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Paleomagnetism of the Grande Ronde (Lower Yakima) Basalt Exposed at Sentinel Gap: Potential Use for Stratigraphic Correlation

**R. S. Coe
S. Bogue
C. W. Myers**

January 1978

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Prepared for the United States
Department of Energy
Under Contract EY-77-C-06-1030

Rockwell International

Atomics International Division
Rockwell Hanford Operations
Richland, WA 99352

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PALEOMAGNETISM OF THE GRANDE RONDE (LOWER YAKIMA) BASALT
EXPOSED AT SENTINEL GAP:
POTENTIAL USE FOR STRATIGRAPHIC CORRELATION

R. S. Coe
S. Bogue
University of California at Santa Cruz

and

C. W. Myers
Rockwell Hanford Operations

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A B S T R A C T

Directions of natural remanent magnetization were measured in each of the twelve superposed Grande Ronde (lower Yakima) Basalt flows exposed at Sentinel Gap, Washington. The sequence of changes in the natural remanent magnetism direction in these flows is sufficiently distinct that identification and correlation at other surface - and subsurface - sampling sites should be possible. Preliminary tests made on the feasibility of measuring variations in the ancient field intensity in these flows indicate they are not suitable for intensity measurements.

INTRODUCTION

REGIONAL GEOLOGY

The Columbia River Basalt is a layered mass of more than 200,000 cubic kilometers of tholeiitic lavas covering an area of more than 150,000 square kilometers in parts of Washington, Oregon, and Idaho (Figure 1). This mass of basalt flows represents the accumulation of repeated eruptions from middle to late Miocene (16 million years to 8 million years before present) that filled a slowly subsiding basin shaped planoconvex downward. In the south-central Washington region, the basalts were folded and locally faulted into a system of east-west-trending anticlinal ridges and synclinal valleys coeval with the eruptions of the younger flows.

In the Pasco Basin, near the center of the area covered by the Columbia River Basalt (Figure 1), the total thickness of the Columbia River Basalt is a minimum of 1,500 meters. There, the Columbia River Basalt apparently overlies a series of older basalts of Oligocene to Eocene age.

POTENTIAL USEFULNESS OF PALEOMAGNETICS AS A BASALT STRATIGRAPHIC TOOL IN THE PASCO BASIN

Rockwell Hanford Operations, a prime contractor for the U. S. Department of Energy, is investigating the feasibility of a nuclear waste terminal storage facility in a mined cavern within basalt. Current activities are focusing on the Pasco Basin of south-central Washington, one of several structural basins within the Columbia River Basalt (Figure 1).

Stratigraphic and structural relations within the Pasco Basin have been obtained primarily through surface mapping and drilling of deep core holes. Most surface mapping has concentrated around the margin of the basin where basalt is exposed along anticlinal ridges. In the central portion of the basin, the basalt is overlain by Quaternary deposits, except for a few isolated outcrops of basalt. Here, interpretations of basalt stratigraphy and structure are based on correlations of basalt units between core holes and on the projection of nearby surface relationships into the basin subsurface. The ability to identify and correlate the various basalt units between surface outcrops and core holes is of fundamental importance to a correct understanding of the stratigraphy and structure.

FIGURE 1

BASINS WITHIN THE COLUMBIA RIVER BASALT

The chemical composition of most flows is relatively homogeneous laterally, and many of the flows and groups of flows differ chemically. This geochemical-stratigraphic relationship has long been recognized in the region^(1, 2) and was recently used to establish a stratigraphic model for the Pasco Basin.⁽³⁾

As part of Rockwell Hanford Operations' work, the sequence of several basalt flows that occurs at approximately 800 to 1,000 feet stratigraphically below the Vantage Sandstone (Figure 2) is being examined in detail. On Figure 2, this sequence overlaps the horizon between the "High Mg Chemical Type" and the "Low Mg-High K Chemical Type." (Note: This terminology is informal and currently under revision.) One important aspect of this work is an attempt to determine the stratigraphic relationships within the sequence in detail. Progress toward this goal has been made using subtle, between-flow chemical differences to make correlations; but, overall, little has been accomplished because of the high degree of chemical similarity between flows above and below the "High Mg, Low Mg-High K" horizon. Currently, however, more reliable chemical correlations for these units are being made using chemical data obtained by X-ray fluorescence (the less precise and less accurate atomic absorption technique was used previously).

Nevertheless, the chemical correlations need to be tested using a method independent of chemistry. Paleomagnetism is a potentially useful method for doing this. In addition, paleomagnetism offers the potential for being able to resolve stratigraphic relations in portions of the section where chemistry cannot provide resolution, and paleomagnetism can be used to test interpretations regarding the lateral extent of individual flows within the sequence.

GENERAL MAGNETIC PROPERTIES OF BASALT

Basalts may contain one or more magnetic minerals of which titanomagnetite is the most important. If the temperature is high enough, the magnetic grains, as a group, will be magnetized in a direction that remains parallel to any external magnetic field. However, as the temperature drops below some critical point known as the Curie temperature, the magnetization becomes "locked in" and provides a record of the external magnetic field at that time.

FIGURE 2

STRATIGRAPHY OF THE PASCO BASIN

Thus, when a basalt cools from high temperature in the presence of the earth's magnetic field, the magnetic grains in the rock acquire a "permanent" or remanent magnetization which is very closely parallel to the earth's field at that time. The intensity of magnetization is a function of the magnetic mineralogy of the rock and the strength of the magnetizing field. A magnetization such as this, acquired upon cooling through the Curie temperature, is known as a thermoremanent magnetization. (4)

If one can measure the direction of the remanent magnetization in a basalt and determine the rock's original orientation, it is possible to determine the direction of the magnetic field that was present when the basalt last cooled through its Curie temperature. It is also possible, with some basalts, to give the rock an artificial thermoremanent magnetization in a known magnetic field in the laboratory without altering the natural magnetic mineralogy. By comparing the natural and artificial thermoremanent magnetizations, the paleofield intensity may be obtained. (5, 6)

The strength and direction of the magnetic field on the earth's surface can change rapidly due to secular variations of and reversals of the earth's magnetic field. A sequence of lavas which is extruded over a period of time will provide a discrete sampling of the continuously varying field. If the lavas span enough time for sufficient field variation, the sequence of directions or intensities recorded in the flows will be a distinctive characteristic useful in correlating isolated outcrops of the flows.

GRANDE RONDE (LOWER YAKIMA) BASALT AT SENTINEL GAP

To test the usefulness of paleofield directions and intensities for stratigraphic correlation in the Grande Ronde (lower Yakima) Basalt, the section exposed at Sentinel Gap, Washington was sampled. Twelve flows were distinguished following the description of Taylor. (7) The lowermost four flows, designated A (stratigraphically lowermost), B, C, and D, were sampled just south of Lower Crab Creek about one-half mile east of its confluence with the Columbia River (Figure 3). The remaining flows, E through J, Rocky Coulee, and Museum, were sampled from roadcuts and natural cliff exposures along Washington State Highway 243 where it passes below Sentinel Bluffs.

FIGURE 3

SAMPLING SITES

Between Flows H and Rocky Coulee (both of which can be traced north along the cliffs to the points where they were identified by Taylor), three flows were found where Taylor described only two. For this work, the lower two flows were designated I and J without being able to positively correlate them with Taylor's Flows I and J. The smaller flow lying between J and Rocky Coulee was not sampled.

DISCUSSION

METHODS

Directional Measurement

At least 7 cores from all 12 flows were drilled using a portable, gasoline-powered diamond drill. A magnetic compass was used in orienting the cores. To correct for any deflection of the compass needle by the magnetized basalts, distant landmarks were sighted. The azimuth reading from this sighting was compared with that measured from the map. The overall orientation errors are estimated at 3 degrees or less.

Lightning strikes, chemical alteration, and the presence of the earth's field over a long span of time can add secondary components of magnetization to basalts. Therefore, to remove these secondary components, the specimens were magnetically "cleaned" in an alternating field at 60 Hertz in a demagnetizing device with a 4-axis tumbler. With the secondary components of the natural remanent magnetization thus removed, the direction measured with the spinner magnetometer was more precisely the thermoremanent magnetization direction.

To choose the optimum demagnetizing field strength, 2 of the 7 samples from each flow were successively cleaned with fields of 25, 50, 100, 200, 300, 400, 600, 800, and 1,000 oersteds and then measured. From these stepwise demagnetization experiments, it was possible to see which alternating field strength would best reduce the secondary magnetization while not seriously affecting the thermoremanent magnetization. Once an optimum demagnetizing field was determined, the remaining 5 samples from each flow were cleaned and their directions remeasured.

Figures 4 and 5 demonstrate the usefulness of the magnetic cleaning technique described above. Figure 4 shows equal area stereoplots of natural remanent magnetization directions from Flow A. The natural remanent magnetization directions of 7 samples from Flow A are plotted on the upper half of the figure. The directions range greatly, but are northerly overall and have shallow inclinations. The lower half of the figure shows the directions after cleaning in a field of 300 oersteds. Here, the directions cluster very tightly about an orientation that is steeply inclined upward and southerly. This shows that the natural remanent magnetization of the samples from Flow A were contaminated by secondary magnetic components. Figure 5 shows the natural remanent magnetization and cleaned direction for a more typical example, Flow E. In this case, cleaning at 200 oersteds changed the directions very little. The grouping of directions is slightly tighter, but the mean direction is not significantly changed, implying relatively little contamination by secondary magnetic components. The directions plotted in Figures 4 and 5 have not been corrected for the slight tectonic dip of Flows A and E.

Magnetization Versus Temperature Experiments

These experiments were performed to test whether the rocks from the flows at Sentinel Gap were suitable for paleointensity studies. Samples were heated in a vacuum under a strong field of several kilo-oersteds and the magnetization versus temperature curve measured as a function of temperature. If the magnetization versus temperature curve obtained by heating a sample is significantly different from that obtained by cooling, the process is irreversible and indicates that the magnetic minerals have been altered. Since one of the many prerequisites for successful paleointensity measurements is that the magnetic minerals be stable to heating, rocks with irreversible magnetization versus temperature curves are not suitable.

RESULTS

Direction and Magnetization Versus Temperature Results

The results of the direction measurements and magnetization versus temperature measurements are compiled in Table I. Properties measured

FLOW A
NATURAL REMANENT MAGNETIZATION
DIRECTIONS BEFORE AND AFTER MAGNETIC
CLEANING AT 300 OERSTEDS

- **PLOTTED ON THE LOWER HEMISPHERE**
- **PLOTTED ON THE UPPER HEMISPHERE**

FIGURE 4

FLOW A

FIGURE 5

FLOW E

TABLE I

DIRECTION AND MAGNETIZATION VERSUS TEMPERATURE MEASUREMENTS

1 Flow	2 Site Lat. (°N)	3 Site Long. (°E)	4 Strike	5 Dip	Natural Remanent Magnetization						Alternating Field Demagnetization						Virtual Geomagnetic Pole		J _s -T Experiment		
					6 N	7 Inclination	8 Declination	9 α ₉₅	10 δ	11 Intensity (emu/cm ³)	12 N	13 H (oe)	14 Inclination	15 Declination	16 α ₉₅	17 δ	18 Intensity (emu/cm ³)	19 Lat. (°N)	20 Long. (°E)	21 Curie Temp.	22 Reversibility
A	46.82°	240.09°	N83°W	5°S	7	-9.09°	349.60°	39.39°	46.35°	5.09 x 10 ⁻⁴	7	300	-86.84°	267.31°	5.61°	7.50°	6.35 x 10 ⁻⁴	-46.75°	69.32°	--	---
B	46.82°	240.09°	N83°W	5°S	7	68.43°	1.08°	2.06°	2.76°	3.93 x 10 ⁻³	7	100	67.07°	359.43°	2.16°	2.90°	3.08 x 10 ⁻³	87.04°	232.92°	174°C	irreversible
C	46.82°	240.09°	N82°W	7°S	7	44.03°	339.29°	8.15°	10.87°	1.96 x 10 ⁻³	7	200	36.90°	337.05°	9.80°	13.03°	1.28 x 10 ⁻³	57.80°	103.33°	--	---
D	46.82°	240.09°	N37°W	6°E	7	49.02°	4.20°	6.47°	8.65°	4.20 x 10 ⁻³	7	300	41.83°	349.33°	9.02°	12.02°	1.09 x 10 ⁻³	65.73°	84.39°	172°C	irreversible
E	46.80°	240.08°	N71°W	6°S	7	69.94°	357.12°	3.22°	4.32°	7.26 x 10 ⁻³	7	200	69.01°	355.01°	1.68°	2.25°	2.32 x 10 ⁻³	83.45°	212.41°	203°C	irreversible
F	46.79°	240.08°	N73°W	8°S	7	64.37°	9.38°	2.86°	3.84°	4.11 x 10 ⁻³	7	200	59.37°	7.08°	1.79°	2.41°	2.25 x 10 ⁻³	81.64°	19.76°	216°C	irreversible
G	46.79°	240.08°	N73°W	8°S	7	61.34°	6.77°	3.97°	5.32°	4.11 x 10 ⁻³	7	100	56.47°	1.30°	2.64°	3.53°	2.64 x 10 ⁻³	80.20°	53.99°	206°C	irreversible
H	46.79°	240.08°	N73°W	8°S	7	70.48°	22.53°	5.01°	6.71°	8.53 x 10 ⁻³	5	200	72.79°	22.52°	2.87°	3.03°	4.73 x 10 ⁻³	72.31°	281.66°	135°C	reversible
I	46.79°	240.08°	N73°W	8°S	7	73.04°	7.10°	4.12°	5.53°	3.88 x 10 ⁻³	7	200	64.73°	0.48°	5.56°	7.44°	1.33 x 10 ⁻³	89.66°	349.85°	292°C	reversible
J	46.79°	240.08°	N74°W	10°S	7	66.72°	2.72°	2.57°	3.45°	4.93 x 10 ⁻³	7	200	60.79°	2.59°	3.49°	4.68°	1.76 x 10 ⁻³	84.68°	38.86°	172°C	irreversible
Rocky Coulee	46.79°	240.08°	N75°W	11°S	7	83.45°	354.86°	2.24°	3.01°	4.98 x 10 ⁻³	7	200	80.37°	332.53°	3.88°	5.20°	7.78 x 10 ⁻⁴	62.32°	221.46°	186°C	reversible
Museum	46.79°	240.08°	N75°W	11°S	7	81.16°	355.17°	2.70°	3.63°	2.70 x 10 ⁻³	7	100	75.89°	344.28°	1.77°	2.37°	1.14 x 10 ⁻³	71.31°	217.76°	255°C	irreversible

EXPLANATION

COLUMN

- 1 Flow designations are from Taylor.⁽⁷⁾ Identification of Flows I and J is uncertain.
- 2 and 3 Latitude and longitude of sampling sites for each flow. Latitude is measured in degrees north and longitude in degrees east.
- 4 and 5 Strike and dip of the flows as measured or estimated at the sampling site. Magnetic directions measured and corrected by assuming the flows were originally horizontal and were rotated about the strike to their present position. The attitudes of the lower four, Flows A, B, C, and D, are the most uncertain. This is partly because the flows are exposed roughly parallel to this strike so that determination of dips was difficult. The dip of Flow B may be as much as 12-degrees; although the 5-degree value in this table is more consistent with overlying flows. These lower flows were sampled very near the hinge of the Saddle Mountains anticline. Dips of the flows in this hinge region can change abruptly. The dip determination of Flow A, which is nearest the hinge and also poorly exposed, may be in error. Flow A is assumed to be parallel to Flow B.
- 6 and 12 Number of samples from the flow that were measured and averaged to give the natural remanent magnetism (NRM) direction for the flow. (Column 12 values are after alternating field demagnetization.) Note that Flow H has an N value of five rather than the usual seven. Two of the samples were not used because they had directions that were more than two standard deviations away from the mean of the other five. This could be due to orienting errors, sampling from a block which was not in place, or an anomalously "hard" component of secondary magnetization.
- 7 and 14 Degrees below the horizontal of the flow-averaged NRM direction after correction for strike and dip. (Column 14 values are after alternating field demagnetization.)
- 8 and 15 Degrees clockwise from true north of the horizontal component of the flow averaged NRM after correction for strike and dip. (Column 15 values are after alternating field demagnetization.)
- 9 and 16 Range in degrees about the calculated mean where the true mean is located with 95 percent confidence. This is a measure of how well the average direction of magnetization is determined. The statistic assumes that the sample directions lie in a so-called Fisherian distribution about their true mean. The Fisherian distribution is approximately the three-dimensional equivalent of the Gaussian or normal distribution of standard statistics. For example, the mean uncleaned NRM direction for Flow A (α₉₅ = 39.39°) is poorly known, but the mean for the Rocky Coulee (α₉₅ = 2.24°) is determined accurately. (Column 16 values are after alternating field demagnetization.)
- 10 and 17 Angular standard deviation of the sample directions from their mean. (Column 17 values are after alternating field demagnetization.)
- 11 and 18 Average intensity of magnetization of the rock in electromagnetic units per cubic centimeter (emu/cm³). (Column 18 values are after alternating field demagnetization.)
- 13 Strength of the demagnetizing field in oersteds (oe) used for each Flow A field of 100 to 200 oe was usually sufficient to remove most of the secondary magnetization.
- 19, 20, 21 and 22 (See Text)

Columns 1 through 18 are described on the table. The inclination and declination values after alternating field demagnetization (Columns 14 and 15) are the best estimates of the paleofield directions.

The latitude and longitude of the virtual geomagnetic pole (Columns 19 and 20) define the position of the pole of the hypothetical geocentric dipole field that would produce the field direction observed at a site. The virtual geomagnetic pole lies along the great circle parallel to the declination. If the inclination is I , then the angular distance, α , between the sampling site and the virtual geomagnetic pole is given by $\tan \alpha = 2 \cot I$. The virtual geomagnetic pole calculated from a single paleofield direction will rarely coincide exactly with the ancient geomagnetic pole, because a substantial non-dipole component of the earth's field is usually present.

The magnetization versus temperature experiment results are shown as Curie temperature and reversibility (Columns 21 and 22, respectively). The Curie temperature is the temperature at which a rock, upon heating, loses its ferromagnetic properties. However, a rock may contain a variety of magnetic minerals, each with its own Curie temperature. As a rock is heated, its magnetization will decrease over a range of temperatures as the different magnetic minerals, in turn, approach their Curie temperature. Thus, the values in Table I are estimates of the Curie temperatures for the major magnetic constituents. Samples from Flows A and C contained opalized vesicles and could not be tested.

The graphical results of two magnetization versus temperature experiments are shown in Figures 6 and 7. A magnetization versus temperature experiment is said to be reversible if the magnetic behavior of the rock is not changed after heating to temperatures around 600 degrees Centigrade. Figure 6 is the record of a reversible magnetization versus temperature test on a sample from the Rocky Coulee Flow. The heating and cooling curves are roughly coincident, indicating that the magnetic mineralogy of the sample did not irreversibly alter at high temperature. Figure 7, however, shows that heating and cooling curves of Flow D are very different from each other. The shape of these curves is characteristic of the mineral titanomaghemite, a cation-deficient form of titanomagnetite. When the temperature reaches about 430 degrees Centigrade, titanomaghemite divides into two nearly pure minerals, magnetite plus ulvospinel. On the

FIGURE 6

ROCKY COULEE FLOW

FIGURE 7

FLOW D

magnetization versus temperature curve, the much higher spontaneous magnetization of the newly formed magnetite causes an increase in the magnetization of the sample. However, as the temperature increases further, the magnetite reaches its Curie temperature and magnetization falls off again. This sequence of events produces a small hump at the high temperature end of the heating curve, as seen in Figure 7. Titanomagnetite is metastable; so, upon cooling, the magnetite remains. This is clearly seen in Figure 7, where heating and cooling have caused a threefold increase in the sample's room temperature magnetization.

Summary of Direction Results

Figure 8 is an equal area stereoplot of the paleofield directions recorded in the twelve Grande Ronde (lower Yakima) flows exposed at Sentinel Gap. Normal directions are plotted in the lower hemisphere and reversed directions are plotted on the upper hemisphere. Flow A is the only reversed flow. Surrounding each point on the plot is a circle whose angular radius is the α_{95} (see Table I, Column 16) for that flow. The size of the circle is thus proportional to the uncertainty in the flow-averaged direction.

Several distinctive features of the directions are represented in Figure 8. The reversed to normal transition that occurs between Flows A and B is a prominent magnetic marker. The reversed direction of Flow A is not apparent in its natural magnetization direction at Sentinel Gap, so alternating field demagnetization is necessary for establishing paleomagnetic correlations at this horizon.

A group of seven flows (B, E, F, G, H, I, and J) has directions which are very close to each other and also to the geocentric dipole direction for a site at this latitude. Directions of Flows C and D differ from these in both declination and inclination. Although declinations may not be preserved during deep core hole drilling due to rotation, the inclinations of C and D are almost 30 degrees shallower than the inclinations of the adjacent Flows B and E. This difference is more than twice the angular standard deviation of samples from Flows C and D, and 10 times greater than those from B and E. Therefore, even a single sample direction from C or D should be distinguishable with at least 95 percent confidence.

FIGURE 8

ROCK STRATIGRAPHIC UNITS AND PALEOMAGNETIC DIRECTIONAL PROPERTIES

Rocky Coulee and Museum comprise a second pair of flows whose directions differ significantly from the rest. Though their inclinations are only 15 degrees steeper than those for J, the 3 flows all have angular standard deviations less than 4 degrees. Statistically, this makes Rocky Coulee and Museum even more distinguishable than C and D.

Altogether, the reversed direction of Flow A, plus the 40-degree range in inclinations from the 11 overlying flows, gives the Grande Ronde (lower Yakima) Basalt sequence at Sentinel Gap a unique magnetic stratigraphy unusually well suited for correlation purposes.

Summary of Magnetization Versus Temperature Results

The Grande Ronde (lower Yakima) Basalt flows at Sentinel Gap have very low Curie temperatures ranging from 135 degrees Centigrade to 292 degrees Centigrade. The low Curie temperatures, plus the irreversible alteration of magnetic minerals that took place in 7 of the 10 flows which could be tested, indicate that these basalts are not suitable for paleointensity determinations.

CONCLUSIONS

The variety of magnetic directions recorded in the 12 Grande Ronde (lower Yakima) Basalt flows at Sentinel Gap makes magnetic stratigraphy a potentially useful tool for stratigraphic and structural studies. Because most of the direction variation is in inclination, unoriented core hole samples can probably be correlated paleomagnetically, even though declinations cannot be determined. Core hole orientations and subsurface flow attitudes must be known, however.

Cleaning by alternating field demagnetization significantly improves resolution of the magnetic stratigraphy. Uncleaned natural remanent magnetization directions are much less useful for correlation purposes.

Correlation using variation in paleointensity is not feasible because the Grande Ronde (lower Yakima) Basalt flows at Sentinel Gap are not suitable for paleointensity determinations.

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