	07	21 N	136 E	0/8																				
24	6/6	159	+45	30	14	22 N	132 E	0/6																				
25	0/7							7/7	51	+49	77	+20	27	10	48 S	198 E	17 S	202 E										
26	0/5							5/5											117	+64	104	+35	26	15	12 S	152 E	2 S	178 E
27	0/4							0/4																				
28	0/5							0/5																				
29	6/6							129											+21	58	07	21 N	168 E	0/6				
30	6/8							144											+53	17	16	10 N	142 E	8/8	281	-30	279	-05
31	6/9	157	+37	24	14	27 N	136 E	0/9																				
32	0/5							0/5																				
15	(IS)	147	+44	21	9	19 N	143 E	9	91	+29	k=8	α95=20			9 S	189 E												
	(TC)	143	+24	03	26	28 N	154 E		92	+17	k=16	α95=13			4 S	193 E												
COMPONENT A																												
Site	n/N	Ds	Is	Dc	Ic	k	α95	Plts	Plgs	Pltc	Plgc																	
2	3/5	191	-81	256	-74	504	6	56 S	118 E	39 S	151 E																	
3	6/6	289	+52	281	+80	154	6	33 S	040 E	40 S	087 E																	
6	1/6	041	-79	133	-80	**	**	21 S	097 E	50 S	090 E																	
8	6/9	164	+89	164	+89	43	8	36 S	113 E	36 S	113 E																	
9	5/6	55	+80	86	+76	334	5	48 S	137 E	36 S	145 E																	
15	4/6	194	-76	203	-86	97	9	63 S	125 E	45 S	116 E																	
16	1/5	297	+82	159	+82	**	**	44 S	091 E	24 S	117 E																	
28	4/5	189	-75	248	-75	730	04	66 S	123 E	44 S	147 E																	
8/8	30/48	330	+83	64	+86			50 S	99 E	42 S	123 E																	
		k=26	α95=11	k=55	α95=7																							
6/8	28/37	346	+81	68	+84			56 S	99 E	43 S	128 E																	
		k=23	α95=14	k=59	α95=9																							

Notes: The means are calculated by giving each site unit weight. The paleomagnetic pole is calculated from the mean Declination and Inclination.

Notes: The second A component mean direction is calculated by deleting Sites 6 and 16 which contain only one sample.

n/N= number of samples used/ number of samples per site

Ds= *In-situ* declination

Is= *In-situ* inclination

Dc=Tilt-corrected declination

Ic=Tilt-corrected inclination

k=Fisher precision parameter

$\alpha 95$ = cone of 95% confidence

Plts= *In-situ* paleomagnetic pole latitude

Plgs= *In-situ* paleomagnetic pole longitude

Pltc= Tilt-corrected paleomagnetic pole latitude

Plgc= Tilt-corrected paleomagnetic pole longitude

TC= Tilt-corrected

IS= *In-Situ*

TABLE II

<u>Pole Name</u>	<u>Pole Latitude</u>	<u>Pole Longitude</u>	<u>Age Range</u>	<u>A95</u>	<u>Q¹</u>	<u>Paleolatitude²</u>	<u>Reference</u>
1. Long Range I ³	69° S	170° E	615 Ma	15°	3	41.3° S	Murthy et al., 1992
2. Catoclin A	43° S	128° E	570-600 Ma	9°	6		this study
3. Callander Complex	46° S	121° E	577 Ma	3°	6		Symons & Chiasson, 1991
4. Sept-Isles B ⁴	44° S	134° E	c. 580 Ma	10°	3		Tanczyk et al., 1987
Mean 2-4	45.5° S	126° E	580 Ma	8°	-	58° S	this study
5. Buckingham Flows ⁵	16° S	165° E	c. 550 Ma	8°	4		Dankers & Lapointe, 1981
6. Long Range dykes	11° S	164° E	c. 550 Ma	18°	3		Murthy et al., 1992
Mean 5-6	13.5° S	164.5° E	550 Ma	11°	-	14° S	this study
7. Welge-Wilberns	11° N	158° E	505-523 Ma	10°	5		Loucks & Elmore, 1986
8. Point Peak-Wilberns	6° N	159° E	505-523 Ma	5°	5		Van der Voo et al., 1976
9. Taum Sauk Ls.	4° S	176° E	505-523	7°	5		Dunn & Elmore, 1985
10. Moores Hollow	1° S	163° E	505-523	9°	5		Farr & Gose, 1991
Mean 7-10	3° S	164° E	505 Ma	12°	-	6° S	this study

Notes:

¹Q-value (quality factor) assigned according to Van der Voo (1990)²Paleolatitudes calculated for a central point on Laurentia (45° N 260° E)³Long Range Dykes I pole calculated from dyke dated at 615 Ma; see text for complete details⁴Sept-Isles B-pole recalculated according to Symons and Chiasson, 1991⁵Buckingham flows recalculated; see text for details

Figure Legends:

Figure 1: Map of the study area showing the location of paleomagnetic sampling sites along the Blue Ridge anticlinorium in Virginia. Most of the sampling was confined to an area within Shenandoah National Park. Sites 5, 8, 10 and 28 were Catoctin feeder dykes or sills.

Figure 2: The late Proterozoic supercontinent (c. 750 Ma) according to Hoffman, 1991. Laurentia occupies the interior portion of the supercontinent that "breaks out" at c. 600 Ma following an earlier separation from East Gondwana (c. 750-700 Ma).

Figure 3: Map of North America showing the locations of selected volcanic-plutonic events associated with the 615-550 Ma opening of the Iapetus ocean.

Figure 4: (a) Orthogonal vector plot (OVP) of sample JTA-15 (site 22) showing the C-component magnetization (open circles= vertical projection; closed circles= horizontal projection); (b) stereoplot of sample JTA-15; (c) OVP of sample JTC-3 (site 24); (d) stereoplot of sample JTC-3; (e) OVP of sample JTB-6 (site 23); (f) stereoplot of sample JTB-6; (g) unblocking temperature spectra for sample JTA-15 and (h) response of sample JTA-15 to isothermal remanence acquisition.

Figure 5: Equal-area stereoplot of site mean directions (*in-situ* and tilt-corrected) for samples carrying the C-component. The precision parameter k decreases from 21 (*in-situ*) to 3 (tilt-corrected) and the cone of 95% confidence (α_{95}) increases from 9° (*in-situ*) to 26° (tilt-corrected) indicative of a negative fold test.

Figure 6: (a) Orthogonal vector plot (OVP) of sample JMA-2 (site 1) showing the high-temperature, B remanence carried by hematite and the C-component overprint (200° - 585° C); (b) OVP of sample TCH-4 (site 30); (c) stereoplot of sample TCH-4 showing the great-circle trajectory of the high-temperature B-component; (d) OVP of the high-temperature portion for sample JMD-5 (site 4); (e) unblocking temperature spectra for a typical sample carrying the B-component and (f) response of sample JMD-5 to isothermal remanence acquisition.

Figure 7: Equal-area stereoplot of site mean directions (*in-situ* and tilt-corrected) for samples carrying the B-component. The precision parameter k increases from 8 (*in-situ*) to 16 (tilt-corrected) and the cone of 95% confidence (α_{95}) decreases from 20° (*in-situ*) to 13° (tilt-corrected) indicative of a positive fold test.

Figure 8: *In-Situ* orthogonal vector plots (OVP) of; (a) sample JMI-1 (site 9) showing the A-component of magnetization (b) sample JMB-4 (site 2) showing the A-component carried by hematite; (c) sample JMO-3 (site 15); (d) unblocking temperature spectra of sample JMI-1 and (e) response of sample JMI-1 to isothermal remanence acquisition.

Figure 9: *In-Situ* orthogonal vector plots for samples (site 8) collected for a baked contact test; (a) sample JMH-6 diabase dyke material in the central portion of a 4 meter dyke; (b) sample JMH-7 diabase dyke adjacent to JMH-6; (c) Pedlar granite sample JMH-3 located 6 centimeters from dyke contact; (d) Pedlar granite sample JMH-1 located 2 meters from dyke contact (e) Pedlar granite sample JMH-11 located 5 kilometers from dyke contact at site 8.

Figure 10: Equal-area stereoplot of site mean directions (*in-situ* and tilt-corrected) for samples carrying the A-component.

Figure 11: Apparent polar wander path for North America (615-505 Ma) based on data compiled in Table II. Δ =represent mean poles for the 580 Ma, 550 Ma and 505 Ma. The key to the paleomagnetic poles is: **LRD-I**= Long Range Dykes I pole (see text); **CAL**= Callander Complex; **SIB**= Sept-Îsles B-pole; **CAA**= Catoctin A-pole; **BF**= Buckingham Flows tilt-corrected; **LRD-B**= Long Range Dykes pole (see text); **CAB**= Catoctin B-pole; **TS**= Taum Sauk pole; **MH**= Moores Hollow pole; **PP**= Points Peak pole; **WLG**= Welge Creek-Wilberns pole; **MOR**= Middle Ordovician mean pole of Van der Voo, 1990; **CAC**= Catoctin C-pole.

Figure 12: (a) Laurentia at c. 650 Ma following the rifting of E. Gondwana away from western North America and prior to the second phase of rifting along the eastern margin; (b) Laurentia following the second rifting phase with passive margin development along the present-day east coast at c. 550 Ma; and (c) Drift history of Laurentia from 615 Ma-505 Ma indicating a period of rapid drift away from the south pole between 580 Ma and 550 Ma.

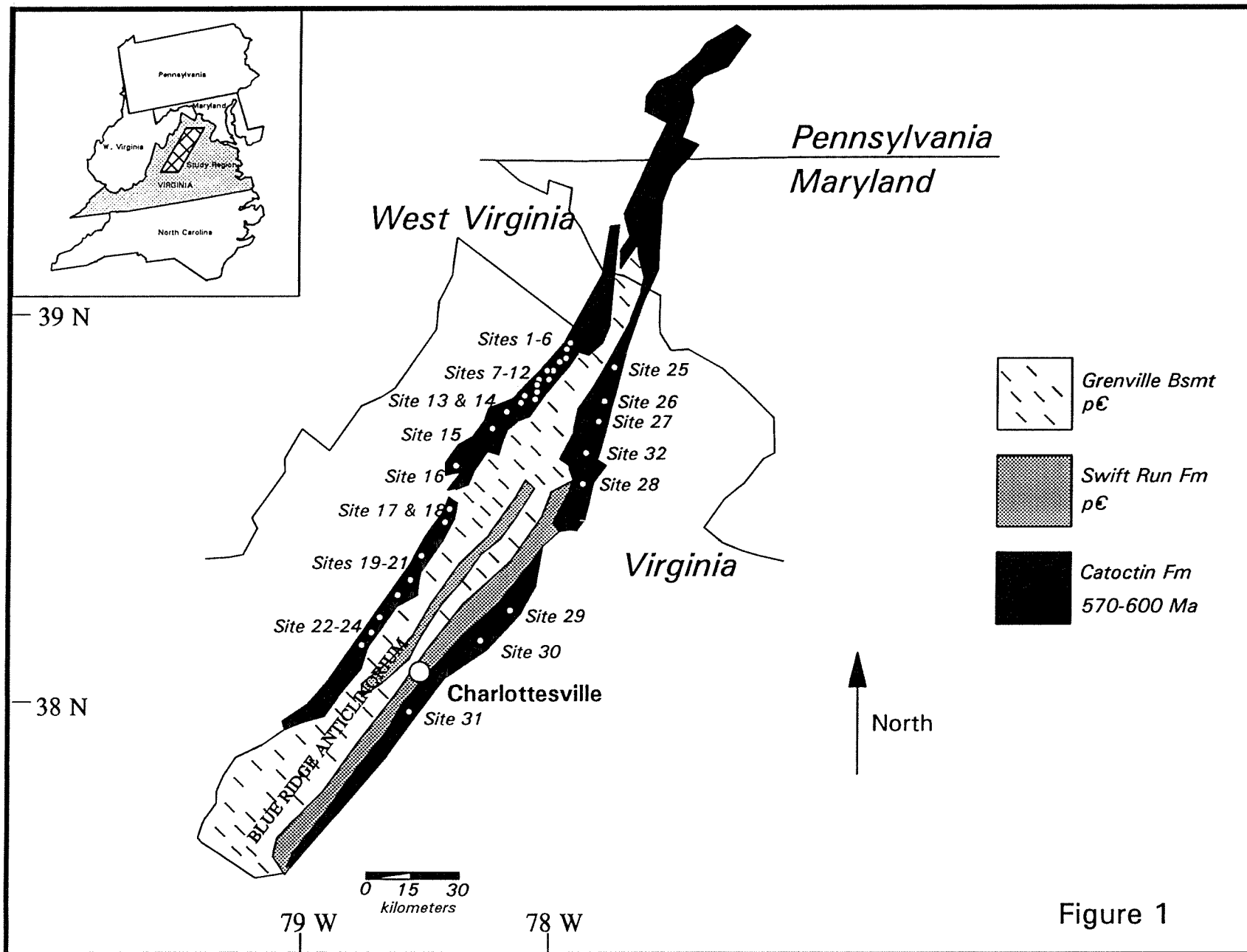
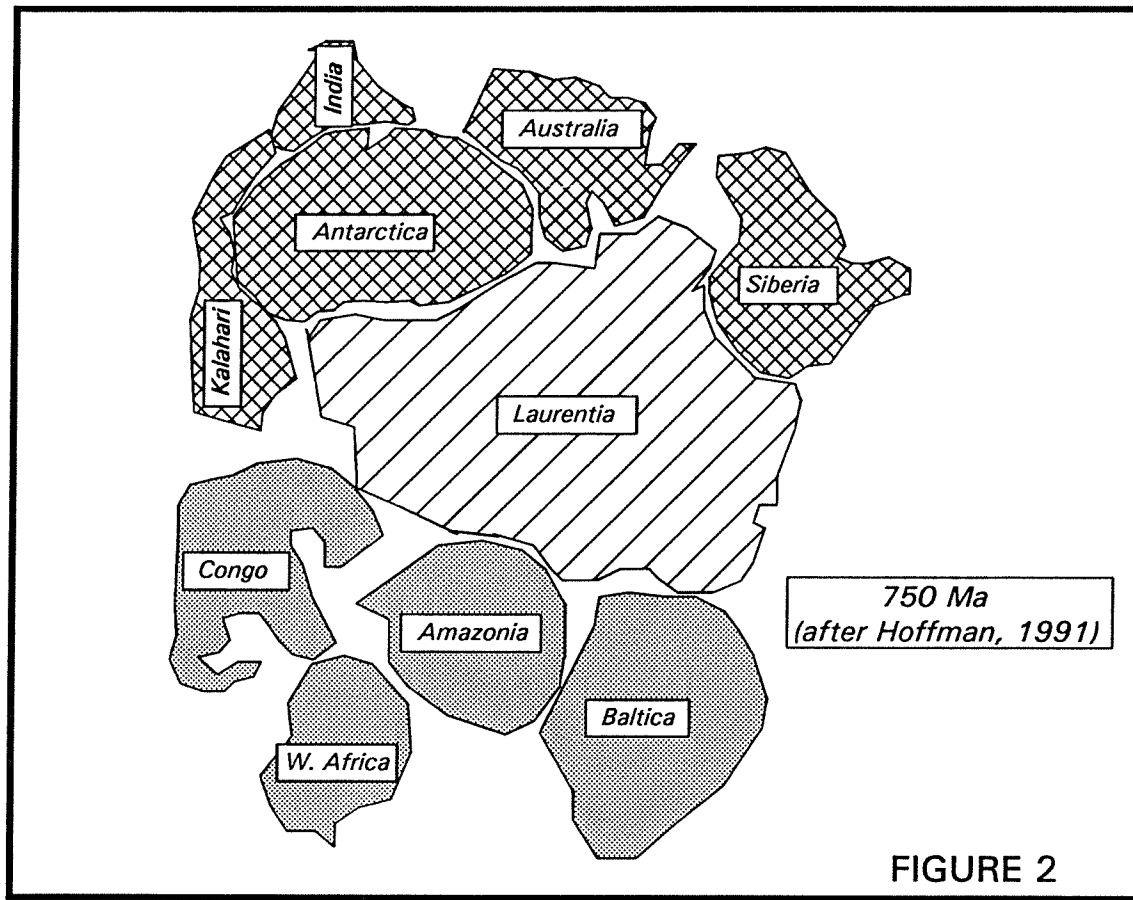
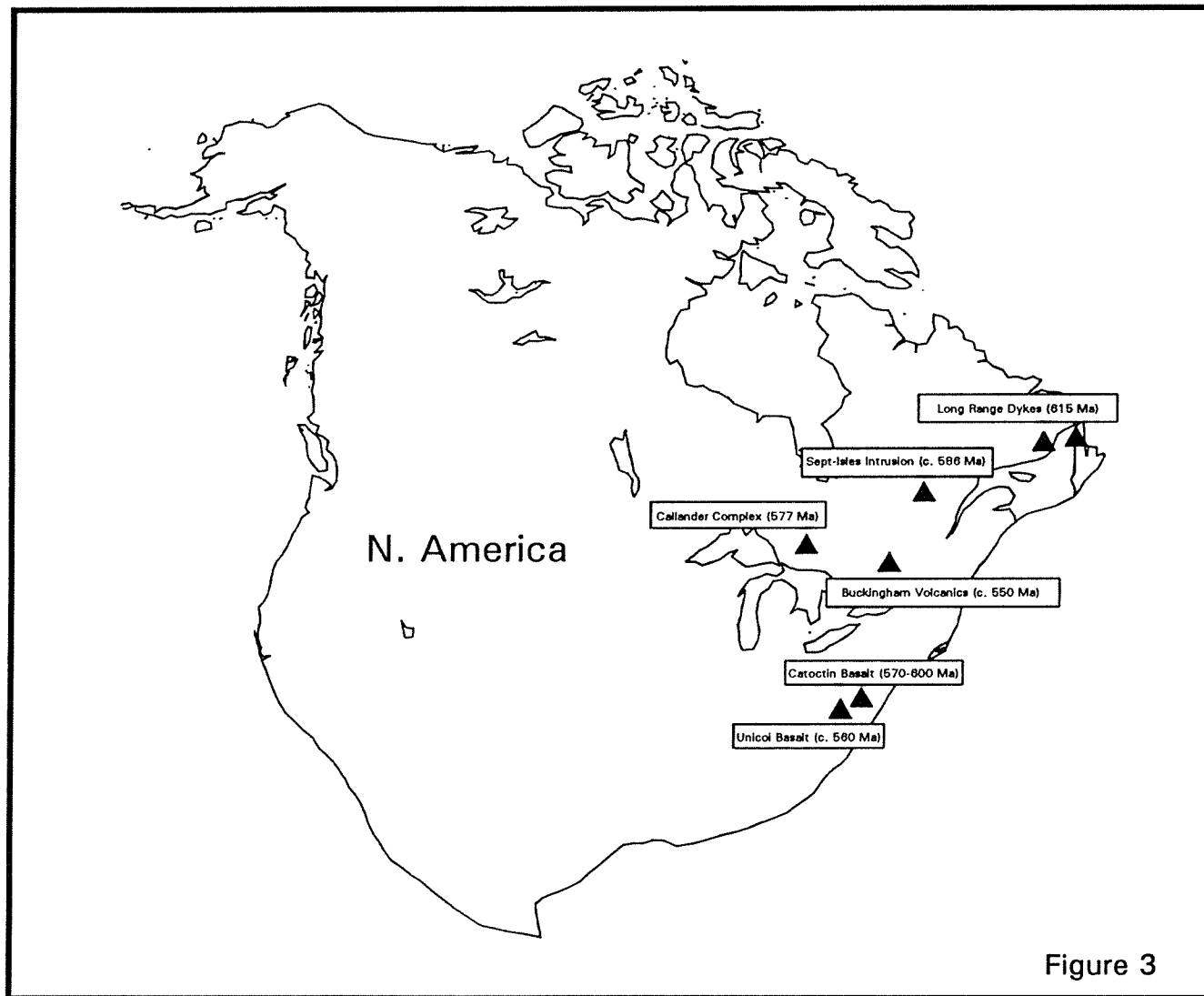
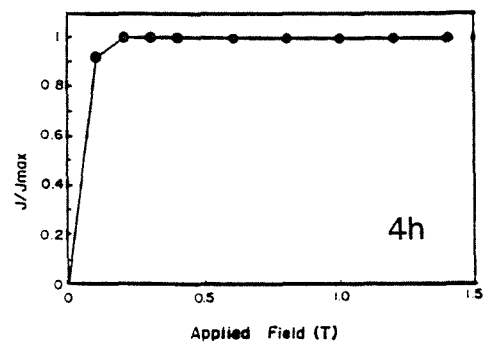
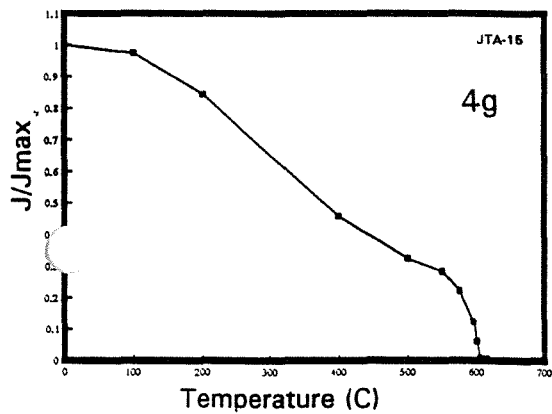
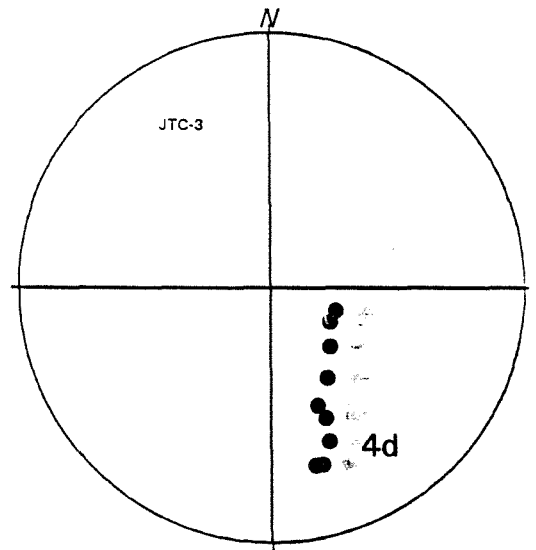
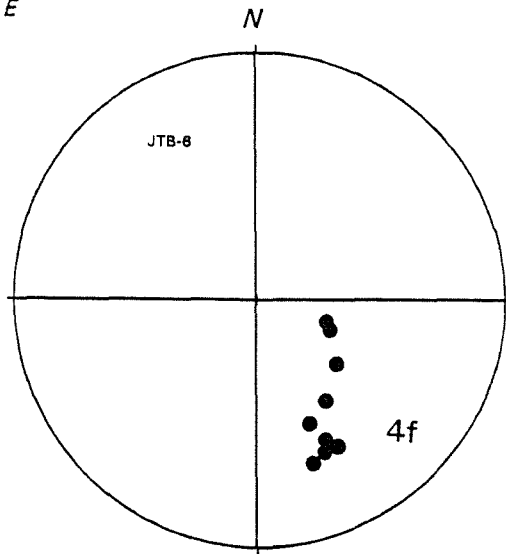
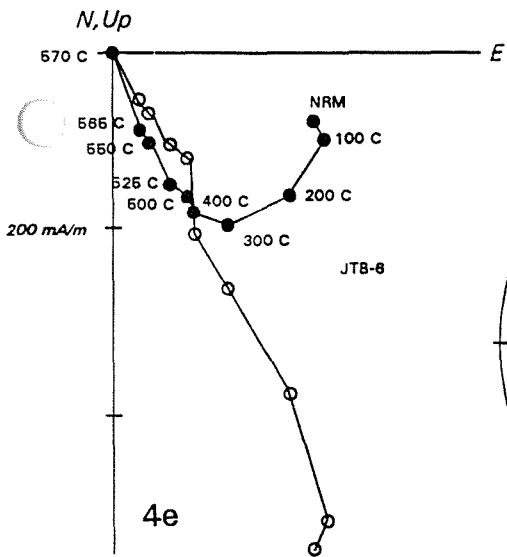
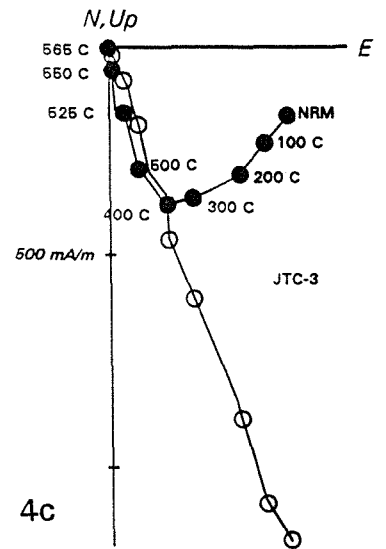
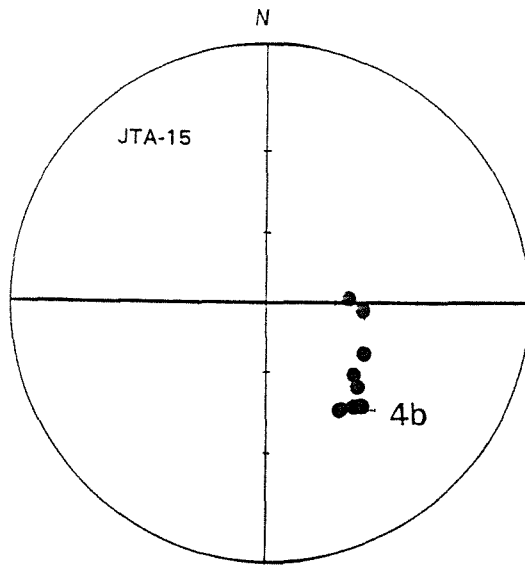
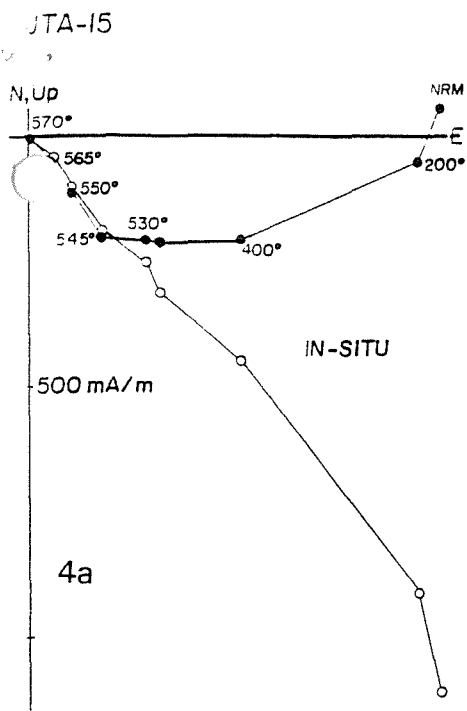
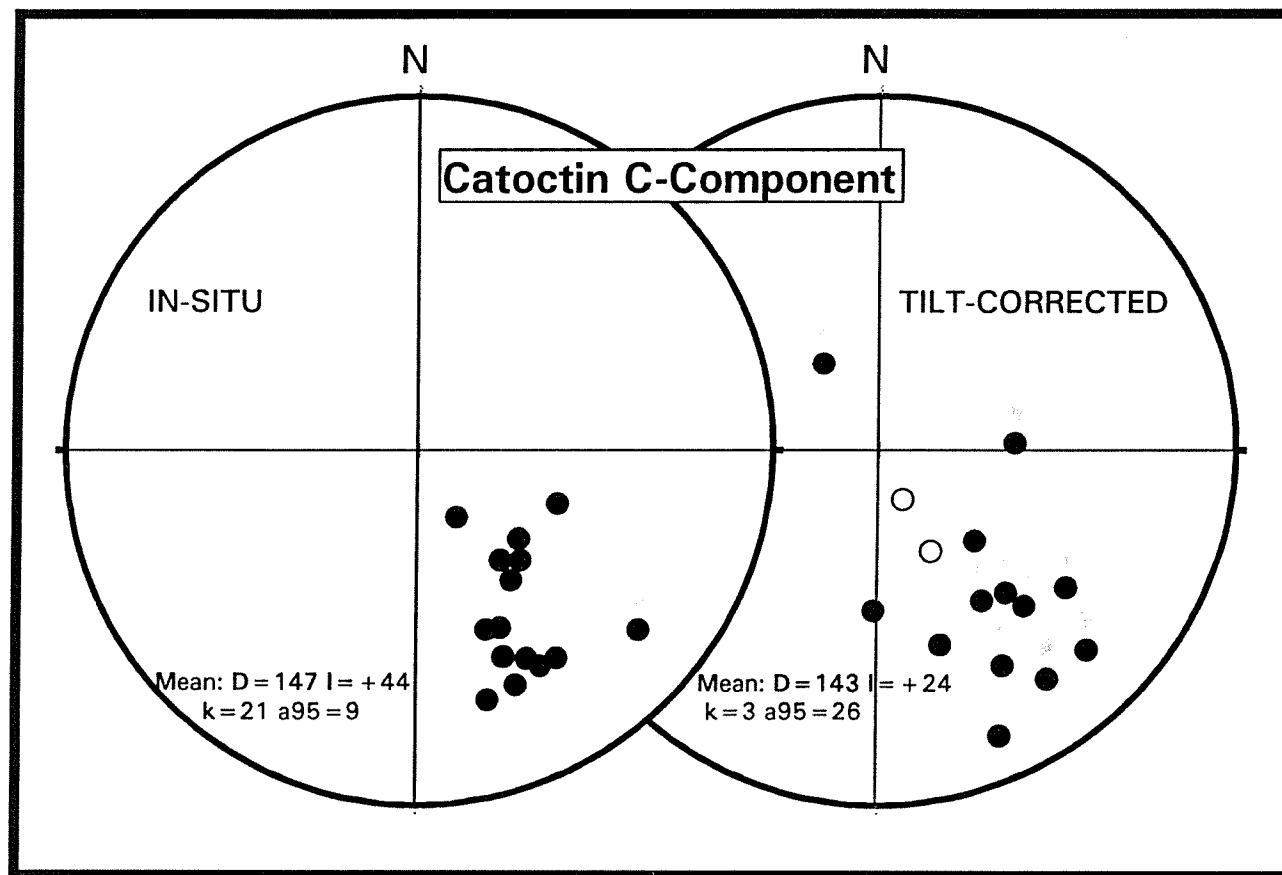


Figure 1



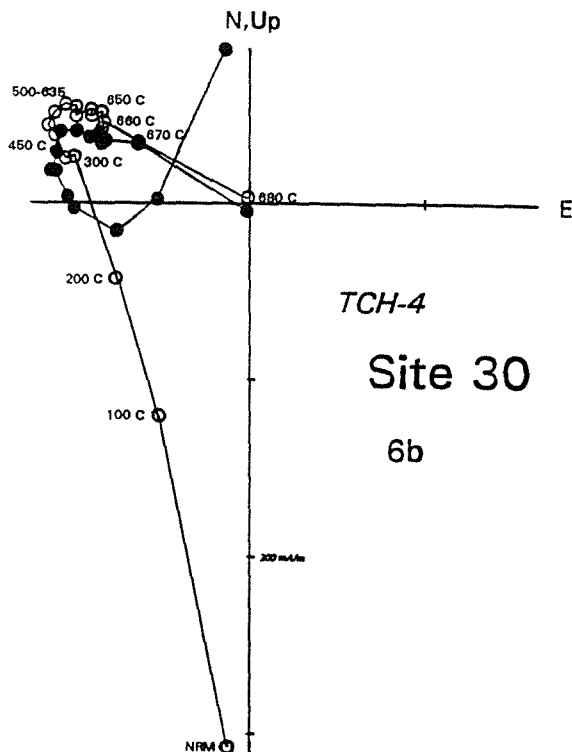
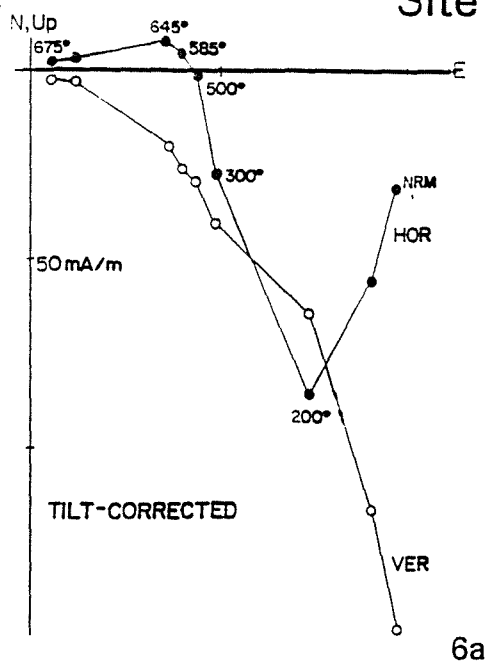






JMA-2

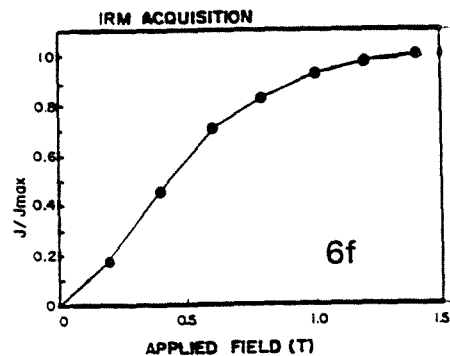
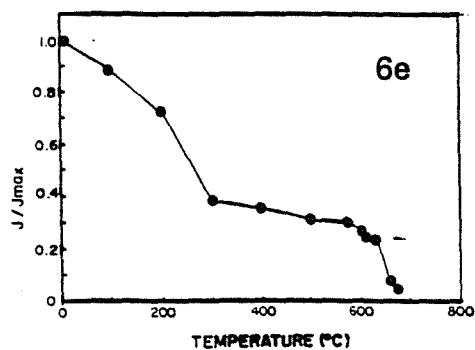
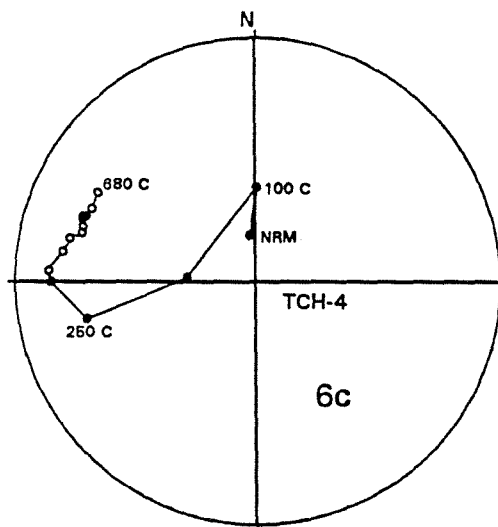
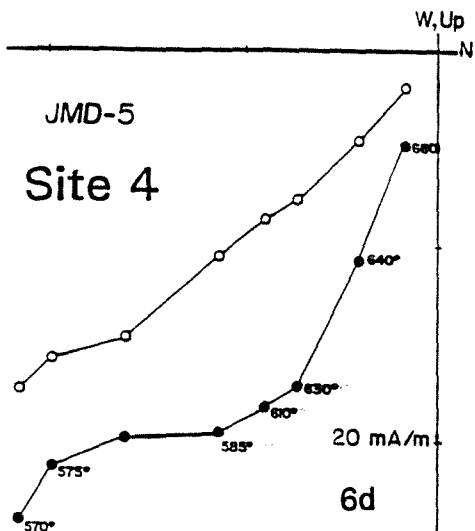
Site 1

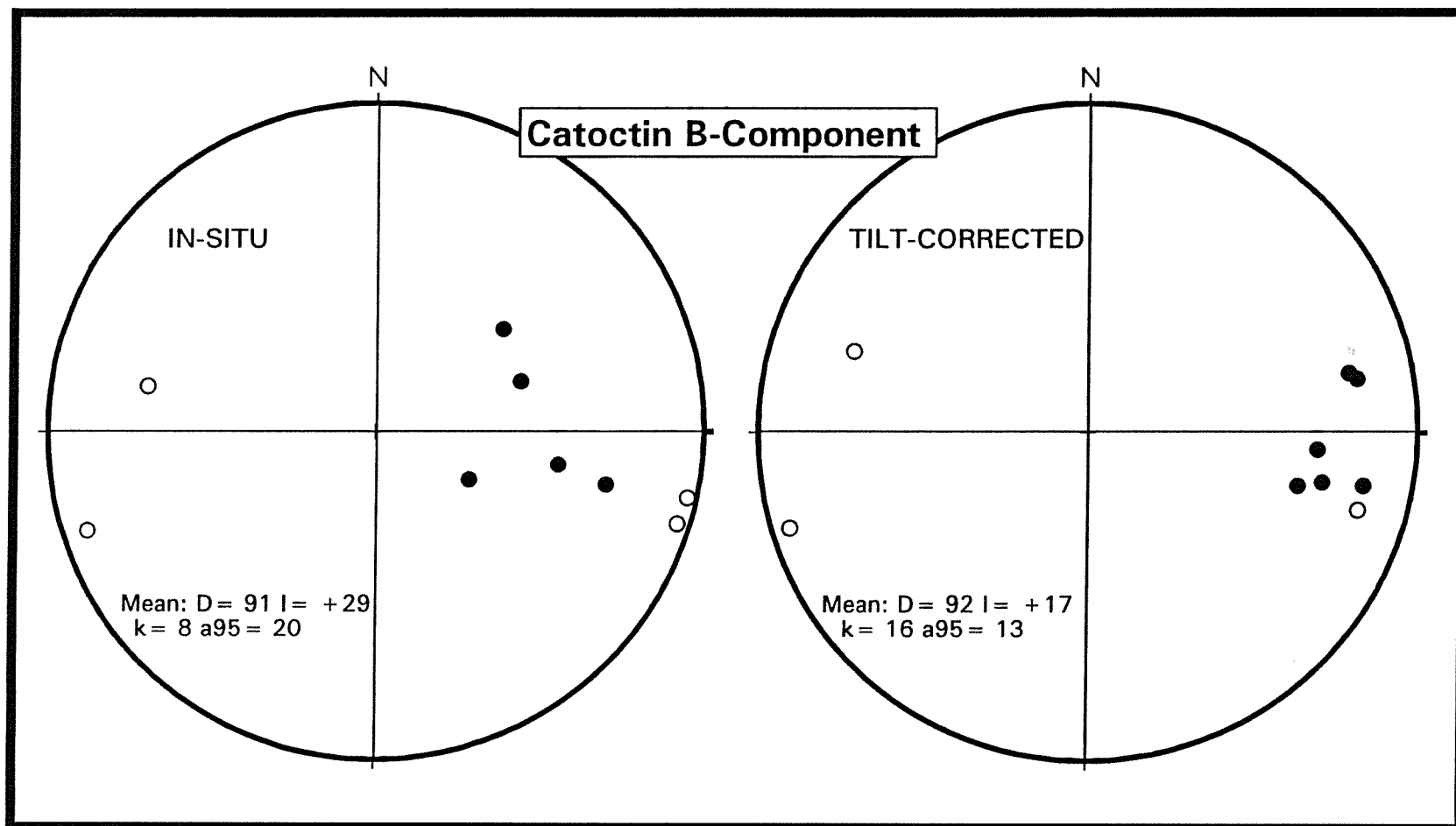


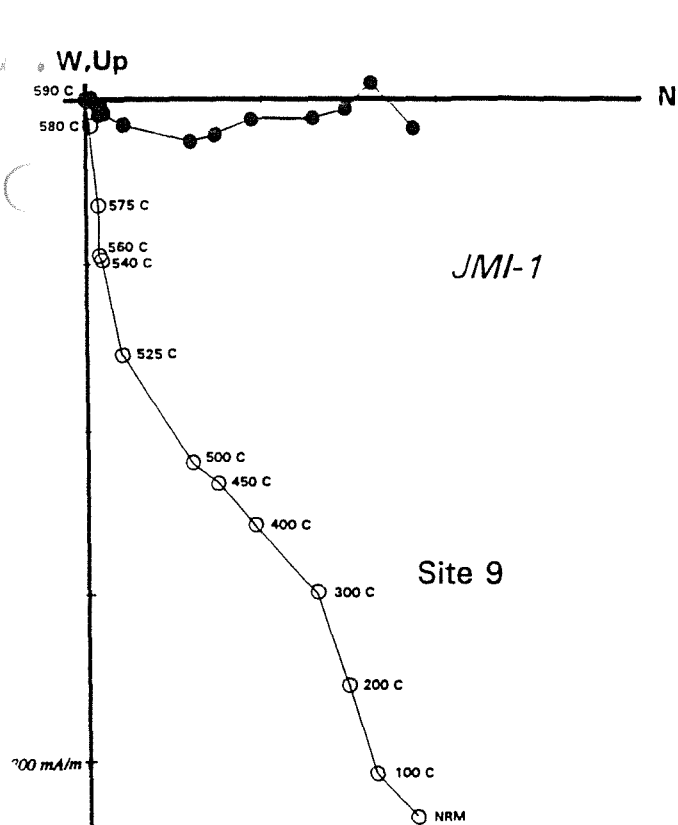
TILT-CORRECTED

JMD-5

Site 4







8a

