RHO-BWI-C-110

Magnetostratigraphy of the Columbia River Basalt, Pasco Basin and Vicinity, Washington

D.R. Van Alstine
S.L. Gillett

Prepared for the United States
Department of Energy
Under Contract DE-AC06-77RL01030

Rockwell International

Rockwell Hanford Operations
Energy Systems Group
Richland, WA 99352

RHO-BWI-C-110

MAGNETOSTRATIGRAPHY OF THE COLUMBIA RIVER BASALT, PASCO BASIN AND VICINITY, WASHINGTON

David R. Van Alstine
and
Stephen L. Gillett

Sierra Geophysics, Inc.

June 1981

Prepared for the United States
Department of Energy under
Contract DE-AC06-77RL01030

Rockwell International

Rockwell Hanford Operations
Energy Systems Group
P.O. Box 800
Richland, Washington 99352

DOE-Richland, WA

ABSTRACT

A paleomagnetic study was performed on about 500 surface and subsurface samples of the Columbia River Basalt Group from the Pasco Basin and vicinity, southeastern Washington. This study also included reanalysis and integration of paleomagnetic data collected during three previous paleomagnetic investigations. Emphasis was placed on testing and extending the magnetostratigraphic interpretation of the Columbia River basalts beneath the Hanford Site.

A consistent magnetostratigraphy of Grande Ronde Basalt emerges from the surface and core hole paleomagnetic data. A change from reversed polarity (below) to normal polarity (above) occurs at a depth of 0,500 ft below the Vantage horizon. This polarity change is the R_2-N_2 contact, previously mapped in surface outcrops on the Columbia Plateau. Within the two magnetozones of the upper Grande Ronde Basalt, between-flow inclination differences of up to 60° probably reflect the Miocene geomagnetic secular variation. These distinctive changes in paleoinclination permit subdivision of the Grande Ronde-R_2 magnetozone into three magnetic intervals (designated GR-$R_2\alpha$ through γ) and of the Grande Ronde-N_2 magnetozone into five magnetic intervals (GR-$N_2\alpha$ through ε).

The Wanapum and Saddle Mountains Basalts contain at least four magnetozones and large variations in magnetic susceptibility as well as in inclination. Thus, the potential for using paleomagnetism to correlate Wanapum and Saddle Mountains Basalts is just as promising as for the Grande Ronde Basalt.

In the Pasco Basin core holes, the consistency of paleomagnetic directions at equivalent stratigraphic horizons indicates that these holes penetrated few if any dikes.

CONTENTS

FIGURES (Contd):

INTRODUCTION

The Columbia River Basalt Group beneath the Hanford Site in the Pasco Basin, Washington is being evaluated for its suitability for underground storage of radioactive waste (e.g., Myers, Price, and others, 1979; BWIP, 1980). Stratigraphic correlation among various units of this thick basaltic section are often difficult to make because many of the flows are chemically and physically similar. Recent paleomagnetic investigations by Coe and others (1978), Beck and others (1978), and Packer and Petty (1979) have demonstrated that certain flows in this sequence can be correlated on the basis of paleomagnetic directions. The purpose of the present investigation is to strengthen magnetostratigraphic correlations within the Columbia River Basalt Group (Figure 1), particularly those involving the upper part of the Grande Ronde Basalt.

This study involved paleomagnetic analysis of 519 samples obtained from 68 flows. These samples were about equally divided between outcrops and core holes, including core from the deepening of borehole DC-7, which was being investigated paleomagnetically for the first time. Emphasis was placed on integrating the surface and subsurface data to test and extend the magnetostratigraphy of the Pasco Basin. A major part of this effort involved merging this new data set with those from previous workers.

SAMPLE COLLECTION

SURFACE EXPOSURES

Twenty-nine surface exposures of Columbia River basalt were sampled over an area of 5,800 mi^2 (Figure 2). These included 20 sites in Saddle Mountains Basalt, four sites in Wanapum Basalt, and five sites in Grande Ronde Basalt. Design of the project was made by P. E. Long and S. P. Reidel, who also provided site locations and structural attitudes. Field sampling was conducted by D. R. Van Alstine, S. W. Bogue, and M. F. Linker of Sierra Geophysics, and M. Hagood and N. J. Davidson of Rockwell Hanford Operations, over the period June 11 through 22, 1980.

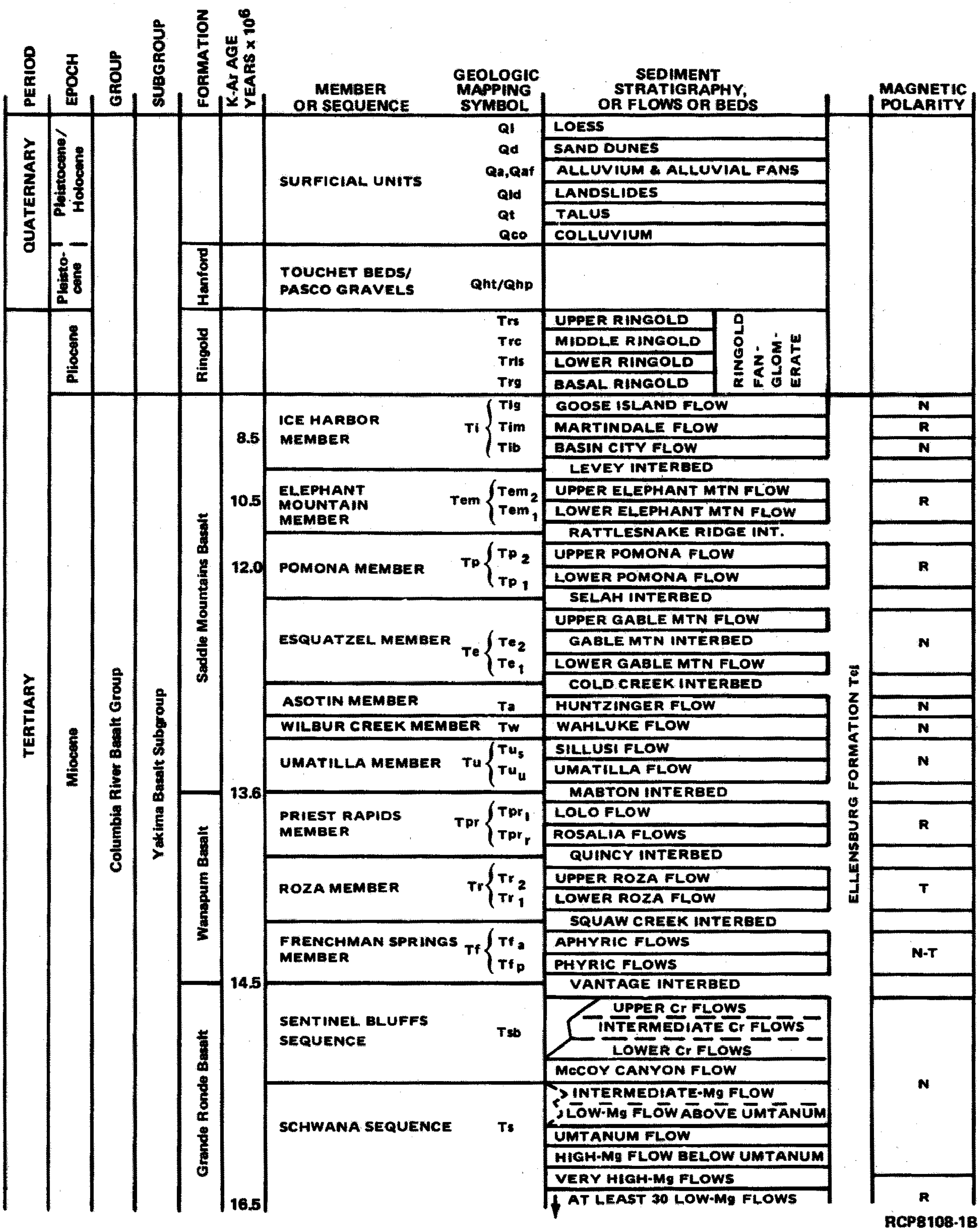


FIGURE 1. Stratigraphy of Columbia River Basalt Group.

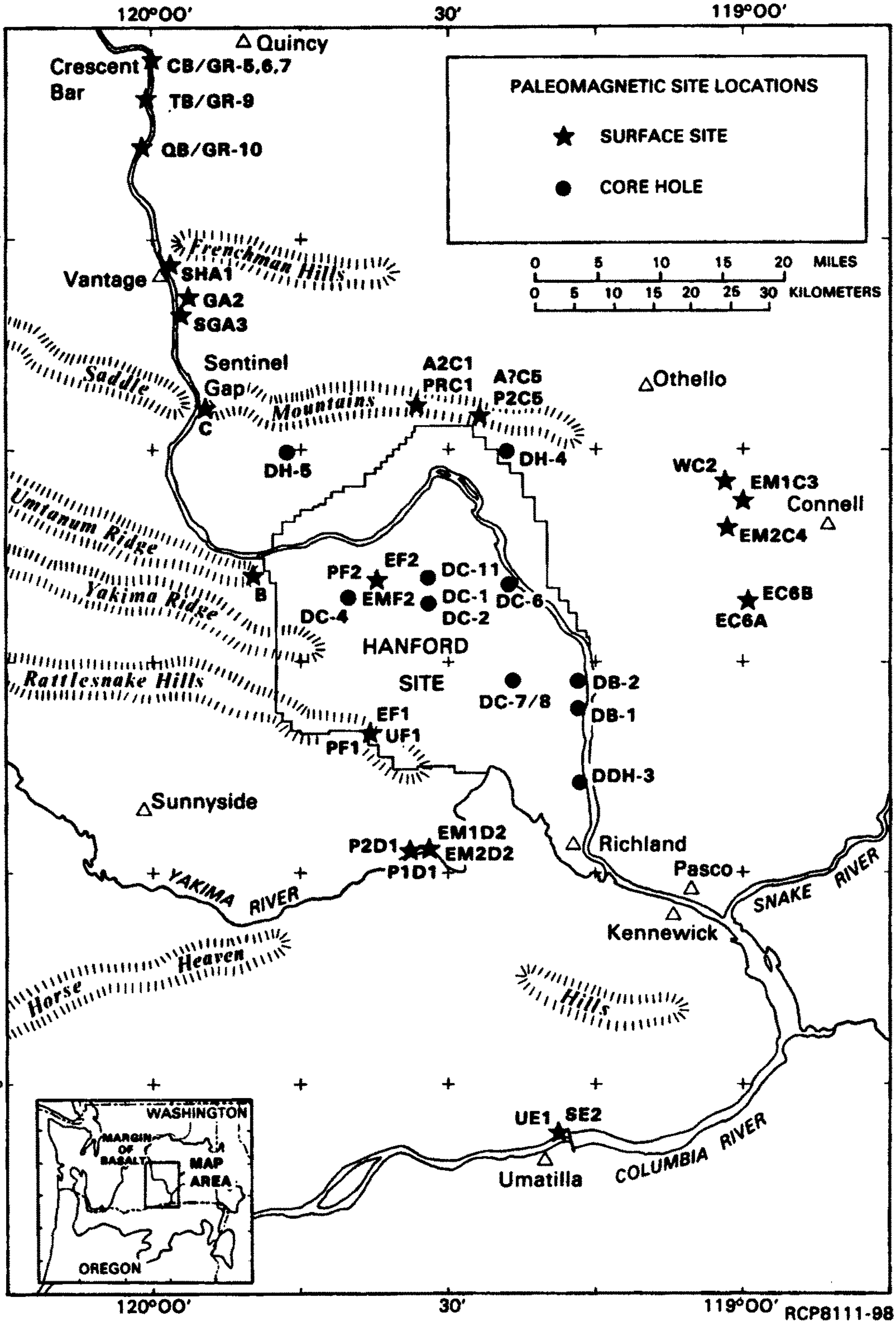


FIGURE 2. Paleomagnetic Site Locations.

Eight samples were collected from a single flow at each site. The samples were obtained using a portable gasoline-powered drill fitted with a diamond bit. To avoid possible secondary magnetizations, samples were obtained away from flow tops, bottoms, or fractures. The samples, which were 3 to 5 in. long, were oriented using both a solar compass and a Brunton compass affixed to a 1.5-ft-long brass sleeve. Wherever possible, magnetic compass measurements were checked by sighting on distant landmarks. For all samples, the sun compass measurements were judged to be more accurate and were used in all paleomagnetic calculations. As in the study by Beck and others (1978), the deviation between solar and magnetic compass measurements was typically a few degrees, although large (>10°); probably lightning-produced deviations were also encountered.

CORE HOLES

Thirty-nine flows were sampled from the continuous core obtained from seven different core holes penetrating Columbia River basalts in the Pasco Basin. These included 30 flows in Grande Ronde Basalt (22 flows in DC-7, five flows in DC-6, and one flow in each of DH-4, DH-5, and DDH-3); seven flows in Saddle Mountains Basalt (two in DC-8, one in DB-7, two in DH-5, and two in DH-4); and two flows in Wanapum Basalt (both from the Roza Member in DH-5). Core hole sampling was conducted between June 20 and 25, 1980 by D. R. Van Alstine and S. W. Bogue of Sierra Geophysics, assisted by R. D. Landon, N. J. Davidson, and M. Hagood of Rockwell Hanford Operations.

Generally, eight samples per flow were collected from DC-7 and seven samples per flow from the six other core holes. As with the surface outcrops, flow tops, bottoms, and fracture zones were avoided. An estimate was made as to whether samples were located in entablature or colonnade to check for possible correlations between flow morphology and paleomagnetic properties.

Samples were collected at the core storage warehouse using a drill press fitted with a water-cooled diamond bit. Before drilling, each core segment was marked with its drilled depth and up direction. Pieces of broken core were fitted together wherever possible, and a common axial line was scribed on each segment to preserve the relative orientation of the pieces. This reference line was parallel to the fluxgate orientation line, if that had been marked. (The fluxgate orientation line is an attempt to define a consistent orientation line using a fluxgate magnetometer.) No fluxgate orientation line had been determined for the DC-7 core.

LABORATORY MEASUREMENTS

All laboratory work was done in the Sierra Geophysics paleomagnetics laboratory. The core samples were first cut into cylindrical specimens 1.0 in. in length using a rock saw. One specimen was cut from each sample. The specimens were taken from the back (least weathered) part of the surface-exposure samples and from the middle of subsurface samples.

All measurements of natural remanent magnetization (NRM) were made on a three-axis, 2.5-in.-access superconducting (SQUID) magnetometer manufactured by Superconducting Technology, Inc. This instrument has a dynamic range between 10^{-8} and 10^{+1} emu. The magnetometer is interfaced to a PRIME 550 computer, which permits real-time computation of magnetic directions, intensities, induced/remanent ratios, uniformity of magnetization parameters, structural corrections, and virtual geomagnetic poles. All data pertaining to the measurement are printed out, simultaneously stored on magnetic disk, and later archived onto magnetic tape, making the complete data set readily accessible to future investigators.

Laboratory analysis consisted of measuring the bulk magnetic susceptibility, NRM, and the progressive alternating field (AF) or thermal demagnetization behavior of all samples from each flow.

Magnetic susceptibilities were measured using a low-field (0.5 Oe) bridge manufactured by Bison Instrument Company. The susceptibility values were periodically checked on the cryogenic magnetometer.

Alternating-field demagnetization was performed using a Schonstedt Model GSD-1 specimen demagnetizer which provides peak fields up to 1,000 Oe (100 mT). Each specimen was demagnetized around three orthogonal axes; the order of the axes around which the specimen was demagnetized was changed from one demagnetization step to the next to minimize any effects from acquisition of anhysteretic remanent magnetization (ARM). In addition, this procedure precludes the acquisition of rotational remanent magnetization (RRM), because specimens are not rotated or tumbled.

To complement the AF demagnetization studies, thermal demagnetization was conducted to investigate the blocking temperature spectra of the NRM of Grande Ronde Basalts. Thermal demagnetization was performed on 50 samples using a Schonstedt thermal demagnetizer modified for insertion of a thermocouple probe to monitor the temperature of each sample.

A minimum of six demagnetization steps (either AF or thermal) were performed on every sample from each flow. The peak alternating fields at these six steps were between 25 and 500 Oe, and the peak temperatures were between 150° and 600°C. If the characteristic magnetization direction had not been isolated by 500 Oe, additional AF steps were performed up to 800 Oe. For several samples, combined thermal-after-AF demagnetization experiments were conducted.

All measurements and all demagnetization experiments were carried out in a 6-ft by 6-ft magnetically shielded room, within which the ambient magnetic field is about 75 gammas (nT). This reduces the contribution of any viscous components of remanent magnetization (VRM) to the total NRM of the specimen and results in smoother vector demagnetization diagrams (Zijderveld, 1967).

DATA ANALYSIS

For each sample, vector analysis was performed to identify the multiple components of magnetization that might be present. This is most accurately accomplished by fitting least-squares lines to segments of the vector demagnetization diagrams that are linear in three-space. The advantage of this technique, which we have refined after a method described by Kirschvink (1980), is that scatter of directions due to effects of VRM or ARM are minimized in the final computation of the mean direction for a flow.

The component with the highest coercivity or blocking temperature was considered to be the characteristic magnetization (Zijderveld, 1967) of the sample. The characteristic magnetization directions were used to compute mean paleomagnetic directions for each flow by a variety of techniques.

For surface flows, where fully oriented samples are obtained, the statistics of Fisher (1953) were calculated; the statistical uncertainty in the estimated mean is represented by the half-angle of the cone of 95% confidence, a_{95} (e.g., McElhinny, 1973). In addition to Fisher statistics, "moment of inertia" statistics (Dimroth-Watson and Bingham cf. Mardia, 1972) were computed for surface flows. These statistics have only recently been applied in paleomagnetism (e.g., Onstott, 1980), and they offer advantages over Fisher statistics in certain instances.

For core hole samples, where only the paleomagnetic inclination has been recovered, Fisher statistics cannot be computed by traditional means. Thus, in past studies of the Pasco Basin core holes, only arithmetic mean inclinations were determined, together with their standard deviations. This made it difficult to compare surface and core hole paleoinclination data, because surface α_{95} values (which measure the uncertainty in the estimated mean inclination) were being compared with core hole standard deviations of mean inclinations (which measure the scatter of inclination values).

Using a technique described by Kono (1980), it is now possible to calculate the Fisher statistics of inclination-only data. In the present investigation, Kono's method has been used in computing mean directions from the subsurface flows. Kono's technique has also been employed to recompute mean flow statistics for each flow sampled in the previous core hole studies (Beck and others, 1978; Packer and Petty, 1979). This results in a homogeneous data set that can be directly compared to the statistics from surface flows.

RESULTS

The results from this paleomagnetic investigation are summarized and interpreted below; they are presented in detail in separate data volumes which are available in the library of the Basalt Waste Isolation Project. The data volumes present, in both tabulated and graphical form, the complete demagnetization history of each of the 519 samples analyzed in this study. The tables list the magnetization directions (before and after structural correction), corresponding virtual geomagnetic poles, intensities as a function of demagnetization step, subtracted vectors between demagnetization steps, bulk magnetic susceptibilities, and output from the statistical analysis programs. The graphs show vector demagnetization information in the form of vector demagnetization diagrams, stereonet plots of directional change upon demagnetization, and normalized intensity versus demagnetization level.

For subsurface samples, color plots are also presented showing paleomagnetic results as a function of depth below the surface. These plots include NRM and cleaned paleomagnetic inclinations, NRM intensities, magnetic susceptibilities, and mean flow inclinations with their α_{95} values.

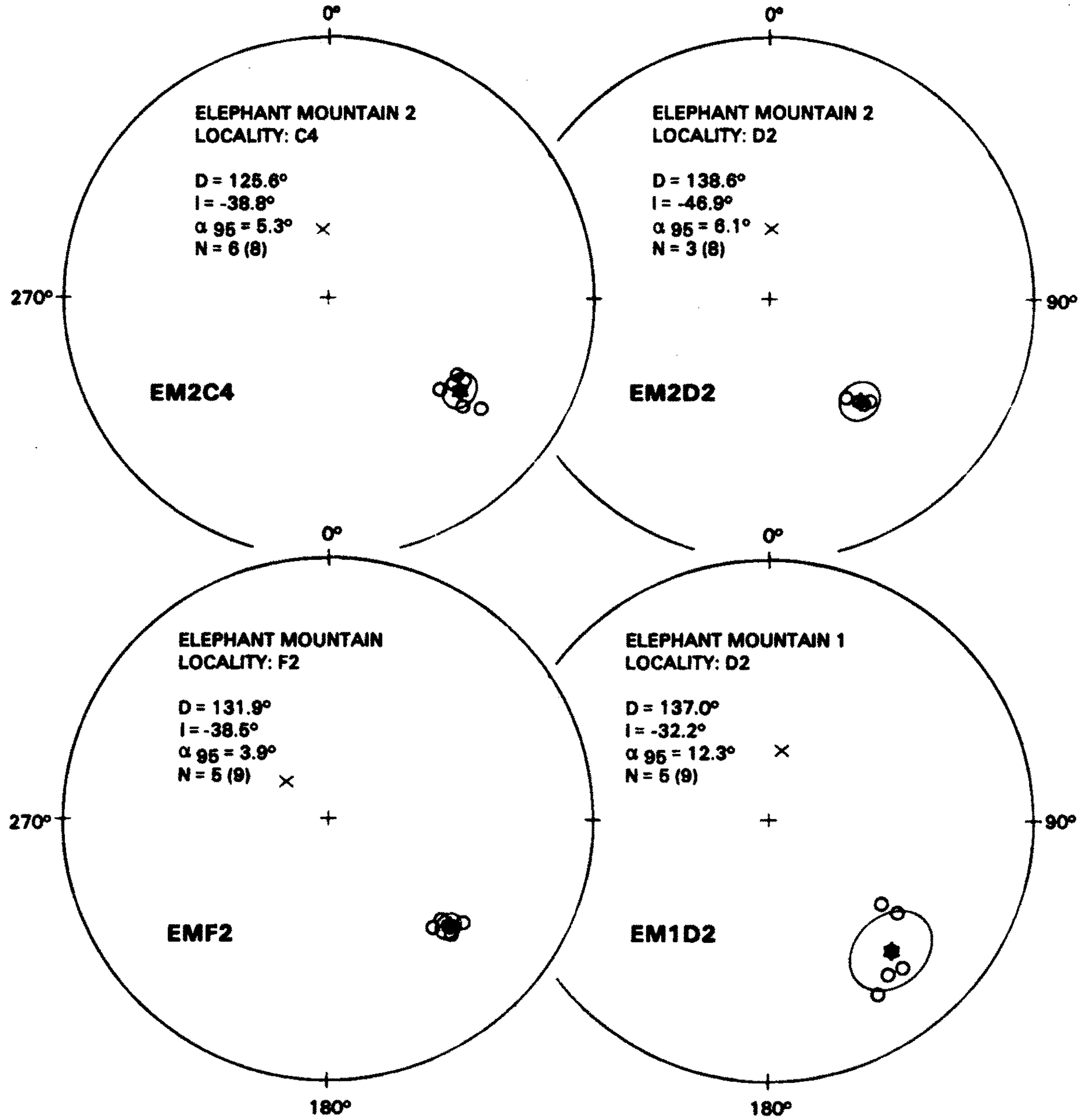
SADDLE MOUNTAINS BASALT

Elephant Mountain Member

Forty-one samples were obtained at five sites in the Elephant Mountain Member. Nearly all samples had NRM directions dominated by a normal-polarity VRM aligned approximately with the present axial dipole field. Upon progressive AF demagnetization, however, most directions moved toward a reversed-polarity inclination in the southeast quadrant (Figure 3). Fewer than half (46%) of the samples actually achieved stable reversed-polarity endpoints on vector demagnetization diagrams. One site (EM1C3) was too overprinted with the normal-polarity component to permit calculation of a characteristic magnetization direction. At another site (EM2D2), three of the samples achieved stable reversed-polarity endpoints, but only after removing over 96% of the NRM intensity. Samples at site EM2C4 best exhibited the reversed-polarity characteristic magnetization of this flow; 75% of these samples achieved stable end-points after cleaning to about 300 Oe.

A mean direction (declination D = 133.2°, inclination I = -39.2°, α_{95} = 8.6°) has been computed giving unit weight to the four Elephant Mountain sites from which reversed-polarity directions could be isolated. This inclination is quite close to that obtained from core hole data.

Two Elephant Mountain flows were sampled by Packer and Petty (1979) in DDH-3, and one Elephant Mountain flow was sampled in this study from DB-7. Packer and Petty (1979) reported a reversed inclination of -39° for "EMI" and were unable to isolate a characteristic magnetization for "EM2," possibly because none of the samples were AF demagnetized higher than 125 Oe. Since their "EMI" samples were obtained stratigraphically higher than "EM2," their reported "EMI" inclination really applies to the upper (EMIT) Elephant Mountain flow. The seven samples from EM1 of Packer and Petty (1979) were combined with the seven samples of this study to yield a mean subsurface paleoinclination of -37.5° (α_{95} = 6.4°).



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

D = DECLINATION

I = INCLINATION

α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)

N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)

X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-99

FIGURE 3. Remanent Magnetization Direction Diagrams: Elephant Mountain Member.

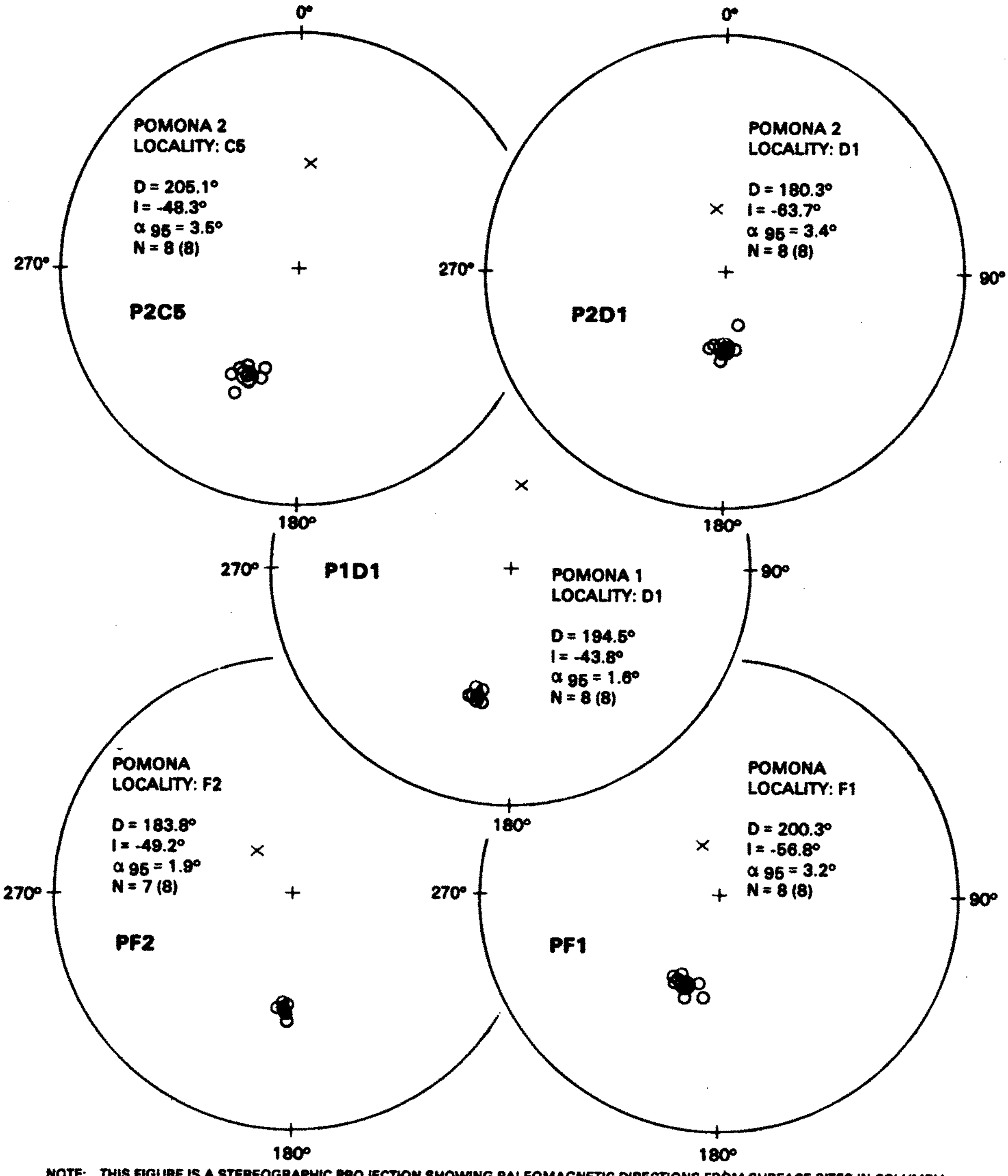
Based on the results from surface outcrops and core holes, it seems certain that both Elephant Mountain flows have reversed-polarity characteristic magnetizations. Both flows, however, tend to be heavily overprinted with normal-polarity VRM. This probably accounts for the normal polarity reported from fluxgate magnetometer measurements of the upper Elephant Mountain flow.

Pomona Member

Thirty-nine samples were obtained at five sites in the Pomona Member. All of these samples had negative-inclination directions at NRM and throughout progressive AF demagnetization (Figure 4). Most samples exhibited a single component of magnetization with a median destructive field (MDF; defined as the peak AF field required to reduce the NRM intensity by one-half) between 300 and 600 Oe. At site PF1, however, the MDF was anomalously low, between 75 and 150 Oe.

The Pomona flows yield some of the best groupings of paleomagnetic directions of any of the Columbia River basalt flows; Fisherian concentration parameters, k, ranged between 250 and 1,200. Even with eight samples per site, the largest α_{95} value obtained for any site was 3.5°. Curiously, the mean directions computed for all Pomona sites, both before and after structural correction, are statistically distinct from one another. This problem, which is not unique to the Pomona flows, will be discussed at greater length in a later section of this report.

A mean Pomona direction (D = 193.5°, I = -52.7°, α_{95} = 9.5°) was computed giving unit weight to each of the five surface site means. This paleoinclination derived from surface flows compares well with the subsurface data of Packer and Petty (1979) from DC-11. Mean inclinations computed separately for each *of* two Pomona flows in DC-11 are nearly identical (-52.5° and -50.1°). Giving unit weight to each of the 14 samples from the DC-11 Pomona flows yields a mean subsurface Pomona inclination *of* -51.3° (α_{95} = 2.8°).



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

- D = DECLINATION
- I = INCLINATION
- α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)
- N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)
- X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-100

FIGURE 4. Remanent Magnetization Direction Diagrams: Pomona Member.

Esquatzel Member

Thirty-two samples were obtained at four sites in the Esquatzel Member. At three of these sites, all samples achieved stable normal-polarity endpoint directions (Figure 5). Most of these samples (particularly at sites EC6A and EC6B) contained only a single component of magnetization with an MDF of about 300 Oe. At site ER, however, five of the eight samples exhibited multiple components of magnetization with overlapping stability spectra. Thus, a reliable characteristic magnetization direction could not be determined for site EF1.

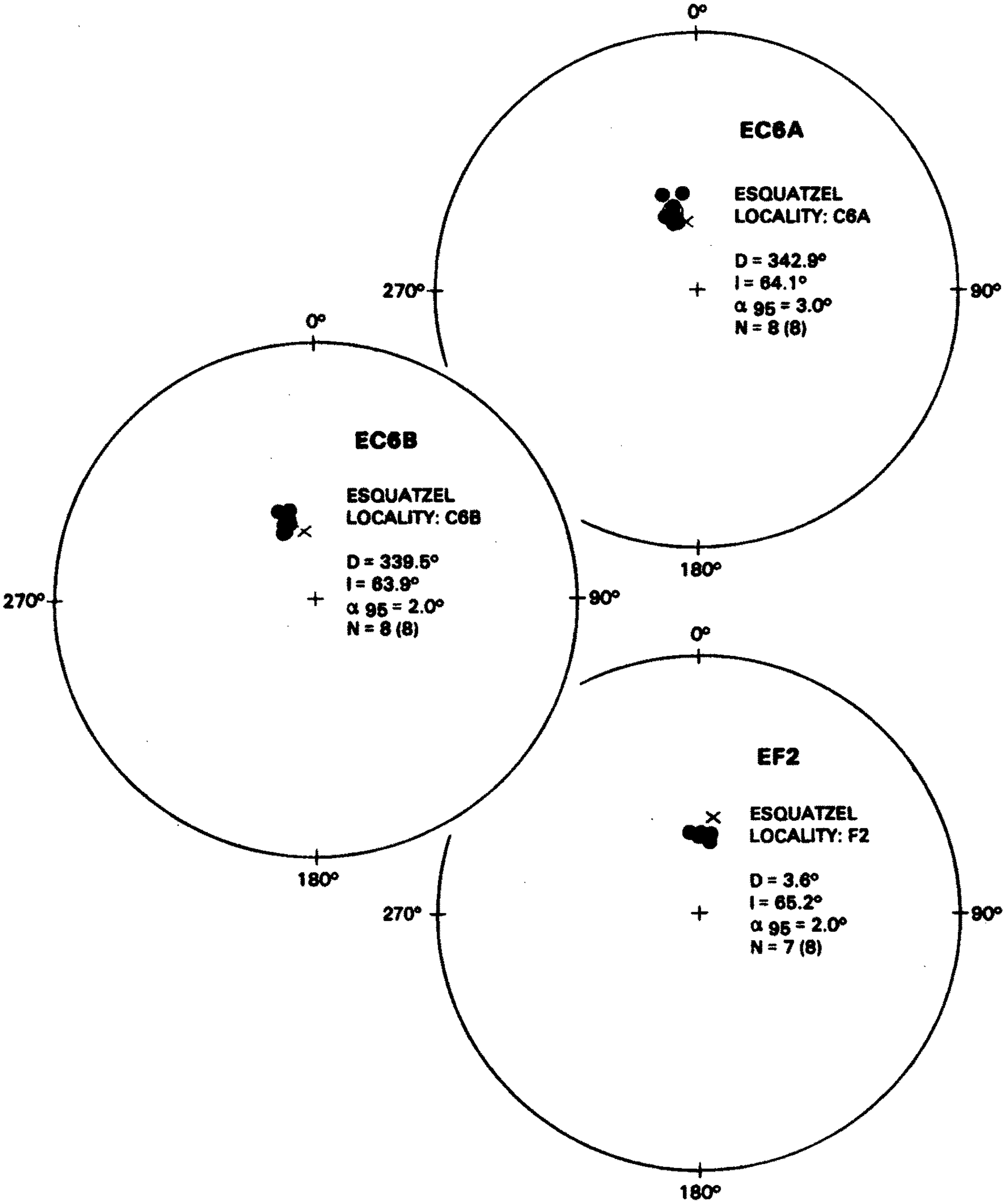
The other three Esquatzel sites yielded well-grouped paleomagnetic directions with $\alpha_{95} < 3.0°$. Although the directions from sites EC6A and EC6B are nearly identical, that from site EF2 is statistically distinct, both before and after structural correction.

A mean Esquatzel direction (D = 348.4°, I = +64.8°, α_{95} = 8.6°) was computed giving unit weight to each of the three surface sites. This inclination is consistent with Esquatzel(?) paleomagnetic directions determined by Packer and Petty (1979) from DB-1. A mean inclination has been recomputed from seven samples of the upper flow (I = +66.2°, (α_{95} = 6.6°) and from five samples of the lower flow (I = +78.3°, α_{95} = 20.6°).

Asotin Member

Eight samples were obtained at one site (A2C1) known to be in the Asotin Member. All of these samples had NRM directions with shallow positive inclinations. After progressive AF demagnetization, six of these directions achieved stable endpoints, tightly clustered about a mean at D = 335.2°, I = +67.4°, a_{95} = 2.6°, after structural correction (Figure 6).

Three Asotin flows were sampled from subsurface core. In DH-4, where the flows dip 2° to the southwest, an Asotin (Huntzinger) flow was sampled by Packer and Petty (1979) and resampled during this study. Combining results from both studies yields a mean inclination of +69.0° (N = 20, α_{95} = 2.3°). In addition, two Asotin flows were sampled during this study in DH-5, in which the flows dip 9° to the south. These flows



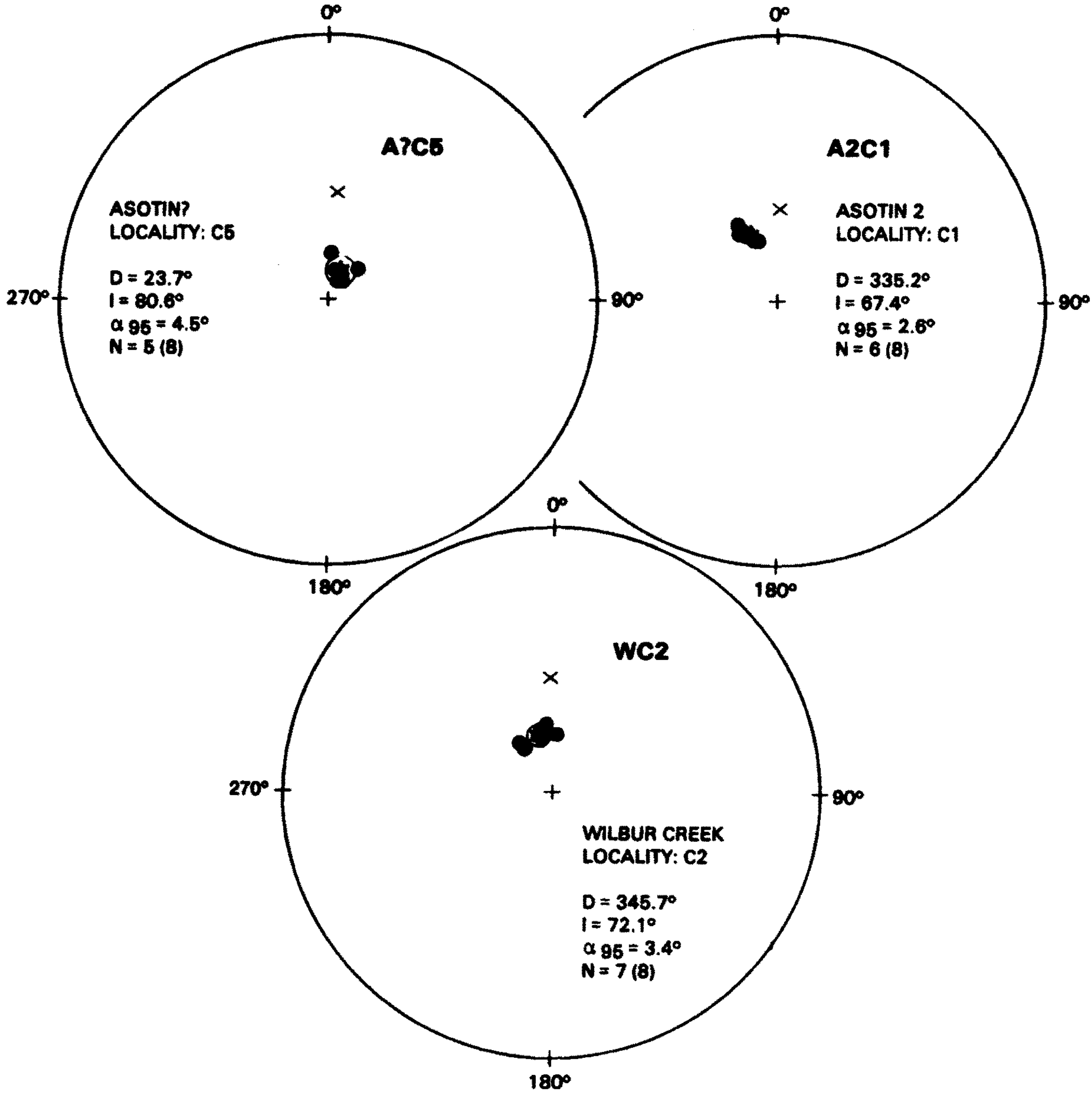
NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

- D = DECLINATION
- I = INCLINATION
- α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)
- N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)
- X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-101

FIGURE 5. Remanent Magnetization Direction Diagrams: Esquatzel Member.



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

D = DECLINATION

I = INCLINATION

α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)

N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)

X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-102

FIGURE 6. Remanent Magnetization Direction Diagrams: Asotin and Wilbur Creek Members.

yielded a structurally corrected mean inclination of +78.8° (N = 7, α_{95} = 8.1°) and +80.7° (N = 7, a_{95} = 2.9°), respectively (+70.6° and +72.9° before correction).

An additional eight samples were collected in surface outcrop from a flow which, on the basis of recent field mapping by S. P. Reidel, is part of the Asotin Member or older. Its chemical composition suggests that it is probably the Asotin Member, but wide variation in Asotin chemical composition makes it impossible to distinguish clearly from older flows based on chemical composition (Reidel and Fecht, 1981). All eight samples have a steep, positive-inclination characteristic magnetization with a mean direction of D = 23.7°, I = +80.6°, α_{95} = 4.5° (Figure 6). Since the Asotin is the only member of the Saddle Mountains or Wanapum Basalts with such a steep inclination, this flow is probably Asotin and has been designated A?C5 in this report.

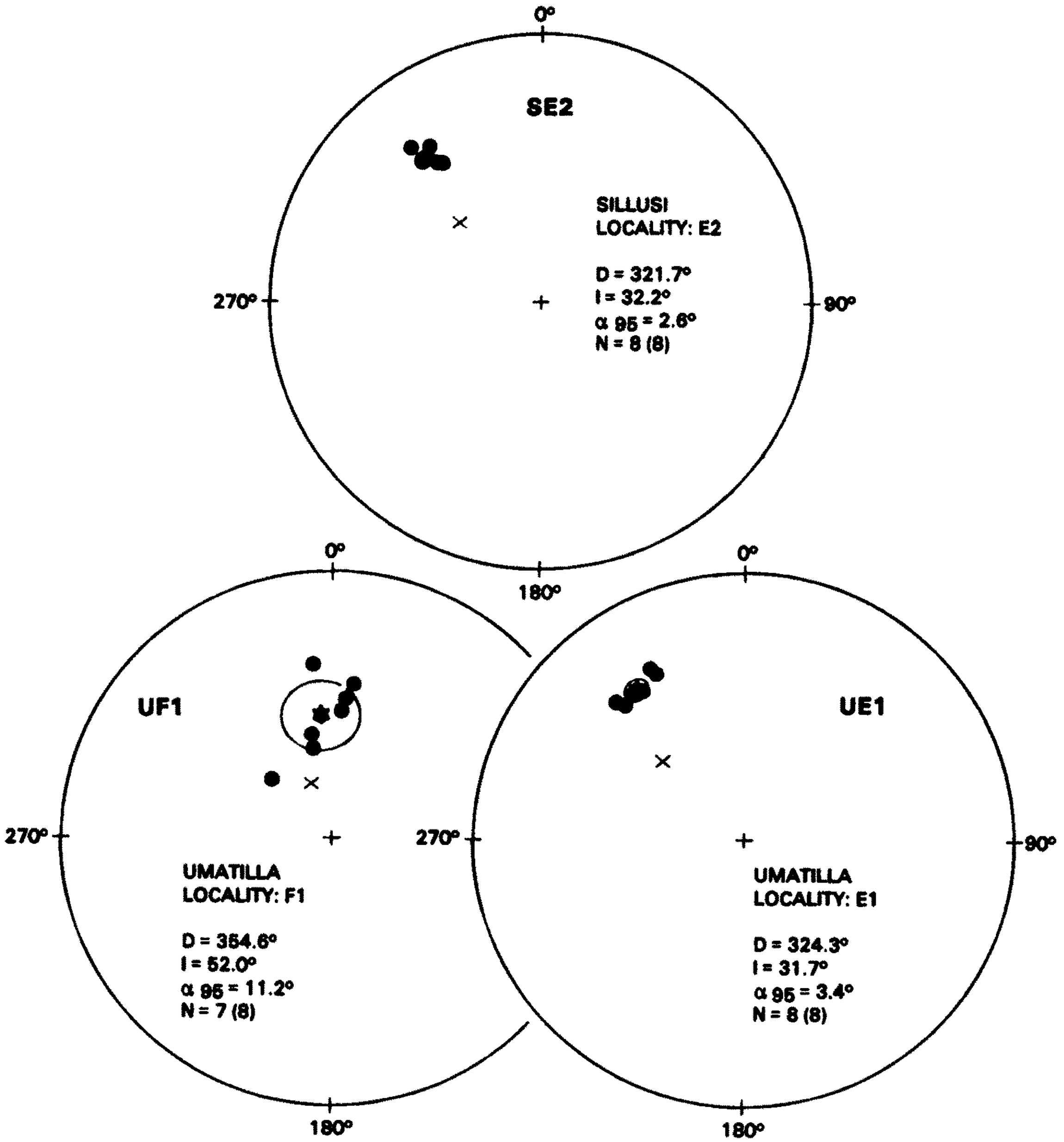
Wilbur Creek Member

Eight samples were collected at one site from the Wilbur Creek Member. Six of these contain only a single, normal-polarity magnetization with a structurally corrected mean at D = 345.7°, I = +72.1°, α_{95} = 3.4° (Figure 6). This component has a high MDF, averaging about 500 Oe. The other two samples contain a second component, which may be a lightning-produced isothermal remanent magnetization (IRM) in this ridge-crest exposure.

A Wilbur Creek (Wahluke) flow was sampled in DH-4 by Packer and Petty (1979) and resampled in this study. Combining results from the two studies yields a structurally corrected mean inclination of +66.1° (N = 14, α_{95} = 3.2°). This inclination is 6° shallower than the inclination found at the single surface site.

Umatilla Member

Twenty-four samples were collected at three sites in the Umatilla Member. Nearly all of these exhibited a single, normal-polarity magnetization with an MDF of 150 to 200 Oe (Figure 7). At locality E, which is



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

D = DECLINATION

I = INCLINATION

α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)

N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)

X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-103

FIGURE 7. Remanent Magnetization Direction Diagrams: Sillusi and Umatilla Flows.

the type locality of the Umatilla Member, eight samples were collected from the Umatilla flow (site UE1), and eight from the overlying Sillusi flow (site SE2). After AF demagnetization, these two flows have well grouped directions with a mean only 2° apart (UE1: D = 324.3°, I = +31.7°, α_{95} = 3.4°; SE2: D = 321.7°, I = +32.2°, α_{95} = 2.6°). This suggests that the Umatilla and Sillusi flows cooled at about the same time.

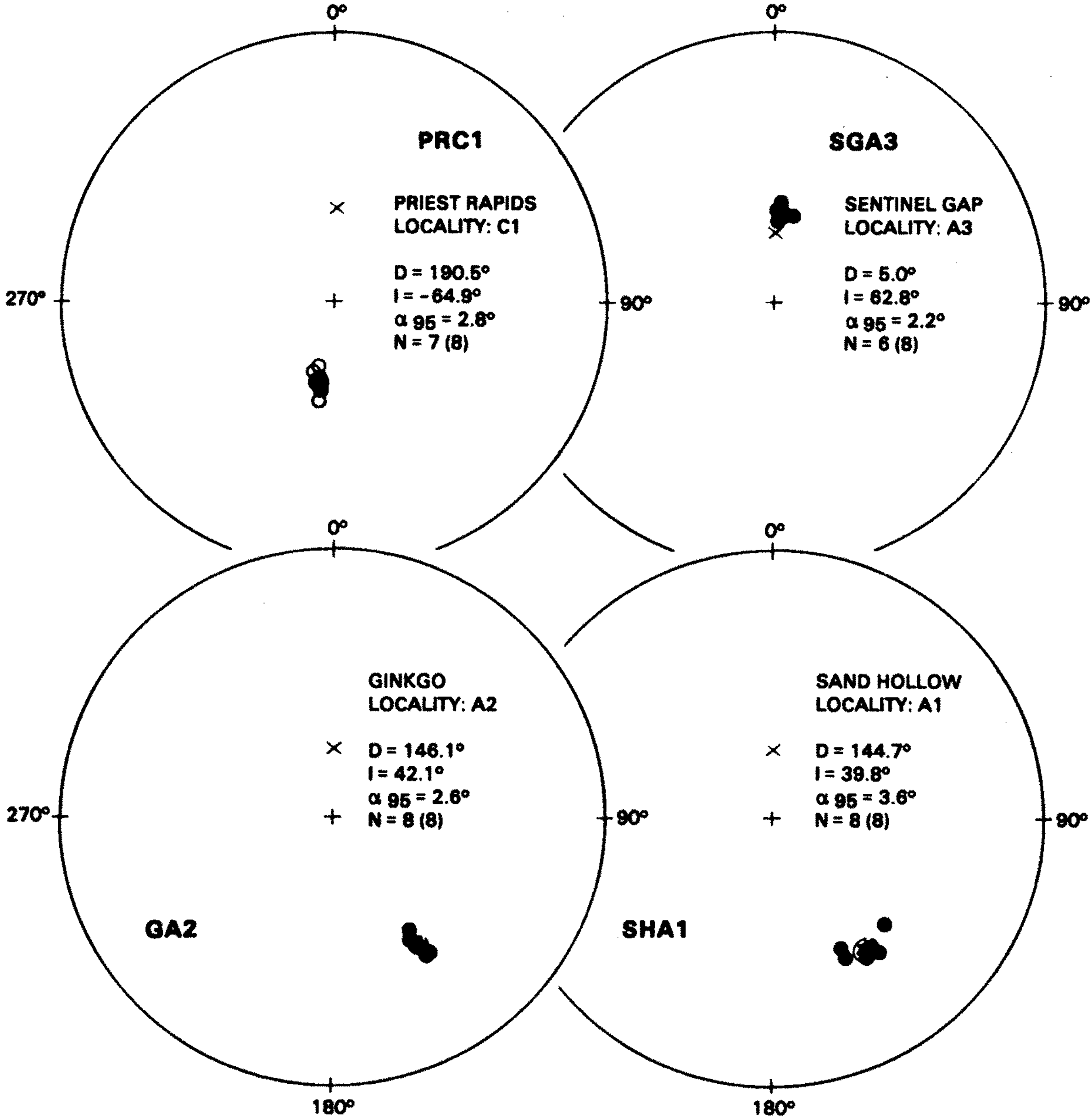
Magnetization directions from the eight Umatilla samples at site UF1 are not well grouped (k = 30), and their structurally corrected mean (D = 354.6°, I = +52.0°, α_{95} = 11.2°) deviates significantly from that of the locality E flows. This undoubtedly reflects the poor outcrop at locality UF1, where only small, probably rotated, blocks are exposed.

The paleomagnetism of the Umatilla has been studied fairly extensively in the subsurface. Two Umatilla flows were sampled by Packer and Petty (1979) from DDH-3 and two were sampled in this study from DC-8. The DDH-3 flows yielded mean stratigraphic inclinations of +50.8° (N = 7, α_{95} = 1.1°) and +53.0° (N = 3, α_{95} = 4.3°), compared with +41.0° (N = 6, α_{95} = 6.1°) and +40.1° (N = 5, α_{95} = 12.0°) from DC-8. The core hole inclination of +40° to +50° is more consistent with the uncorrected surface mean inclination of +41° from the locality E sites, suggesting that the structural attitudes used to correct the data may be in error.

WANAPUM BASALT

Priest Rapids Member

The eight paleomagnetic samples collected from the Priest Rapids Member, Lolo flow at site PRC 1 exhibited only reversed-polarity directions, well grouped about a mean at D = 190.5°, I = -64.9°, α_{95} = 2.8° (Figure 8). This is entirely consistent with results from DC-2, where Packer and Petty (1979) sampled two flows (WI and W2) in the stratigraphic position of the Priest Rapids that gave inclinations of -60.5° (N = 7, α_{95} = 4.5°) and -65.3° (N = 7, α_{95} = 3.8°), respectively.



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

D = DECLINATION

I = INCLINATION

α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)

N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)

X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-104

FIGURE 8. Remanent Magnetization Direction Diagrams: Priest Rapids, Sentinel Gap, Sand Hollow and Ginkgo Flows.

Roza Member

Although the Roza Member was not sampled at the surface during this study, it was sampled in two flows from DH-5. These flows yielded structurally corrected mean inclinations of +3.3° (N = 7, α_{95} = 5.3°) and +7.5° (N = 5, α_{95} = 5.2°). The Roza was also sampled in DC-2 by Packer and Petty (1979). Of nine samples obtained in that study, only five yielded stable directions on vector demagnetization diagrams; these five samples have a mean inclination of -1.9° (α_{95} = 9.0°). The Roza has the shallowest paleomagnetic inclination of any flow sampled from the Saddle Mountains, Wanapum, or Grande Ronde Basalts.

Frenchman Springs Member

Twenty-four samples were collected at three sites in the Frenchman Springs Member. Five of eight samples from the Sentinel Gap flow at site SGA3 contain only a single component of magnetization. The other three samples apparently contain a lightning-produced IRM, since their NRM directions are scattered and their intensities are anomalously high. The six samples from which stable endpoint directions were isolated had a structurally corrected mean of D = 5.0°, I = +62.8°, α_{95} = 2.2° (Figure 8).

Paleomagnetic results from the Sand Hollow (site SHA1) and Ginkgo (site GA2) flows were nearly identical, with each flow exhibiting two components of magnetization. One component, removed below 300 Oe, had a steep northerly direction, probably reflecting the present axial dipole field direction. The other component, isolated at higher demagnetization steps in all samples, had a structurally corrected mean of D = 144.7°, I = +39.8°, α_{95} = 3.6° for the Sand Hollow and D = 146.1°, I = +42.1°, α_{95} = 2.6° for the Ginkgo (Figure 8). Sheriff and Bentley (1980) reported a nearly identical direction of D = 147°, I = +41°, a_{95} = 4.5° from six sites in Ginkgo flows near Vantage. This direction, which is about 90° from the Miocene axial dipole field direction, probably records part of a geomagnetic reversal or excursion.

GRANDE RONDE BASALT

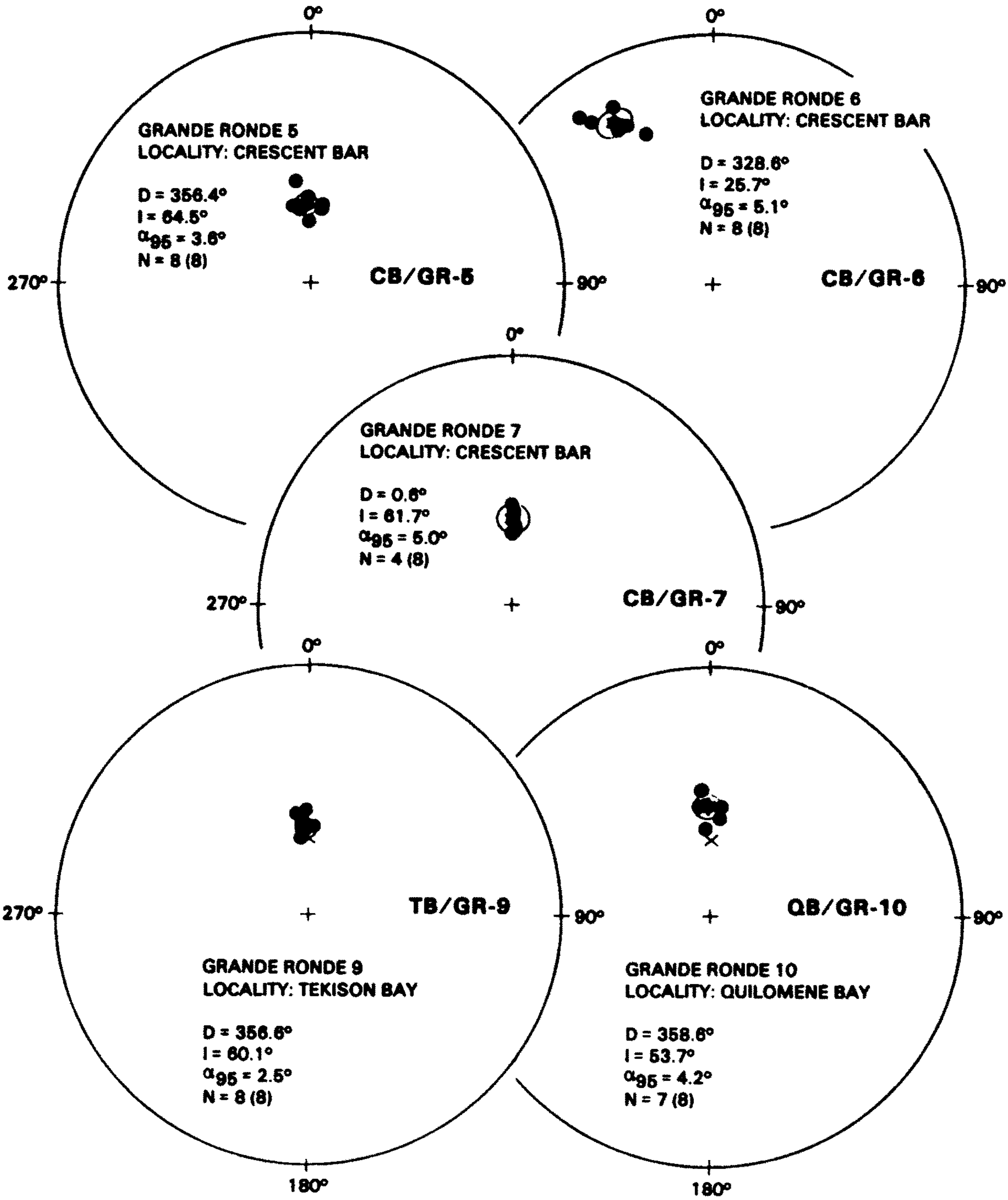
Surface Exposures

Forty samples of Grande Ronde Basalt were obtained at three localities on the Columbia River north of Vantage. Three flows were sampled at Crescent Bar, one flow at Quilomene Bay, and one flow at Tekison Bay. The flows at all three localities are essentially flat lying, so no structural corrections were applied to the paleomagnetic directions.

The goal of the sampling at Crescent Bar was to determine paleomagnetic directions of flows directly above and below the magnesium (Mg) horizon. This horizon is a prominent chemical marker in the upper Grande Ronde Basalt, dividing low-Mg flows of the Schwana sequence below from higher Mg flows of the Sentinel Bluffs sequence above (Myers, Price, and others, 1979). In the Pasco Basin, the flow directly underlying the Mg horizon is, in all but one core hole, the Umtanum flow. This flow is recognized by its distinctive chemistry relative to other Grande Ronde flows that lie stratigraphically close to the Mg horizon. The Mg horizon coincides with a magnetostratigraphic marker, a change from high paleomagnetic inclination above to shallow inclination below (cf. Packer and Petty, 1979). At Crescent Bar, the Mg horizon occurs at the top of the flow sampled at site CB/GR-6.

In the highest flow sampled at Crescent Bar (site CB/GR-5), all eight samples contained a single component of magnetization with an MDF of about 150 Oe and a mean at D = 356.4°, I = +64.5°, α_{95} = 3.6° (Figure 9).

The underlying flow (site CB/GR-6) contains two components of magnetization with partly overlapping stability spectra. During progressive AF demagnetization, the magnetization directions consistently migrate away from the present axial dipole field direction toward a shallow-inclination direction in the northwest quadrant. None of these directions can confidently be said to have achieved a stable endpoint even at the highest demagnetization step of 700 Oe. Thus, the +26° inclination calculated for this flow (D = 328.6°, I = +25.7°, α_{95} - 5.1°) should be regarded as an upper limit.



NOTE: THIS FIGURE IS A STEREOGRAPHIC PROJECTION SHOWING PALEOMAGNETIC DIRECTIONS FROM SURFACE SITES IN COLUMBIA RIVER BASALT. SAMPLE LOCALITIES ARE SHOWN ON THE LOCATION MAP (FIGURE 2).

D = DECLINATION

I = INCLINATION

α_{95} = HALF-ANGLE OF THE CONE OF 95% CONFIDENCE ABOUT THE MEAN (INDICATED BY *)

N = NUMBER OF SAMPLES FROM WHICH THE MEAN DIRECTION IS DERIVED (THE TOTAL NUMBER OF SAMPLES ANALYZED FROM EACH SITE IS INDICATED IN PARENTHESES)

X = DIRECTION OF THE PRESENT AXIAL DIPOLE FIELD AT THE SAMPLING SITE AFTER CORRECTION FOR THE DIP OF THE BEDS.

ALL PALEOMAGNETIC DIRECTIONS REPRESENT LEAST-SQUARE FITS TO LINEAR SEGMENTS OF VECTOR DEMAGNETIZATION DIAGRAMS DERIVED FROM AF DEMAGNETIZATION UP TO 700 Oe. ALL DIRECTIONS HAVE BEEN CORRECTED FOR STRUCTURAL TILT BY ROTATING ABOUT THE STRIKE.

RCP8111-105

FIGURE 9. Remanent Magnetization Direction Diagrams: Grande Ronde Flows.

Of the eight samples from the lowest flow sampled at Crescent Bar (site CB/GR-7), four contain a single component of magnetization with an MDF of 200 to 400 Oe and a mean at D = 0.6°, I = +61.7°, α_{95} = 5.0°. The other four samples from this site contain scattered but stable components that mask any characteristic magnetization of the flow.

From these results, it appears that the magnetostratigraphic interval of shallow inclination below the Mg horizon is restricted to a single flow at Crescent Bar.

All eight samples collected from the single flow at Tekison Bay (site TB/GR-9) contain a single component of magnetization with an MDF between 150 and 250 Oe and a mean at D = 356.6°, I = +60.1°, α_{95} = 2.5° (Figure 9). In the flow sampled at Quilomene Bay (site QB/GR-10), seven of the eight samples contain a single component with an MDF of 200 Oe and a mean at D = 358.6°, I = +53.7°, α_{95} = 4.2° (Figure 9). These results indicate that the flows sampled at Tekison and Quilomene Bays both lie above the R_2-N_2 magnetic polarity transition, which separates reversed from normal polarity flows in the upper Grande Ronde sequence.

Core Hole DC-7

Paleomagnetic investigation of DC-7 included 169 samples from 22 flows. These flows, numbered GR-16 (highest) through GR-37 (lowest), occurred at depths between 4,137 and 5,008 ft below the surface.

The upper five flows, to a depth of 4,326 ft, contain only positive inclination (normal-polarity) characteristic magnetizations (Figure 10). Most of these samples exhibited only a single component of magnetization with an MDF ranging between 100 and 300 Oe. In some samples, however, other components were revealed at lower demagnetization steps (below 75 Oe). These components, which commonly have shallow inclinations, may reflect secondary magnetizations acquired during storage or sample preparation, while the cores are in a horizontal position.

From the top of flow GR-21 (4,326 ft) to the bottom of DC-7, all characteristic magnetizations have reversed polarity. In many samples,

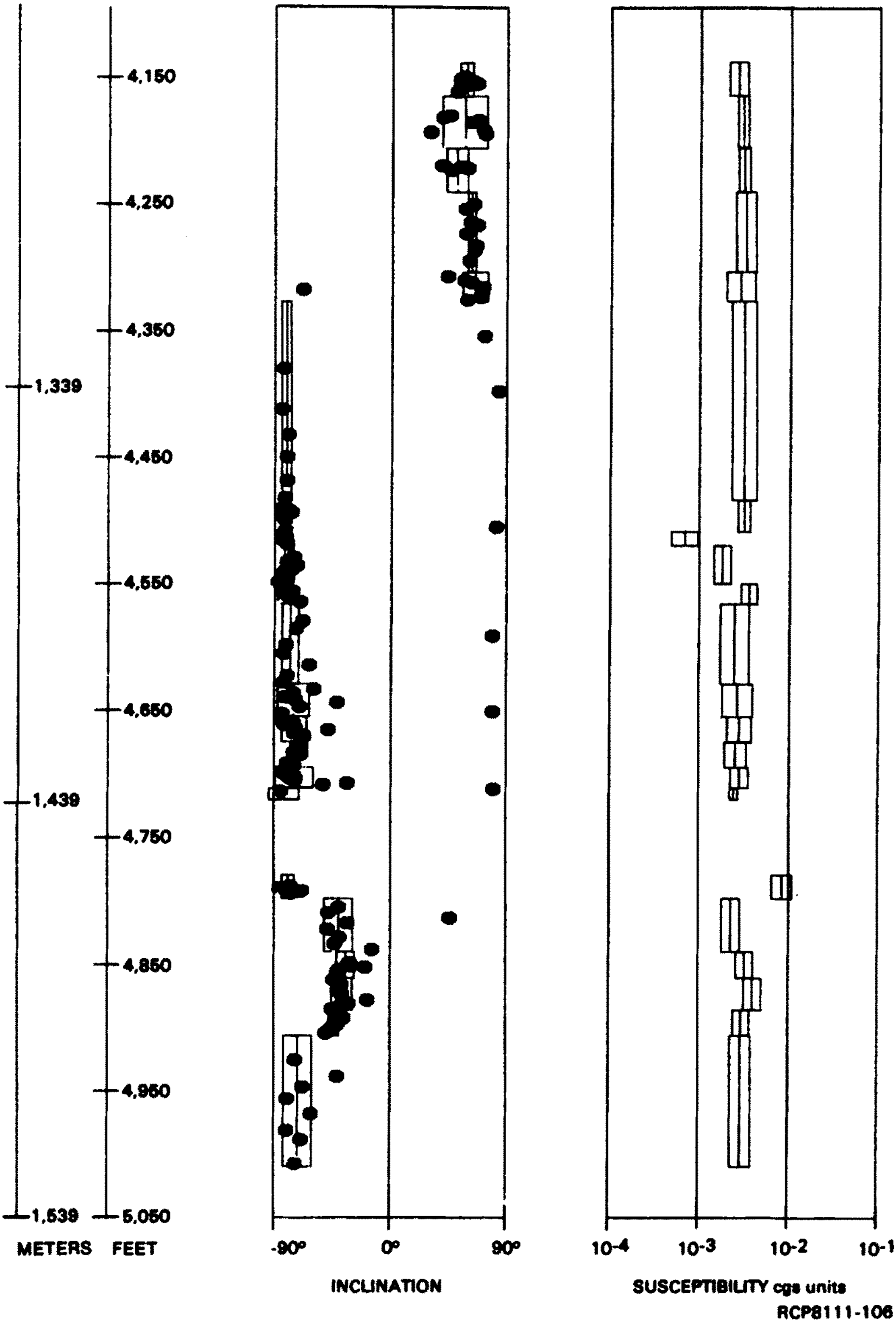


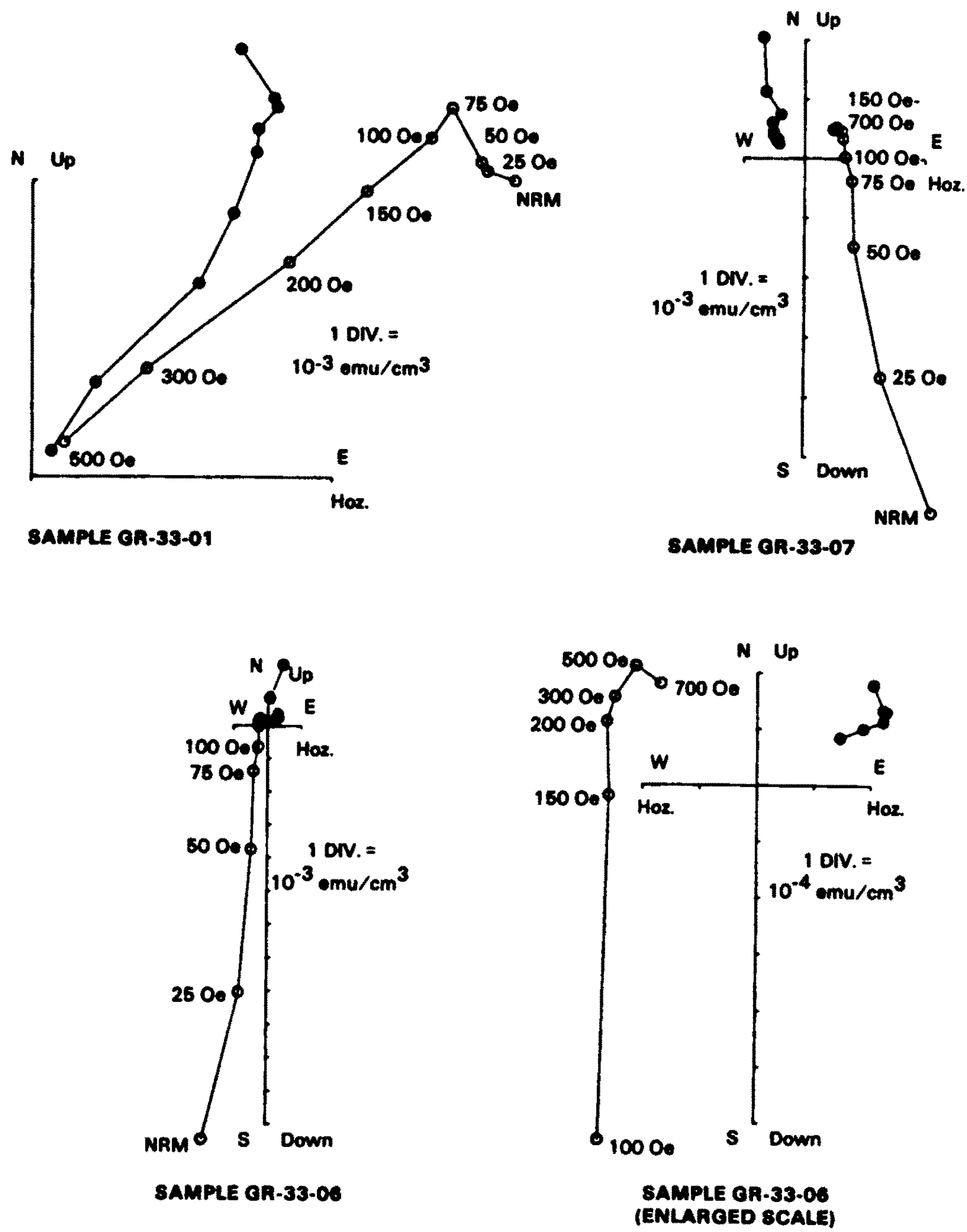
FIGURE 10. Log of Paleomagnetic Inclination and Magnetic Susceptibility of Samples from Core Hole DC-7.

the reversed-polarity component has been almost totally obscured by a lower coercivity normal-polarity component. The relative magnitude of the normal and reversed components determines the polarity of the NRM vector, which can be of either sign even within a single flow. As illustrated in Figure 11, the normal-polarity component can be as much as 98% of the NRM intensity. In most cases, the stability spectra of the two components are sufficiently different that the lower coercivity magnetization can be totally removed by AF demagnetization to 500 Oe. Commonly, however, there is no trace of an underlying reversed-polarity component until about 150 Oe.

Except for the hematitic flows described below, all flows beneath flow GR-20 exhibited some degree of two-component magnetization. Within each flow, there is no apparent correlation between ratio of normal to reversed polarity component versus such morphological features as colonnade, entablature, or zones of core disking. There is a suggestion, however, that the more vesicular intervals exhibit less normal-polarity overprinting.

The most hematitic flows consistently had the least amount of normal-polarity overprinting. In particular, flows GR-22 through GR-25 and flow GR-36 showed little or no evidence of normal-polarity components. Results of combined AF and thermal demagnetization experiments (Figure 12) suggest that the characteristic magnetization of these flows resides in both magnetite and hematite. Although AF demagnetization removes most of the NRM intensity by 500 Oe, the presence of up to 25% of the NRM intensity at 600°C (cf. magnetite's Curie temperature of ~580°C) indicates that a substantial fraction of the NRM resides in hematite. The similarity in magnetization direction between the high-blocking-temperature component (in hematite) and the component removed by AF demagnetization (in magnetite) suggests that the hematite formed penecontemporaneously (within 1,000 yr) with flow emplacement.

The inclination of the characteristic magnetization of normal-polarity flows GR-16 through GR-20 (4,137 to 4,326 ft) averages about +65°, with a variation of only about ±7°. Similarly, the inclination of

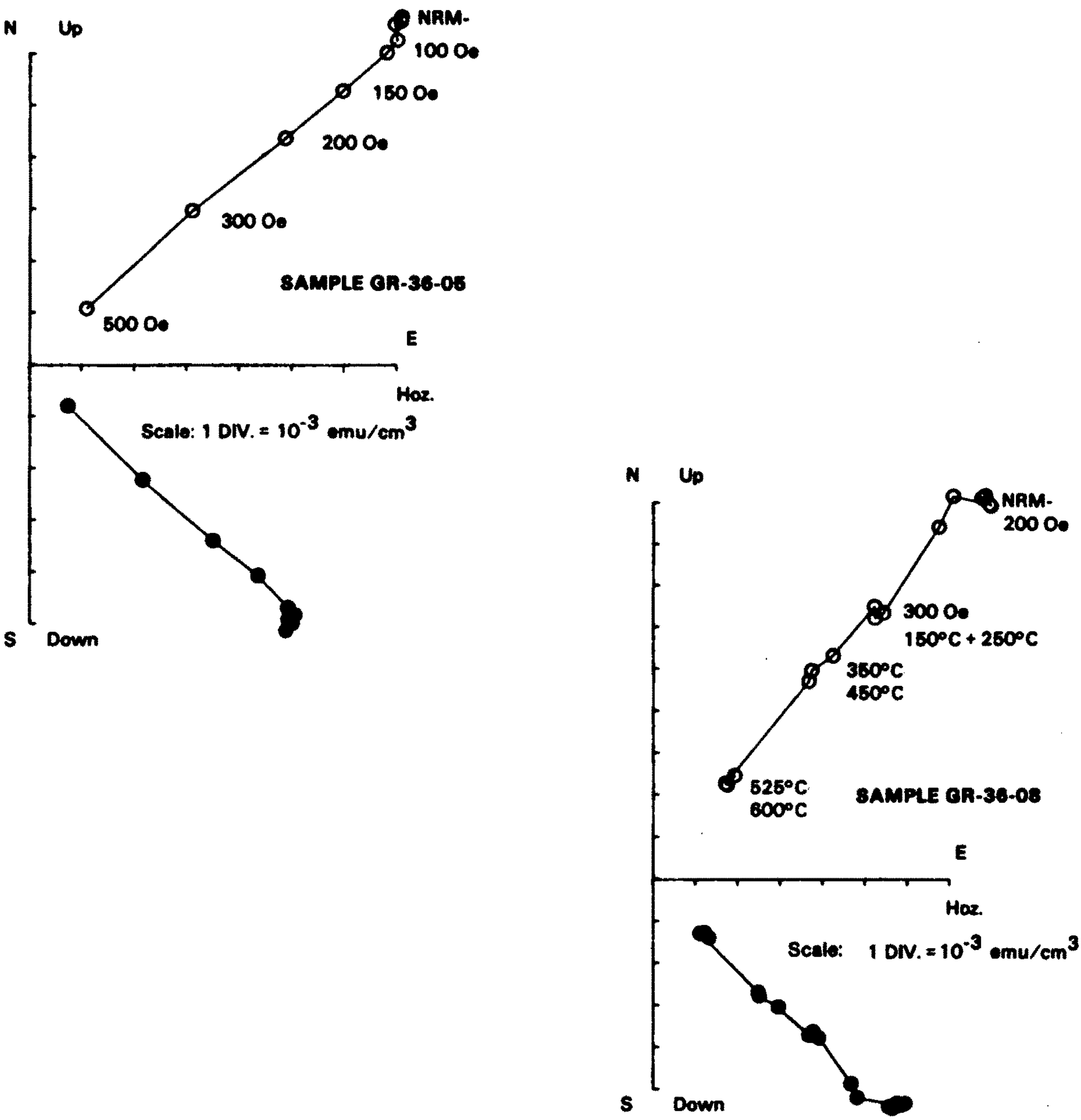


NOTE: THIS FIGURE IS A VECTOR DEMAGNETIZATION DIAGRAM, WHICH SIMULTANEOUSLY DISPLAYS CHANGES IN REMANENT MAGNETIZATION DIRECTION AND INTENSITY UPON PROGRESSIVE DEMAGNETIZATION. SHADED CIRCLES REPRESENT THE END-POINT OF THE MAGNETIC VECTOR PROJECTED ONTO THE HORIZONTAL PLANE; THE DECLINATION IS THE ANGLE (MEASURED CLOCKWISE FROM DUE NORTH) BETWEEN THE NORTH-SOUTH AXIS AND THE HORIZONTAL COMPONENT. THE DISTANCE FROM OPEN CIRCLES TO THE ORIGIN IS THE TOTAL LENGTH OF THE MAGNETIC VECTOR; THE ANGLE BETWEEN THE ABSCISSA AND THE RAY FROM THE ORIGIN THROUGH THE OPEN CIRCLE IS THE INCLINATION. THE DEMAGNETIZATION STEPS ARE LABELED BESIDE THE INCLINATION POINTS:

AF STEPS ARE LABELED WITH G = GAUSS = OERSTED = 0.1 millitesla
THERMAL STEPS ARE LABELED WITH C = °C

RCP8111-107

FIGURE 11. Vector Demagnetization Diagrams of Three Samples from Flow GR-33 of DC-7.



NOTE: THIS FIGURE IS A VECTOR DEMAGNETIZATION DIAGRAM, WHICH SIMULTANEOUSLY DISPLAYS CHANGES IN REMANENT MAGNETIZATION DIRECTION AND INTENSITY UPON PROGRESSIVE DEMAGNETIZATION. SHADED CIRCLES REPRESENT THE END-POINT OF THE MAGNETIC VECTOR PROJECTED ONTO THE HORIZONTAL PLANE; THE DECLINATION IS THE ANGLE (MEASURED CLOCKWISE FROM DUE NORTH) BETWEEN THE NORTH-SOUTH AXIS AND THE HORIZONTAL COMPONENT. THE DISTANCE FROM OPEN CIRCLES TO THE ORIGIN IS THE TOTAL LENGTH OF THE MAGNETIC VECTOR; THE ANGLE BETWEEN THE ABSCISSA AND THE RAY FROM THE ORIGIN THROUGH THE OPEN CIRCLE IS THE INCLINATION. THE DEMAGNETIZATION STEPS ARE LABELED BESIDE THE INCLINATION POINTS:

AF STEPS ARE LABELED WITH G = GAUSS = OERSTED = 0.1 millitesla
THERMAL STEPS ARE LABELED WITH C = °C

RCP8111-108

FIGURE 12. Vector Demagnetization Diagrams of Two Samples from Flow GR-36 of DC-7.

flows GR-21 through GR-32 (4,326 to 4,798 ft) is remarkably uniform at -80±7°. Except for the change in geomagnetic polarity between flows GR-20 and GR-21 at 4,326 ft, the paleomagnetic signature of these flows is rather featureless.

Flows GR-33 to GR-36 (4,798 to 4,906 ft), however, record a much shallower negative inclination of -40°, while flow GR-37 again has a steep inclination of -70°. This interval of relatively shallow negative inclination provides a valuable stratigraphic marker in the upper R_2 magnetozone of the Grande Ronde sequence.

The bulk magnetic susceptibility of the 22 flows in DC-7 generally shows little variation about a mean of 5 x 10^{-3} cgs units (centimeter gram seconds) (Figure 10). Two notable exceptions are flows GR-23 and GR-32. Flow GR-23 has an anomalously low susceptibility of 8 x 10^{-4} cgs units, probably reflecting the high hematite content suggested by the red coloration of this flow. The cause of the high susceptibility of flow GR-32 is less certain, but might reflect an unusually high magnetite content.

It is noteworthy that the two samples from flow GR-31 do not have anomalously high susceptibility. These two samples were collected to test whether the interval from 4,711 to 4,798 ft might consist of a single flow. Apparently, either flow GR-32 is a separate unit from flow GR-31, or flow GR-32/31 has a large gradient in magnetic susceptibility.

<u>Other Core Holes</u>

Fifty-six samples were obtained from eight additional Grande Ronde flows from four other core holes. These flows were sampled to investigate particularly important intervals, especially where there were discrepancies among the previous paleomagnetic studies. Results from these flows will be presented in the context of the specific problem to which they are addressed.

Polarity of Flows in the Upper Sentinel Bluffs Sequence. Packer and Petty (1979) concluded that there is a reversed-polarity flow in DDH-3 and DH-5, less than 250 ft below the Vantage horizon (FBV). However, reversed-polarity flows had not been found in the Grande Ronde this near the Vantage in any of the other core holes or in surface exposures. Moreover, Beck and others (1978) had sampled the same flow in DH-5 (GR-3) as Packer and Petty (1979), but had found only normal-polarity directions.

Upon further analysis, it can be demonstrated that both observations of reversed-polarity flows just beneath the Vantage are artifacts of sampling errors. The original core sampling log from the study of Packer and Petty (1979) lists flows GR-1 through GR-8 as having been sampled at depths of 3,184 to 4,083 ft in DH-5. Thus, the top of these eight flows lies at 1,470 FBV, not the 136 FBV shown in Figure 5 of Packer and Petty (1979). The boundary between magnetozones GR-R_2 and GR-N_2 (magnetic correlation line W of Packer and Petty, 1979) occurs at a depth of 3,152 ft in DH-5 (or 1,438 FBV). Thus, the sequence of eight flows sampled by Packer and Petty (1979) falls below this boundary and would be expected to have reversed-polarity magnetization, as is indeed apparent by inspection of vector demagnetization diagrams.

The absence of a reversed-polarity flow just beneath the Vantage in DH-5 is confirmed by resampling of this interval in this study. Of seven samples obtained between 1,858 and 1,961 ft below the surface, all but one showed only normal-polarity components of magnetization upon both AF and thermal demagnetization. (The uppermost sample, which exhibits apparently reversed polarity, is probably from an inverted core segment as it is also reversed at NRM.) Moreover, the mean inclination of these samples agrees with that from the same interval reported by Beck and others (1978).

In the revised magnetostratigraphic correlation chart (Figure 13), the DH-5 samples of Packer and Petty (1979) have been included at the stratigraphic depths indicated in their original core logs.

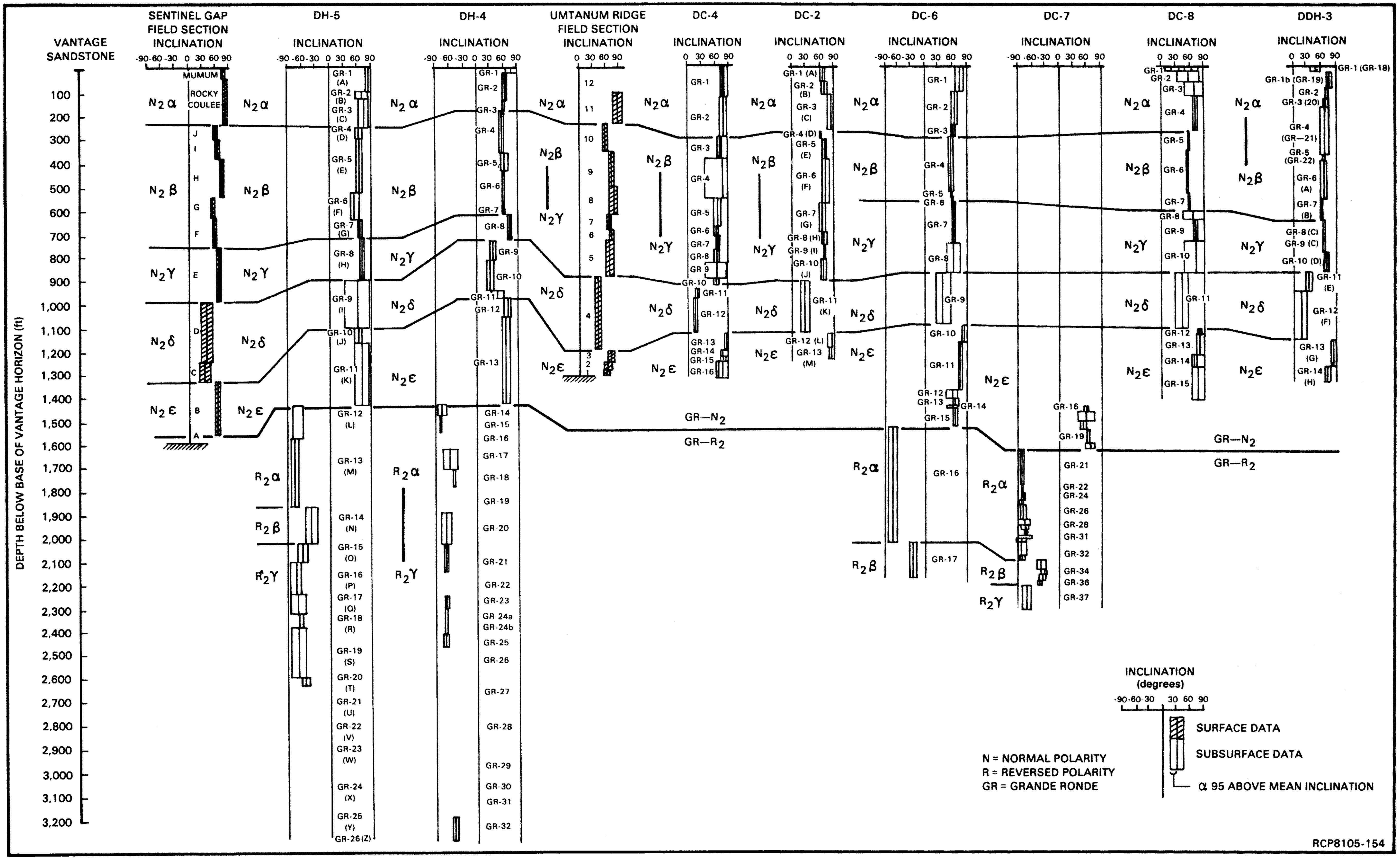


FIGURE 13. Magnetostratigraphy of the Grande Ronde Basalt, Pasco Basin.

The report of a reversed-polarity flow 100 FBV in DDH-3 is also spurious. Packer and Petty (1979) concluded that flow GR-2 (GR-19; at a depth between 2,289 and 2,300 ft) has reversed polarity. However, inspection of core from this interval revealed that the up arrows marked on the core during the original paleomagnetic sampling are inverted with respect to the true up-hole direction as labeled on the core box. This is further supported by resampling of this same flow in DDH-3 during this study. All seven samples showed only single-component, normalpolarity magnetizations upon both AF and thermal demagnetization. The absolute value (73°) of the paleomagnetic inclination of these samples is the same as the- mean inclination for this flow reported by Packer and Petty (1979).

The corrected core hole data are now consistent with the surface observations of only normal-polarity flows within the first 1,500 FBV (Figure 13).

<u>The Lower Part of DC-6</u>. Packer and Petty (1979) found the paleomagnetic signature in the lower part of DC-6 to be complicated by the presence of both normal- and reversed-polarity components in the same flow. Flow GR-16 was particularly puzzling, as it "appears to consist of a magnetically reversed section and a normal section." It was concluded that this flow has a normal-polarity characteristic magnetization, although it was noted that this conflicted with observations of reversed polarity at this horizon in DH-4 and DH-5.

To help resolve this ambiguity, 28 additional samples were obtained in this study from flows GR-13 through GR-16 of DC-6. The 17 samples from flows GR-13 through GR-15 exhibited only normal-polarity magnetizations upon both progressive AF and thermal demagnetization. Nearly all of these samples showed a large loss of NRM intensity by 130 Oe or 250°C. The vector subtracted at these low steps pointed steeply downward, generally between 70° and 80°. At higher demagnetization steps, the intensity loss was much less pronounced and usually resulted in vector demagnetization diagrams that were linear to the origin.

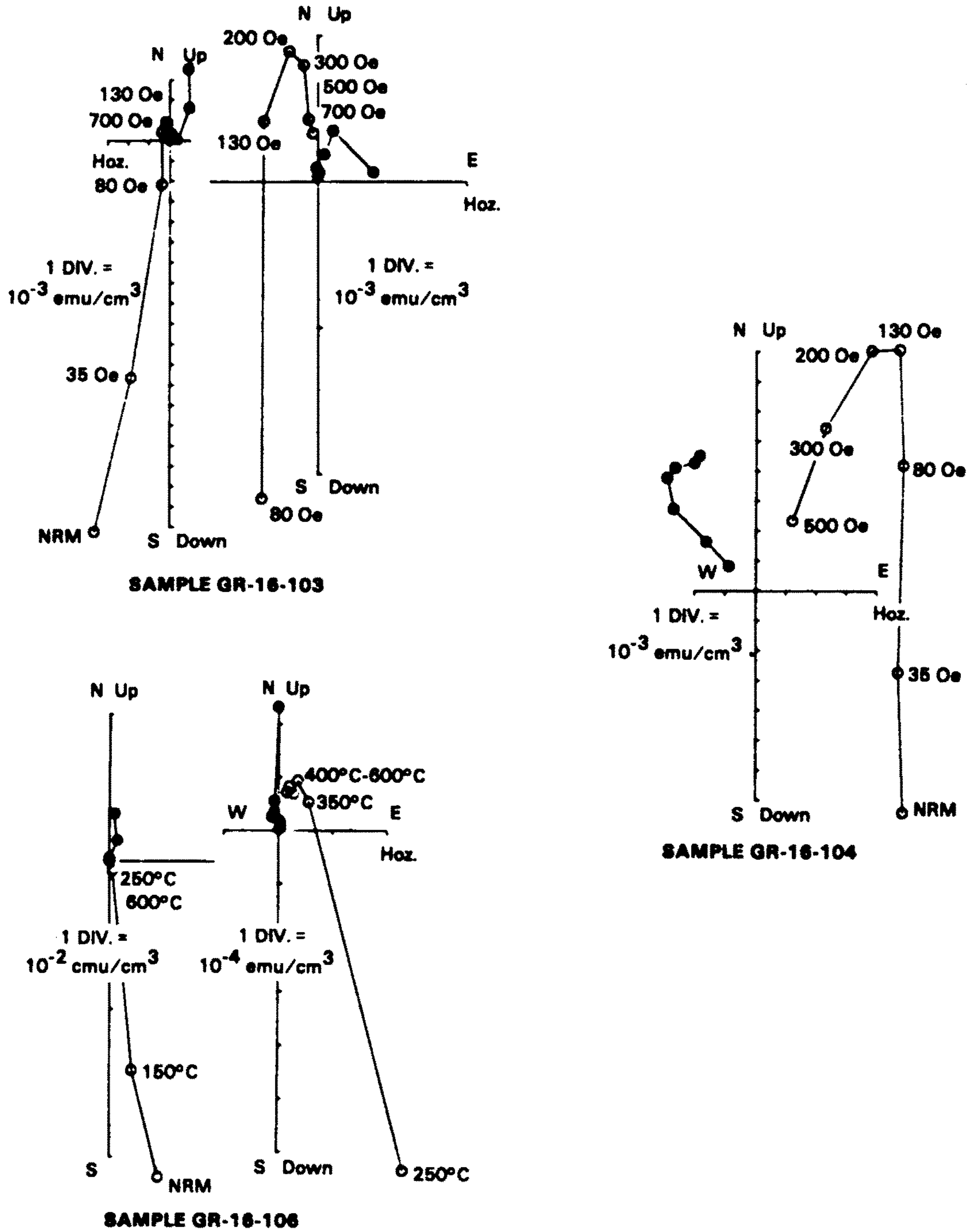
Of the 11 samples obtained from flow GR-16, all exhibited reversed-polarity characteristic magnetizations upon AF demagnetization above 100 Oe. In most of these samples, however, this reversed-polarity component was isolated only after stripping away more than 97% of the NRM intensity, and in five samples more than 99.5% of the NRM intensity had to be removed (Figure 14). This was generally not achieved until AF demagnetization to at least 300 Oe.

Based on these results, the reluctance of Packer and Petty (1979) to identify flow GR-16 as reversed can be attributed largely to insufficient demagnetization. Of the 15 samples obtained from this flow by Packer and Petty (1979), only one was AF demagnetized above 100 Oe and that sample displays an unambiguously reversed-polarity characteristic magnetization. Of the samples obtained from this flow in this study, over 80% would have been declared "normal polarity" if demagnetization had been stopped below 150 Oe.

Flow GR-16 of DC-6 provides an excellent example of the difficulty in determining characteristic magnetization directions from core holes in Grande Ronde Basalt. As discussed below, inadequate AF cleaning is probably responsible for most of the discrepancies in previous magnetostratigraphic correlations of these flows.

DISCUSSION

This investigation has revealed a difficulty in determining the in situ paleomagnetic directions of Columbia River basalts using samples from core holes; in many core holes, the original thermoremanent magnetization (TRM) of the flows has been strongly overprinted by a normal-polarity magnetization that is probably induced by drilling. This problem is described in more detail below, and a revised magnetostratigraphy of the Saddle Mountains, Wanapum, and Grande Ronde Basalts is presented.



NOTE: THIS FIGURE IS A VECTOR DEMAGNETIZATION DIAGRAM, WHICH SIMULTANEOUSLY DISPLAYS CHANGES IN REMANENT MAGNETIZATION DIRECTION AND INTENSITY UPON PROGRESSIVE DEMAGNETIZATION. SHADED CIRCLES REPRESENT THE END-POINT OF THE MAGNETIC VECTOR PROJECTED ONTO THE HORIZONTAL PLANE; THE DECLINATION IS THE ANGLE (MEASURED CLOCKWISE FROM DUE NORTH) BETWEEN THE NORTH-SOUTH AXIS AND THE HORIZONTAL COMPONENT. THE DISTANCE FROM OPEN CIRCLES TO THE ORIGIN IS THE TOTAL LENGTH OF THE MAGNETIC VECTOR; THE ANGLE BETWEEN THE ABSCISSA AND THE RAY FROM THE ORIGIN THROUGH THE OPEN CIRCLE IS THE INCLINATION. THE DEMAGNETIZATION STEPS ARE LABELED BESIDE THE INCLINATION POINTS:

AF STEPS ARE LABELED WITH G = GAUSS = OERSTED = 0.1 millitesla
THERMAL STEPS ARE LABELED WITH C = °C

RCP8111-109

FIGURE 14. Vector Demagnetization Diagrams of Three Samples from Flow GR-16 of DC-6.

DRILLING-INDUCED REMAGNETIZATION IN CORE HOLES

A low-coercivity low-blocking-temperature magnetization is observed in basalt samples from most core holes in the Pasco Basin. This component always points steeply downward, commonly at an angle exceeding 80°. Although this magnetization is present to some degree in nearly every flow, it is most insidious where it has strongly overprinted a reversed-polarity TRM. In this case, vector demagnetization diagrams show the remanence vector decaying almost linearly to the origin, losing over 90% of its intensity by 100 Oe. This gives a false sense that the sample contains only a single, normal-polarity magnetization and encourages the experimenter to discontinue further demagnetization. At higher demagnetization steps, however, the remanence vector will change sign (possibly even increasing in Intensity) and then decay linearly to the origin (cf. Figures 11 and 14).

A spectacular example of the effects of magnetic overprinting is presented in Figure 15, which compares NRM intensities and NRM inclinations from DH-4, studied by Packer and Petty (1979). Note that the NRM intensity varies with depth by nearly two orders of magnitude (between 3×10^{-3} emu/cm^3 and 1×10^{-1} emu/cm^3). Moreover, there is a distinct tendency for the NRM inclinations to steepen with increasing NRM intensity; when the NRM intensity rises above 2×10^{-2} emu/cm^3, the NRM inclination becomes nearly vertical. Yet another interesting relationship emerges by comparing Figure 15 with the magnetostratigraphic correlation chart of Packer and Petty (1979). Below about 2,800 ft in DH-4, normal-polarity flows on their chart correspond to maximums in the NRM intensity oscillations, and reversed-polarity flows correspond to minimums.

These trends in the paleomagnetic data from DH-4 are curious for at least three reasons. First, given the relatively homogeneous chemistries and magnetic susceptibilities of the Grande Ronde flows, it is highly unlikely that their TRM intensities would vary by two orders of magnitude. Second, the inclination angle of a TRM generally should not correlate with its intensity. Finally, there is no geophysical reason why the polarity of a TRM should correlate with its intensity.

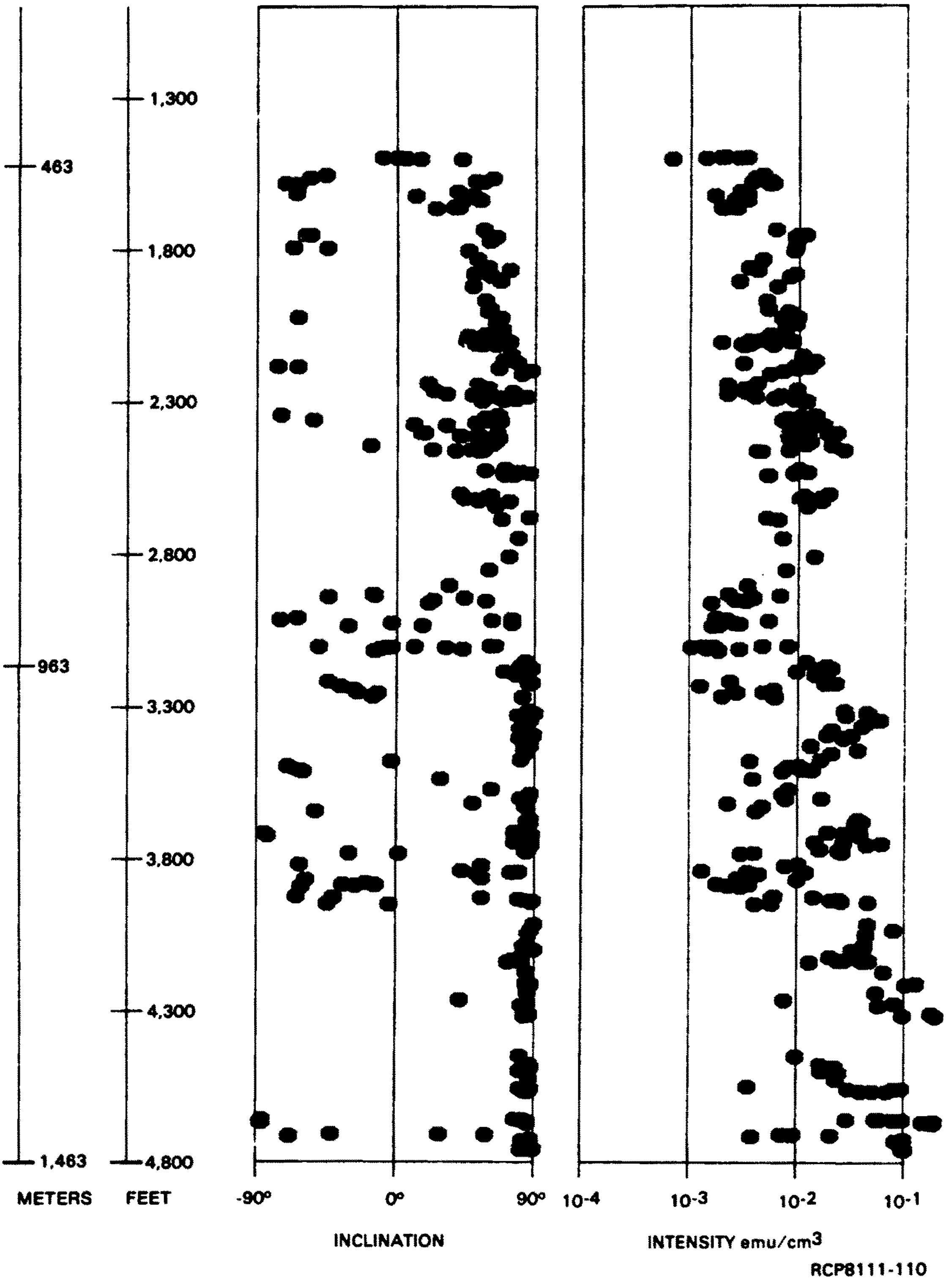


FIGURE 15. Log of Inclination and Intensity of Natural Remanent Magnetization Vectors from Core Hole DH-4.

Further suspicions about the core hole paleomagnetic data are aroused by comparing results from DC-8 (Packer and Petty, 1979) and DC-7 (this study). As shown in Figure 16, the NRM intensity in DC-8 increases with depth from about 5×10^{-3} emu/cm^3 (at 2,650 ft) to 8×10^{-2} emu/cm^3 (at 4,100 ft). In contrast, the NRM intensity in DC-7 increases less dramatically with depth and is systematically lower than in DC-8, varying between 8×10^{-4} and 2×10^{-2} emu/cm^3. Moreover, the NRM inclinations in DC-7 are nearly all shallower than in DC-8. Even more spectacular is the sharp drop (by a factor of 25) in NRM intensity between the bottom of DC-8 and the top of DC-7; yet, these two core holes are separated by a horizontal distance of only about 50 ft (Fenix and Scisson, 1979). It would be highly fortuitous if this difference in NRM intensity reflected a real difference in the TRM intensity, especially since the susceptibility log in DC-7 is so uniform at its top (Figure 10). Nor can this discordance be attributed to miscalibration of the two different magnetometers used in the DC-8 versus DC-7 studies; eight Grande Ronde flows sampled by Packer and Petty (1979) were resampled in this study, with no discernible difference in NRM intensity.

The evidence presented above strongly suggests that the original TRM of these Grande Ronde flows has been distorted by a drilling-induced remanent magnetization (DIRM) pointing almost directly down hole. This magnetization cannot be a chemical remanent magnetization (CRM) or a VRM acquired during storage. Because the cores are stored horizontally, any component acquired while the cores are in this position will have a shallow apparent paleomagnetic inclination (between ±21°).

Although the exact origin of DIRM is unknown, it has been observed in paleomagnetic samples from core holes in deep-sea basalts (e.g., Johnson and Ade-Hall, 1975; Ade-Hall and Johnson, 1976; Johnson, 1979; Rice and others, 1980). A near-vertical (downward) DIRM is also present in paleomagnetic results of Van der Voo and Watts (1978) from basic igneous rock at 3.3 mi depth in a Michigan basin core hole; this DIRM was not removed until AF demagnetization at 800 Oe. We have also observed near-vertical (downward) DIRM in several core holes from sedimentary rocks of the western United States. Any explanation of the DIRM

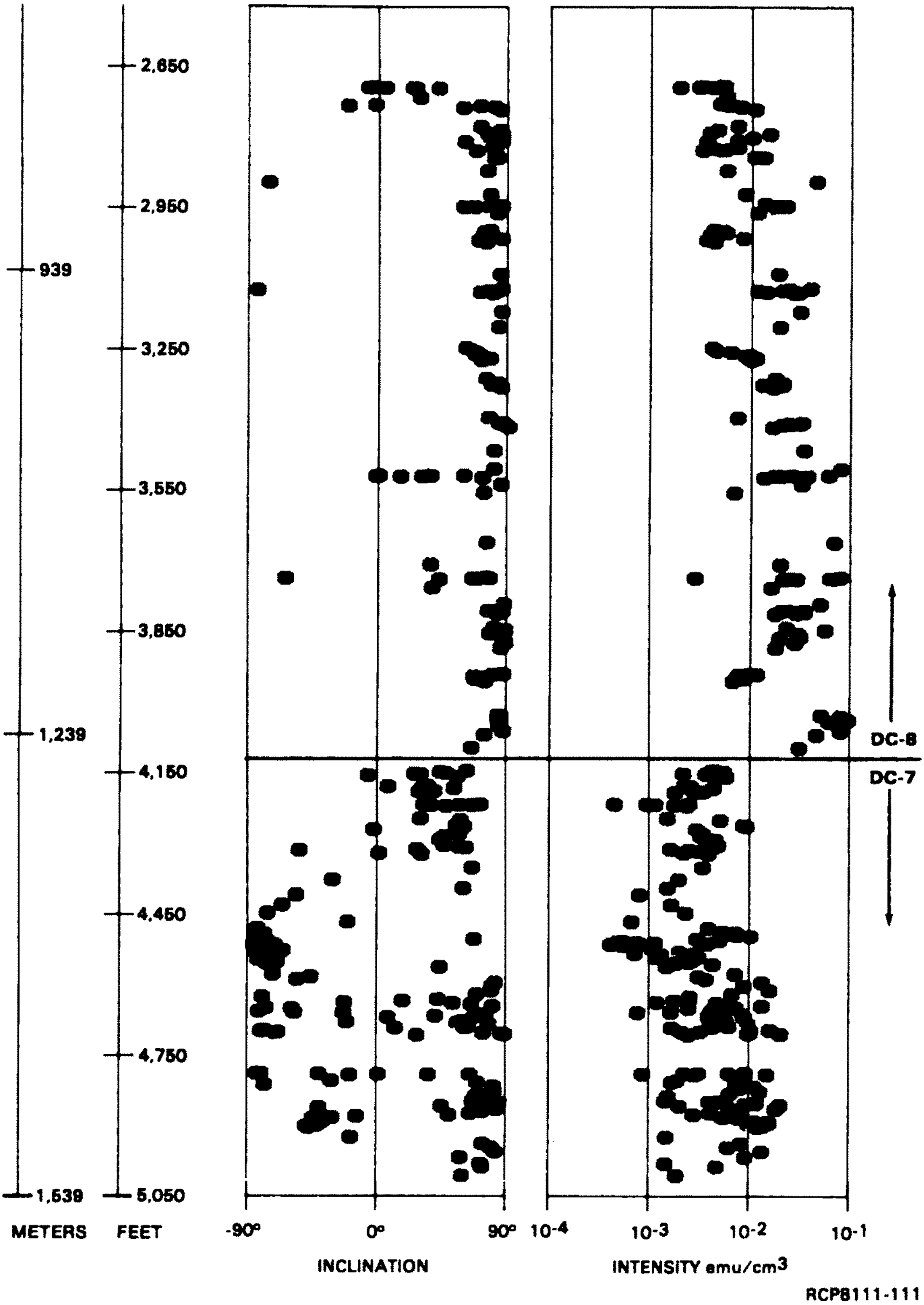


FIGURE 16. Log of Inclination and Intensity of Natural Remanent Magnetization Vectors from Core Holes DC-7 and DC-8.

in the Columbia River basalts must account for the different degrees to which it is developed in various core holes; it is strongly developed in DH-4 and DC-8, but is far less pervasive in DC-2 and DC-7. Efforts are currently being made to understand this phenomenon.

MAGNETOSTRATIGRAPHY OF THE COLUMBIA RIVER BASALT

In establishing a magnetostratigraphy of the Columbia River basalts, differences in TRM directions of flows are used to identify chronostratigraphic units. The presence of geomagnetic reversals in these basalts facilitates magnetostratigraphic correlations, because flows with opposite polarities have paleomagnetic directions more than 90° apart. However, because geomagnetic reversals are relatively infrequent (the highest known reversal rate is one per ~200,000 yr--in the late Cenozoic), geomagnetic fluctuations over a shorter time scale would be even more useful as time markers.

Fortunately, the geomagnetic dipole and non-dipole fields interact over a time scale of decades to produce just the required directional variations for high-resolution magnetostratigraphy. Termed "geomagnetic secular variation" (GSV), these directional fluctuations have a quasiperiod of several thousand yr and produce deviations of up to 45° from the "time-averaged" or axial dipole field direction.

Unraveling the stratigraphy of the Columbia River basalts using geomagnetic reversals and secular variation is a major goal of this and previous paleomagnetic investigations of this sequence.

Saddle Mountains and Wanapum Basalts

Current knowledge of the magnetostratigraphy of the Saddle Mountains and Wanapum Basalts is summarized in the composite stratigraphic section of Figure 17. Paleomagnetic results from Packer and Petty (1979) and from this study are shown for all flows (both surface and core hole) from which at least five samples yielded reliable characteristic magnetization directions based on analysis of vector demagnetization diagrams.

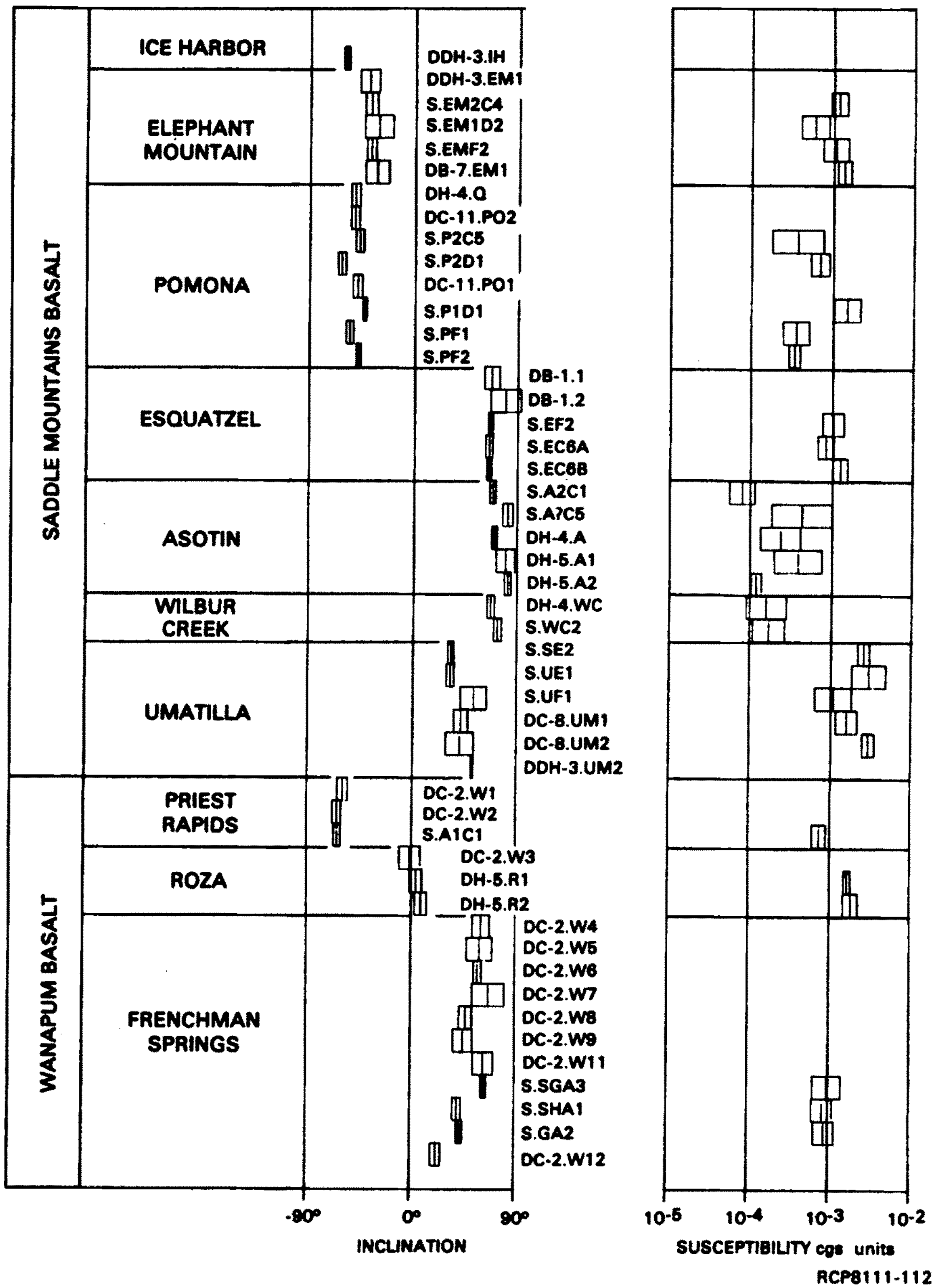


FIGURE 17. Composite Magnetostratigraphic Correlation Chart for Wanapum and Saddle Mountains Basalts, Both Surface Sites and Core Holes. Prefix S. = surface site.

The paleomagnetic data are plotted as logs of mean site inclinations (with 95% confidence circles) and geometric mean magnetic susceptibilities (with standard deviations).

Paleomagnetic directional variations provide a number of stratigraphic markers in the Saddle Mountains and Wanapum Basalts. At least four magnetozones can be recognized in this sequence. A reversed zone in the upper Saddle Mountains Basalt includes the Ice Harbor, Elephant Mountain, and Pomona Members. An underlying normal-polarity zone extends to the base of the Saddle Mountains Basalt and includes the Esquatzel, Asotin, Wilbur Creek, and Umatilla Members. The underlying Priest Rapids Member of the Wanapum Basalt is reversely magnetized, the Roza Member is transitional, and the Frenchman Springs Member is normal, except for some transitional flows (Sand Hollow and Ginkgo) near its base.

Within these polarity zones, additional magnetostratigraphic correlation horizons are provided by the GSV. In the reversed zone of the Saddle Mountains Basalt, the Elephant Mountain Member has a distinctly shallower inclination than the overlying Ice Harbor or underlying Pomona Members. Similarly, in the normal zone of the Saddle Mountains Basalt, the Umatilla Member has a considerably shallower inclination than the Esquatzel, Asotin, or Wilbur Creek Members.

Variations in magnetic susceptibility also show promise for correlating Saddle Mountains and Wanapum Basalts. Values for flow-average magnetic susceptibility vary between 7.6×10^{-5} cgs units (Asotin at surface site A2C1) and 2.9×10^{-3} (Umatilla at site UE1). The between-flow variation (factor of 40) is considerably larger than the within--flow variation, which is always less than a factor of 6. Thus, magnetic susceptibility may provide another means of correlating certain Saddle Mountains and Wanapum Basalts, particularly for distinguishing flows with similar paleomagnetic inclinations (e.g., Esquatzel versus Wilbur Creek).

Grande Ronde Basalt

Because of the effects of the previously unrecognized DIRM in samples from Pasco Basin core holes, the paleomagnetism of some Grande Ronde flows has been misinterpreted in past core hole studies. The revised magnetostratigraphy of the Grande Ronde Basalt is displayed in Figure 13 and Plate 1 (in the pocket). This represents a synthesis of data sets of Coe and others (1978), Beck and others (1978), Packer and Petty (1979), and this study. All flow averages from previous core hole studies have been recomputed, using only samples that had been AF demagnetized to at least 100 Oe. Error bars around the mean inclinations are not the standard deviations, as reported in previous studies, but 95% confidence (α_{95}) circles (cf. Kono, 1980).

Although a cutoff of 100 Oe has been used as a minimum AF demagnetization, this by no means solves the problem of inadequate AF cleaning of the DIRM. Much of the core hole data still reflect some amount of unremoved overprint. This has the effect of smoothing out and steepening paleomagnetic inclinations within normal-polarity zones and of causing large scatter in inclinations within reversed-polarity zones. With this caveat, we will first discuss the revised polarity zonation of the Grande Ronde flows in the subsurface and then comment on magnetostratigraphic units defined by the GSV.

Magnetozones. The stratigraphically highest polarity change in Grande Ronde flows of the Pasco Basin occurs at a depth of about 1,500 FBV. (The presence of a reversed-polarity flow Just beneath the Vantage has been discounted, as discussed previously in this report.) This change from reversed (below) to normal (above) was designated magnetic correlation line W by Packer and Petty (1979). Correlation line W had been recognized in DH-5 at 1,438 FBV (Beck and others, 1978), in DH-4 at 1,429 FBV (Packer and Petty, 1979), and in the Sentinel Gap field section at 1,560 FBV (Coe and others, 1978).

Magnetic correlation line W had not been positively identified by Packer and Petty (1979) in DC-6, because of the extensive drilling-induced normal-polarity overprinting of flow GR-16. Based on resampling and reanalysis of GR-16 in this study, it now seems certain that this flow has a reversed-polarity TRM and that correlation line W occurs in DC-6 between GR-16 and GR-15 at a depth of 3,687 ft (1,531 FBV).

Correlation line W was identified in the present study at a depth of 4,326 ft (1,641 FBV) in DC-7. Thus, correlation line W has now been recognized in every section that has included flows at a sufficient depth (1,535 ± 105 FBV).

All other reported geomagnetic reversals below correlation line W in the Pasco Basin core holes are probably artifacts of the drilling-induced normal-polarity remagnetization. The correlation chart of Packer and Petty (1979) shows five alternations in polarity below correlation line W in DH-4 and two below correlation line W in DH-5.

In DH-4, every "normal-polarity" flow below correlation line W has an anomalously high NRM intensity and steep inclination, probably reflecting more pervasive overprinting of the original TRM. These flows were judged to be "clean" at very low demagnetization steps; no sample from GR-19, for example, was demagnetized above 50 Oe. In many of these "normal-polarity" flows, those samples that had been demagnetized at steps above 100 Oe consistently had, or trended toward, reversed inclinations (e.g., flows GR-17 and GR-32). The "selected demagnetization level" for flows GR-26 through GR-31 are all between 25 and 100 Oe (Packer and Petty, 1979); the anomalously small standard deviations and steep inclinations of these flows merely reflect the pervasive DIRM and tell nothing about any underlying TRM.

In studying DH-5, Beck and others (1978) reported two additional polarity changes below correlation line W. Both of these apparent polarity changes are probably artifacts of the previously unrecognized normal-polarity overprinting of these flows. Most samples from flow GR-20 (flow T of Beck and others, 1978) were demagnetized at a single step (600 Oe) and showed negative inclinations, generally after 98% of the NRM intensity had been removed. No sample from a flow lower than GR-20 was demagnetized higher than 400 Oe, except those from GR-22 (flow V).

All samples from flow GR-22 exhibit a reversed-polarity high-coercivity magnetization on vector demagnetization diagrams. Most samples from the lower part of DH-5 have the signs of a strong normal-polarity overprint: steep positive NRM inclinations, NRM intensities >2 x 10^{-2} emu/cm^3, and MDF's <100 Oe.

Thus, the lower parts of DH-4 and DH-5 have apparently been extensively remagnetized during drilling. Previous reports of normal-polarity TRM from these intervals are probably erroneous, since the most thoroughly demagnetized samples contain reversed-polarity characteristic magnetizations. In particular, correlation line X, proposed by Packer and Petty (1979) to mark a change from normal polarity below to reversed polarity above, is not a reliable magnetostratigraphic horizon.

In summary, the presently available paleomagnetic data suggest that the Grande Ronde Basalt is entirely normally magnetized from 0 to about 1,500 FBV and may be entirely reversely magnetized from 1,500 to at least 3,300 FBV.

It seems likely that the polarity change at about 1,500 FBV is the "R_2-N_2" contact (cf. Swanson and others, 1979), an important regional stratigraphic horizon in the Grande Ronde Basalt mappable over most of the Columbia Plateau. In this report, magnetic correlation line W of Packer and Petty (1979) is redesignated GR-R_2/GR-N_2.

Geomagnetic Secular Variation. Packer and Petty (1979) established four correlation lines (S, T, U, and V) in the normal-polarity flows of the GR-N_2 zone. These lines, which define significant changes in mean paleomagnetic inclinations, can be recognized in many of the core hole and field sections at about the same stratigraphic position. The inclination differences may well reflect changes in the paleofield direction produced by GSV. In this report, correlation lines S, T, U, and V have been used to subdivide the GR-N_2 and GR-R_2 magnetozones into intervals of relatively uniform paleoinclination. These intervals are here designated GR-N_2a through GR-N_2e and GR-R_2a through GR-R_2Y (Figure 13 and Plate 1).

The GR-N_2a interval is bounded by the Vantage horizon at the top and is characterized by paleoinclinations of +75° to +80°. The GR-$N_2\alpha$ interval is underlain by GR-$N_2\beta$, which has a typical inclination of +60° to +65°. The contact between GR-$N_2\alpha$ and GR-$N_2\beta$ can be recognized in the two field sections and in all core holes except DDH-3.

The next magnetostratigraphic marker is a subtle change to a somewhat steeper inclination of +70° within GR-$N_2\gamma$. The contact between GR-$N_2\beta$ and GR-$N_2\gamma$ can be recognized in the Sentinel Gap field section and in DH-5, DH-4, DC-6, DC-8, and DDH-3; however, it is obscure or absent in the Umtanum Ridge field section and in DC-4 and DC-2.

The GR-$N_2\gamma$ interval is underlain by GR-$N_2\delta$, which has a much shallower paleomagnetic inclination. The GR-$N_2\delta$ interval includes a thick flow (the Umtanum flow) that is distinguished from flows above and below on the basis of Mg and titanium (Ti) content. This interval is readily recognized in every surface and core hole section of the upper Grande Ronde Basalt. The large variation (+15° to +60°) in reported paleomagnetic inclinations from this interval, however, suggests that the TRM of the Umtanum flow is obscured in surface and subsurface samples by secondary components (high-coercivity VRM or DIRM) with steeper positive inclination.

The cleaned direction (D = 344°, I = +40°) determined by Beck and others (1978) for the Umtanum flow at the Umtanum Ridge field section is based on AF demagnetization to 200 Oe. Vector demagnetization diagrams of two Umtanum samples from that study suggest that the characteristic magnetization of the Umtanum is considerably shallower than observed at the 200-Oe step. The Umtanum flow (D) at the Sentinel Gap field section (Coe and others, 1978) yielded a similar direction (D = 349°, I = +42°). However, that mean direction, which was based on cleaning at 300 Oe, was derived from one of the most scattered distributions of the entire Sentinel Gap section. This scatter in paleomagnetic directions may reflect the presence of unremoved secondary magnetizations, causing a steepening of the apparent TRM direction of the Umtanum.

In this study, a Grande Ronde flow in the stratigraphic position of the Umtanum (directly beneath the Mg horizon) was sampled at surface site CB/GR-6. After demagnetization at 700 Oe, the direction from this flow was D = 329°, 1 = +26°. However, vector demagnetization diagrams show that even at the highest demagnetization steps, the remanence vector is still moving toward a shallower inclination. This suggests that the inclination of interval GR-$N_2\delta$ might be even <+26°.

The base of GR-$N_2$6 is well defined by a change to the +65° to +85° inclination of GR-$N_2\varepsilon$. The GR-$N_2\varepsilon$ interval is the lowest recognized in the GR-N_2 magnetozone of the upper Grande Ronde Basalt.

Directly beneath the GR-N_2/GR-R_2 contact is GR-$R_2\alpha$, characterized by paleomagnetic inclinations of -75° to -85°. This interval is underlain by GR-$R_2\beta$ which has a distinctively shallower reversed inclination of about -40°. The contact of GR-$R_2\beta$ with underlying GR-$R_2\gamma$ is easily recognized in DC-7 as a change to a markedly steeper inclination of about -70°.

Subdivisions of the GR-R_2 magnetozone are difficult to recognize in the other deep core holes (DH-4, DH-5, and DC-6). The extensive normal-polarity overprinting in these core holes generally has not been removed, causing large scatter in paleomagnetic inclinations. There is a suggestion, however, that GR-$R_2\beta$ may include flows GR-18 and GR-19 in DH-4, flow GR-14 in DH-5, and flow GR-17 in DC-6.

<u>Magnetic Susceptibility</u>. Magnetic susceptibilities were determined for all Grande Ronde flows from DC-7, for the five Grande Ronde flows sampled in surface exposures, and for eight Grande Ronde flows resampled in DH-4, DH-5, DC-6, and DDH-3. In GR-$N_2\alpha$ through GR-$N_2\delta$, flow-average susceptibilities are about 8×10^{-4} cgs units, very similar to susceptibilities of the overlying Wanapum and Saddle Mountains Basalts. Magnetic susceptibility of Grande Ronde flows appears to increase with depth, rising to about 2×10^{-3} cgs units at the GR-N_2/R_2 boundary and to 3×10^{-3} cgs units in GR-$R_2\beta$ and GR-$R_2\gamma$. This increase in susceptibility with depth may partly explain the tendency for deeper Grande Ronde flows to be more affected by DIRM.

Magnetic susceptibility variations appear to be smoother in the Grande Ronde Basalt than in Wanapum and Saddle Mountains Basalts. Whereas average susceptibility values for Wanapum and Saddle Mountains flows vary by a factor of 40, values for Grande Ronde flows vary by little more than a factor of 10. Thus, magnetic susceptibility is probably less useful for correlating Grande Ronde flows than for correlating Wanapum and Saddle Mountains Basalts.

ADDITIONAL COMMENTS

The Problem of Structural Corrections

A potential limit to the accuracy of magnetostratigraphic correlations involves uncertainties in correcting for geologic structure. For many of the Columbia River basalts, the TRM is so stable and the paleomagnetic directions so well grouped that α_{95} circles smaller than 3° are attainable, even with fewer than 10 samples per flow. It is disconcerting, therefore, when mean directions from the same flow from different sites fail to converge upon structural correction.

This problem is perhaps best illustrated in comparing the surface and subsurface paleomagnetic data from the Pomona flows (Figure 18). The Pomona was sampled in this study at five surface sites and by Packer and Petty (1979) in DC-11. The average dip of these flows was 10°, with a range between 5° (sites P1D1 and P2D1) and 16° (site PF2). Before structural correction, all of the mean paleomagnetic directions from surface sites are statistically distinct, since none of their α_{95} circles overlap; the Fisherian concentration parameter (giving unit weight to the five site means) is 55. Upon structural correction (rotating about the strike), the α_{95} circles still do not overlap, and the concentration parameter increases insignificantly (to 65). At the two sites with the lowest dips (P1D1 and P2D1), the means actually move apart upon structural correction. This is unlikely to reflect a significant time difference (and, hence, secular variation) between the two Pomona flows, since two contiguous Pomona flows in DC-11 yield paleomagnetic inclinations differing by only 1°. Nor does this dispersion in Pomona mean directions reflect incomplete cleaning of

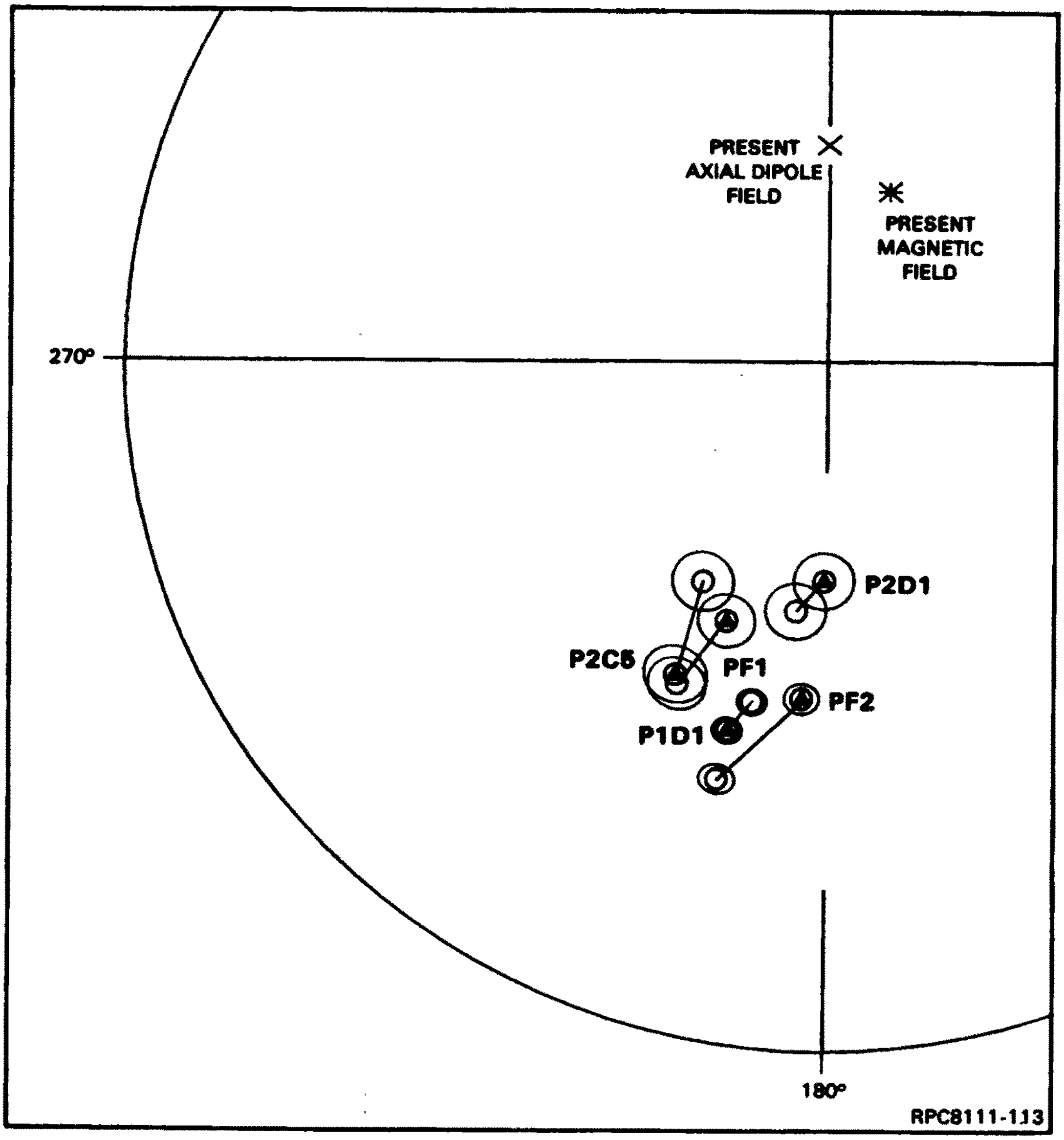


FIGURE 18. Mean Site Poles for Pomona Flows Before (circles) and After (circles with triangles) Structural Correction. Means are surrounded by 95% conficence circles.

multicomponent NRM. Pomona samples usually contain only a single component of magnetization, yielding distributions of directions from each site with k ranging between 250 and 1,200.

The scatter of mean flow directions cannot be attributed solely to vertical-axis tectonic rotations documented for other parts of the Columbia Plateau (cf. Watkins and Baksi, 1974). Vertical-axis rotations produce dispersion only in paleomagnetic declinations; this would not account for the 10° to 20° between-site differences in observed inclinations for the Pomona, Esquatzel, Asotin, and Umatilla Members (Figure 17).

It is unlikely that these 10° to 20° discrepancies result from local anomalies in the Miocene ambient field recorded by the flows. In an extensive paleomagnetic study of Holocene lava flows from throughout the western United States, Champion (1980) considered the possible sources of dispersion in paleomagnetic directions from different sites in the same flow. He found that local magnetic anomalies (at 5 ft height above flows free of edge and lightning effects) averaged <1.5° and that sites in the same flow separated by up to 19 mi could yield mean directions <0.3° apart. Champion determined that the angular standard deviation of mean directions from sites in the same flow ranged from 1.5° to 10.8°, with a mean of 4.0°. He concluded that "review of the known sources of error suggests that rotation of relatively small structural blocks at each sampling site is the principal cause of observed dispersion of measured directions of magnetization."

The paleomagnetic results of the present study indicate that uncertainties in the actual paleofield directions at the time each flow cooled may be considerably larger than the α_{95} values obtained at individual sites.

The Question of Dikes in Core Holes

When directions are found in one core hole that are not reproducible in any other section at comparable stratigraphic depth, there is a possibility that a dike has been sampled. Inconsistencies of this kind were noted by Packer and Petty (1979) in DH-4 (near the base of GR-$N_2\delta$ of this study) and in DC-6 (near the base of GR-$N_2\beta$). The presence of dikes was also a possibility in units that exhibited both normal and reversed magnetizations, such as flow GR-16 of DC-6 (Packer and Petty, 1979) and flow GR-14 of DH-5 (Beck and others, 1978).

Many of these candidates for dikes now can be dismissed in recognition of the probability that much of the core hole paleomagnetic data reflect DIRM. This phenomenon certainly accounts for the presence *of* two components of opposite polarity in a single flow, especially in the GR-R_2 magnetozone.

There will always be some core hole samples with characteristic magnetizations differing from others in the same flow (e.g., eight of 169 samples in DC-7). In most cases, these can be explained as inverted core segments, which often are derived from the most fractured parts of flows. The inversion of core segments can generally be inferred with high confidence by comparing the vector demagnetization diagram from a suspect sample with those from adjacent samples in the same flow.

Detecting a dike of the same polarity as a host flow is extremely difficult, unless the sampling density is high and the two units have much different inclinations. While this might explain the absence of some magnetostratigraphic boundaries in several of the core holes, many of these discrepancies probably reflect inadequate cleaning of the DIRM. Unrecognized changes in structural attitudes in the core holes would also blur the more subtle magnetostratigraphic features.

A totally different approach to testing for the occurrence *of* dikes in the Pasco Basin core holes was suggested by recent work of Buchan and others (1980). These authors reported results from a paleomagnetic investigation of the contact zones between Columbia River basalts and feeder dikes. They showed that thermal demagnetization successfully isolated the primary TRM *of* the host rock; whereas, AF demagnetization yielded only a stable but widely scattered direction. In this case, the flow and dike had overlapping coercivity spectra, but distinctly different blocking temperatures. Moreover, the dikes and contact zones studied by Buchan and others (1980) consistently showed far lower MDF's than the host flows. These observations suggested that two magnetic signatures of a dike might be an unusually low coercivity and low blocking temperature.

These two characteristics proved to be inadequate for distinguishing possible dikes from flows in the Pasco Basin core holes. As discussed previously, many of the core hole paleomagnetic samples contain a drilling-induced magnetization. This DIRM generally exhibits a coercivity <200 Oe and a blocking temperature <25C°C. Thus, unless the TRM of a dike had a reversed or shallow paleomagnetic inclination, it could not be distinguished from the DIRM on the basis of low coercivity or blocking temperature.

Discordance Between Fluxgate Orientation Lines and NRM Declinations

On many of the Pasco Basin bore cores, an effort has been made to mark a consistent orientation line, as determined using a fluxgate magnetometer. This procedure, which measures the component of the NRM perpendicular to the core axis, is used in determining relative orientation of fractures.

In an attempt to check the accuracy of these fluxgate orientation lines, Packer and Petty (1979) computed angular differences between the fluxgate lines and the NRM declinations as measured on the cryogenic magnetometer in the laboratory. Because the angular differences in samples from five core holes showed a wide scatter, they concluded that there was little correspondence between NRM declinations and fluxgate orientation lines.

This observation is puzzling, especially since Packer and Petty (1979) reported that "discrepancies of approximately 30° occurred between the actual physical fit of the section of core and the marked [orientation] line." This suggests that the direction of magnetization measured by the fluxgate was relatively uniform and certainly not as diffuse as suggested by the laboratory NRM values.

One explanation for this discrepancy is that perhaps a secondary magnetization had been acquired by the samples between the time of the fluxgate and cryogenic magnetometer measurements. If this were the case, the distribution of NRM directions could be either (1) random, if the spurious magnetization were non-systematically imparted; or (2) biased toward some preferred declination, if the spurious component were systematically imparted.

Addition of a systematic secondary magnetization is strongly suggested by analysis of stereographic projections of NRM directions from the Pasco Basin core holes (Figures 19 and 20). In DC-4, for which ~85% of the samples collected by Packer and Petty (1979) were drilled on the fluxgate orientation line, the distribution of NRM declinations is biased toward a declination of 296° (the mode of specimen directions as determined by the technique of Van Alstine, 1980). If the fluxgate orientation line were accurate and if no additional magnetic components were subsequently imparted, the direction of bias should have been 0°. Moreover, the distribution of NRM directions from DH-4 is biased toward about the same declination as specimens from DC-4. Yet, specimens from DH-4 were not drilled on a fluxgate orientation mark, so their NRM declinations should have been randomly distributed.

The most likely time of acquisition of a systematic secondary component is during sample collection or specimen preparation. This could occur either during coring with a drill press or during trimming with a rock saw (cf. Burmester, 1977). The drill press is the more likely source of systematic bias, since the specimens are drilled perpendicular to their reference scribe line.

This interpretation of NRM declination bias in core hole paleomagnetic data was independently formulated by Bleil (1980). Massive flow basalts drilled from the Bermuda Rise on Leg 51 of the Deep Sea Drilling Project showed a strong bias in NRM declination; whereas, pillow basalts from the same core hole did not. Bleil concluded that a systematic spurious component had been acquired during the ship-board minicoring process.

Acquisition of a secondary remanence from the drill press would be a milder form of DIRM imparted during drilling of the core in the subsurface. The component of DIRM acquired during specimen preparation is easily removed by AF demagnetization, as evidenced by the reduction or absence of directional bias in cleaned magnetization directions (Figure 20). However, the absence of directional bias in cleaned directions from fluxgate-oriented core (e.g., DC-4) indicates that the fluxgate is not measuring the TRM declinations.

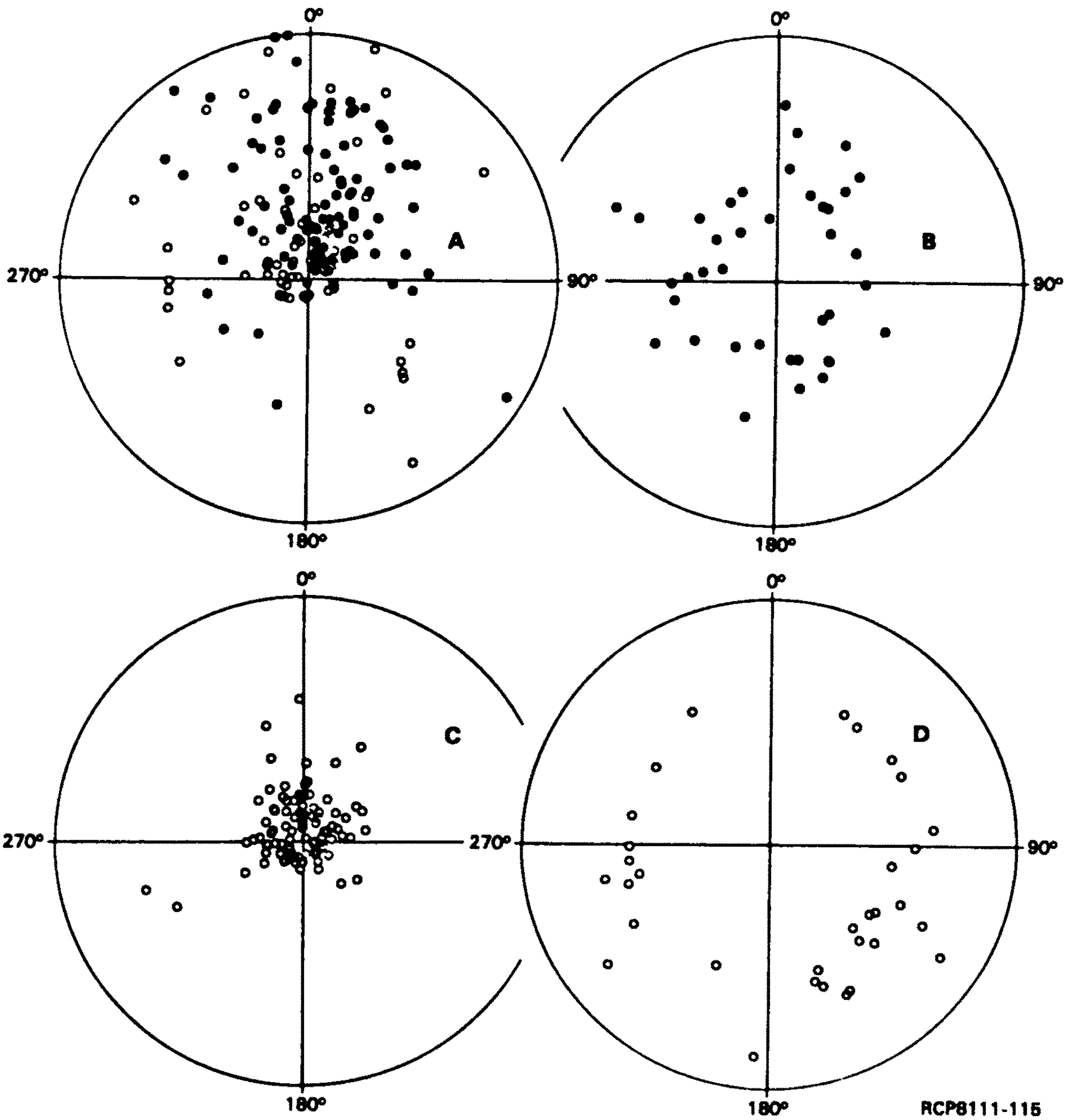


FIGURE 19. Remanent Magnetization Direction Diagrams from Core Hole DC-7 (this study). A = natural remanent magnetization, B = least-squares (cleaned) directions from GR-$N_2\varepsilon$, C = cleaned directions from GR-$R_2\alpha+\gamma$, D = cleaned directions from GR-$R_2\beta$.

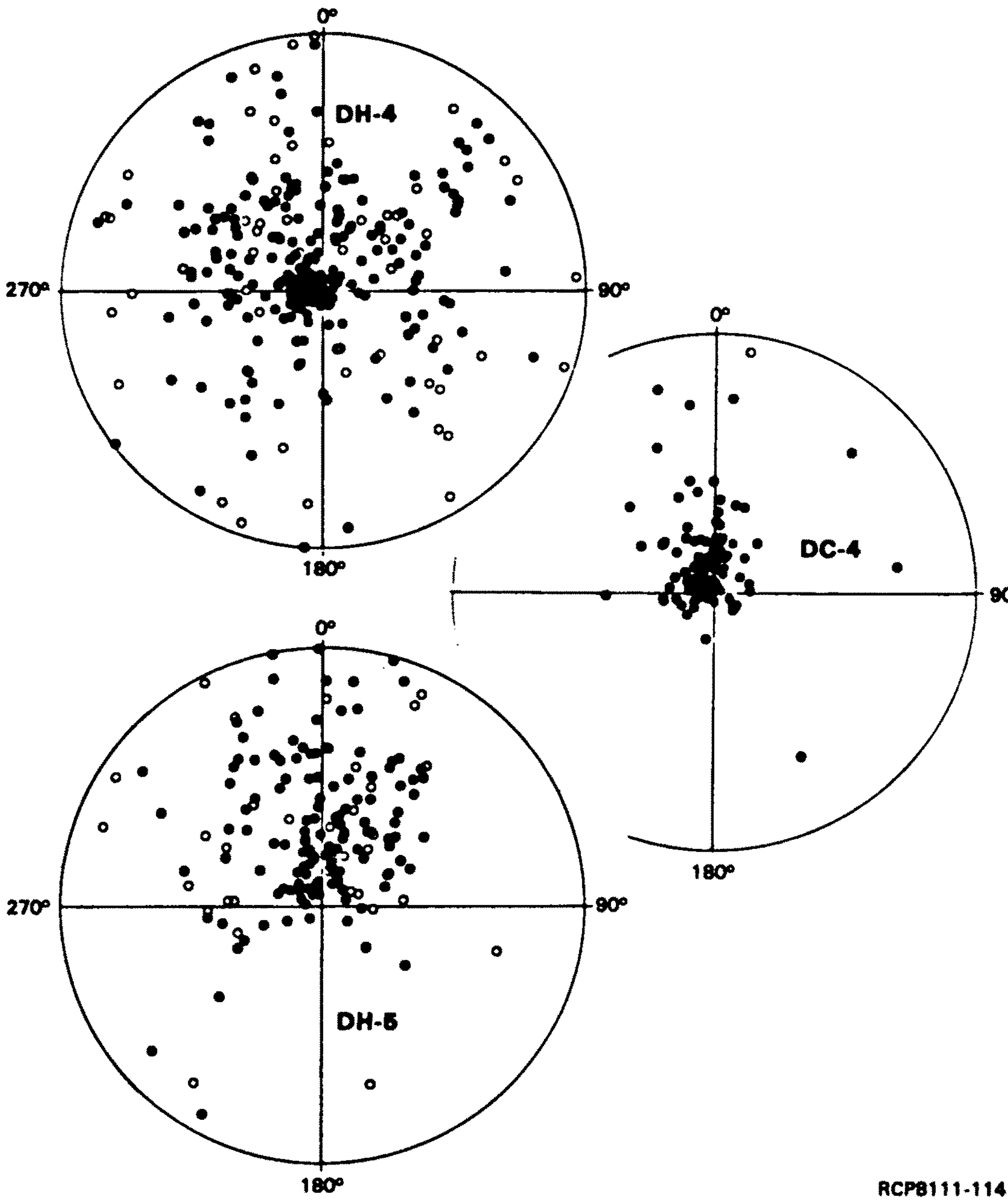


FIGURE 20. Natural Remanent Magnetization Direction Diagrams from Core Holes DH-4 (Packer and Petty, 1979), DC-4 (Packer and Petty, (1979), and DH-5 (data of Beck and others, 1978).

These results indicate that in situ magnetization directions of Columbia River basalts are difficult to extract from NRM directions of specimens from subsurface cores. These results also suggest that the fluxgate magnetometer is generally not measuring the actual TRM directions of the flows, especially considering so many of the cores had already been overprinted with DIRM acquired in the drill string. In no way, however, does this impugn the accuracy of paleomagnetic directions based on thoroughly cleaned specimens.

CONCLUSIONS

Paleomagnetic correlation within the Columbia River Basalt Group is as promising as ever, especially now that a consistent magnetostratigraphy is emerging. The Grande Ronde Basalt of the Pasco Basin (to a depth of ~5,000 ft below the surface) contains two magnetozones: reversed-polarity zone GR-R_2 underlies normal-polarity zone GR-N_2, with a contact at a depth of ~l,500 FBV.

In addition to the R_2-N_2 contact, six distinctive changes in paleomagnetic inclination can be recognized at equivalent stratigraphic horizons in basalts of the Pasco Basin. These inclination differences of up to 60° probably reflect the Miocene GSV and permit subdivision of the R_2 and N_2 magnetozones into three and five magnetic intervals, respectively. A new nomenclature has been established in which these magnetic intervals are designated GR-$R_2\alpha$ through γ and GR-$N_2\alpha$ through ε.

The Wanapum and Saddle Mountains Basalts contain four magnetozones. As in the Grande Ronde Basalt, paleomagnetic inclination variations in the Wanapum and Saddle Mountains Basalts are large and should permit subdivision of these formations into additional magnetic intervals.

Although magnetic susceptibility of the Grande Ronde Basalt is relatively uniform, susceptibility variations in the Wanapum and Saddle Mountains Basalts are large and could be used to complement correlations based on flow chemistry and paleomagnetic directions.

The consistency of paleomagnetic directions at equivalent stratigraphic horizons in Pasco Basin core holes indicates that these holes penetrated few if any dikes.

Although the Columbia River basalts preserve an excellent record of the Miocene geomagnetic field, several sources of "noise" evidently can blur the paleomagnetic signal. In specimens from subsurface core, the main source of magnetic noise is DIRM acquired predominantly in the drill string. The coercivity and blocking temperature spectra of the DIRM and TRM are sufficiently distinct, however, that the TRM can usually be isolated by AF demagnetization to 500 Oe or thermal demagnetization to 300°C. In surface outcrops of the Pasco Basin and vicinity, inclination discrepancies of 10° to 20° are observed between different sites in the same flow. These between-site differences, which may be caused by local structural rotations, suggest that ~15° inclination differences may be the limit of magnetostratigraphic resolution in this part of the Columbia Plateau.

REFERENCES

Ade-Hall, J. M. and Johnson, H. P., 1976, Paleomagnetism of basalts, Leg 34: Initial Repts. Deep Sea Drilling Project, v. 34, p. 513-532.

Beck, M. E., Engebretson, D. C., and Plumley, P. W., Western Washington University, 1978, Magnetostratigraphy of the Grande Ronde sequence: RHO-BWI-C-18, Rockwell Hanford Operations, Richland, Washington.

Bleil, U., 1980, Paleomagnetism of basalts, Leg 51: Initial Repts. Deep Sea Drilling Project, v. 51, p. 1351-1357.

Buchan, L. L., Schwarz, E. J., Symons, D. T. A., and Stupavsky, M., 1980, Remanent magnetization in the contact zone between Columbia Plateau flows and feeder dikes: Evidence for groundwater layer at time of intrusion: Jour. Geophys. Res., v. 85, p. 1888-1898.

Burmester, R. F., 1977, Origin and stability of drilling induced remanence: Geophys. Jour. Roy. Astron. Soc., v. 48, p. 1-14.

BWIP, 1980, Basalt Waste Isolation Project, annual report - fiscal year 1980: RHO-BWI-80-100, Rockwell Hanford Operations, Richland, Washington.

Champion, D. E., 1980, Holocene geomagnetic secular variation in the western United States: Implications for the global geomagnetic field: Ph.D. Dissert., Calif. Inst. of Tech., 314 pp.

Coe, R. S. and Bogue, S., University of California at Santa Cruz, and Myers, C. W., 1978, Paleomagnetism of the Grande Ronde (lower Yakima) Basalt exposed at Sentinel Gap: Potential use for stratigraphic correlation: RHO-BWI-ST-2, Rockwell Hanford Operations, Richland, Washington.

Fenix & Scission, Inc., 1979, Hole history, core hole DC-8, Hanford, Washington: RHO-BWI-C-29, Rockwell Hanford Operations, Richland, Washington.

Fisher, R. A., 1953, Dispersion on a sphere: Proc. Roy. Soc. Lond., v. A125, p. 54-59.

Johnson, H. P., 1979, Paleomagnetism of igneous rock samples -- DSDP Leg 45: Initial Repts. Deep Sea Drilling Project, v. 45, p. 387-395.

Johnson, H. P. and Ade-Hall, J. M., 1975, Magnetic results from basalts and sediments from the Nazca plate: Nature, v. 257, p. 471-473.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: Geophys. Jour. Roy. Astron. Soc., v. 62, p. 699-718.

Kono, M., 1980, Statistics of paleomagnetic inclination data: Jour. Geophys. Res., v. 85, p. 3878-3882.

Mardia, K. V., 1972, Statistics of directional data: Academic Press, New York.

McElhinny, M. W., 1973, Paleomagnetism and plate tectonics: Cambridge Univ. Press, 358 pp.

Myers, C. W., Price, S. M., Caggiano, J. A., Cochran, M. P., Czimer, W. J., Davidson, N. J., Edwards, R. C., Fecht, K. R., Holmes, G. E., Jones, M. G., Kunk, J. R., Landon, R. D., Ledgerwood, R. K., Lillie, J. T., Long, P. E., Mitchell, T. H., Price, E. H., Reidel, S. P., and Tallman, A. M., 1979, Geologic studies of the Columbia Plateau: a status report: RHO-BWI-ST-4, Rockwell Hanford Operations, Richland, Washington.

Onstott, T. C., 1980, Application of the Bingham distribution function in paleomagnetic studies: Jour. Geophys. Res., v. 85, p. 1500-1510.

Packer, D. R. and Petty, M. H., Woodward-Clyde Consultants, 1979, Magneto-stratigraphy of the Grande Ronde Basalt, Pasco Basin, Washington: RHO-BWI-C-46, Rockwell Hanford Operations, Richland, Washington.

Reidel, S. P. and Fecht, K. R, in Myers, C. W. and Price, S. M., eds., Subsurface geology of the Cold Creek syncline, RHO-BWI-ST-14, Rockwell Hanford Operations, Richland, Washington.

Rice, P. D., Hall, J. M., and Opdyke, N. D., 1980, Deep drill 1972: A paleomagnetic study of the Bermuda Seamount: Can. Jour. Earth Sci., v. 17, p. 232-243.

Sheriff, S. D. and Bentley, R. D., 1980, Anomalous paleomagnetic directions from the Miocene Wanapum Basalt, Washington and Oregon: Trans. Am. Geophys. Un. (E.O.S.), v. 61, GP-67.

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G.

Van Alstine, D. R., 1980, Analysis of the modes of directional data, with particular reference to palaeomagnetism: Geophys. Jour. Roy. Astron. Soc., v. 61, p. 101-113.

Van der Voo, R. and Watts, D. R., 1978, Paleomagnetic results from igneous and sedimentary rocks from the Michigan Basin borehole: Jour. Geophys. Res., v. 83, p. 5844-5848.

Ward, A. W., 1976, Petrology and chemistry of the Huntzinger flow, Columbia River basalt, Washington: ARH-SA-272, Atlantic Richfield Hanford Company, Richland, Washington.

Watkins, N. D., and Baksi, A. K., 1974, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee basalts in Oregon, Washington, and Idaho: Amer. Jour. of Sci., v. 274, p. 148.

Zijderveld, J. D. A., 1967, A. C. demagnetization of rocks: Analysis of results: in Methods in paleomagnetism, edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn, Elsevier, New York, p. 254-286.