*Geophys. J. R. astr. Soc.* (1967) **12**, 405-424.

# Correlation of Petrology and Natural Magnetic Polarity in Columbia Plateau Basalts

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(Received 1966 August 8)



*Summary*

This paper reports clear petrological differences between normally and reversely magnetized lavas from the Columbia Plateau basalts. We conclude that self-reversal of magnetization cannot explain this correlation, but that perhaps a causal connection between polarity of the Earth's magnetic field and oxidation state in lavas is necessary to reconcile all the facts.

## Introduction

This paper reports a palaeomagnetic and petrological investigation of Columbia Plateau basalts collected from eleven sites in south-eastern Oregon. We have attempted to discover whether any differences exist between normally and reversely magnetized lavas. Clear differences were found. There was also evidence supporting the idea that the reversed and normal specimens represent field reversal and not self reversal.

There is a growing literature concerning differences between normally and reversely magnetized rocks. The observed differences and possible interpretations have been commented upon generally by Blackett (1962), Wilson (1965), and Wilson & Haggerty (1966). Reporters of such differences include Balsley & Buddington in America, Faynberg *et al.* in the U.S.S.R., Ade-Hall *et al.* in Britain, and several others. All of these references of which we are aware are included in the 'special references' following our other references at the end of this paper.

Geological descriptions and experimental methods are described in detail by Watkins (1965a, b). The particular sections studied here are sections A to J (Watkins 1965a) and a sequence of lavas 600 metres below the summit of Steens Mountain (Watkins 1965b) here designated as section L. The plan of this paper is to present first a combined investigation of sections A to J. Then the results from the eleventh section, from Steens Mountain, are presented separately, because this special section contains many lavas of direction intermediate between normal and reversed polarities, and it is therefore of particular interest. We also have much more data from this ' transition section ' than from any one of the other ten. Finally all the results will be discussed together.

Before beginning the presentation of our data, it is necessary to discuss the techniques of petrological investigation.

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**Petrological methods**

We have observed polished surfaces of our specimens using a Reichert Zeto-pan Pol microscope in oil immersion at 1200 magnification. No other microscope we have yet tried was able to give as good colour contrast and definition of fine structure at this high magnification. This is a critical point.

In this particular investigation, our attention has remained principally upon the states of titanomagnetite grains (or pseudomorphs thereof), although olivine and separate ilmenite can also be oxidation indicators. Each titanomagnetite grain almost invariably falls into a distinct state of oxidation, defined in order of progressive oxidation as follows (see Plate 1):

Class I.—Homogeneous titanomagnetite grain (no intergrowths visible at $\times 1200$). Colour is very light tan in our Reichert microscope with sometimes ill-defined whitened patches (maghemitization). Occasionally the grain may include one or at most two irregular ilmenite inclusions.

Class II.—A few ilmenite lamellae may appear in some or all of the titanomagnetite grains. They do not fill the grain, and may be any width. They are visible down to $\frac{1}{4}$ micron wide or slightly less.

Class III.—The process begun in Class II is complete. The titanomagnetite grain is filled with ilmenite lamellae, usually on a very fine scale. Sometimes an extremely high resolution microscope is needed to see them, since they do not contrast highly with their host. Some reddening of silicates is beginning to appear.

Class IV.—The ilmenite lamellae of Class III have been altered to a silver brightly reflecting form. Much silicate reddening is present expecially in and near olivines.

Class V.—The (what was originally) titanomagnetite may now be pseudomorphed one or both of two ways. It may contain an irregular 'jig-saw' or wavering intergrowth of dull grey pseudobrookite and brighter whitish hematite. Or it may consist of a brown isotropic host containing short black rods of spinel, and surrounded by wide laths or lamellae of rutile and hematite intergrown, leaving sharply angular and straight-sided areas of the brown cubic host (this latter is not shown in Plate 1).

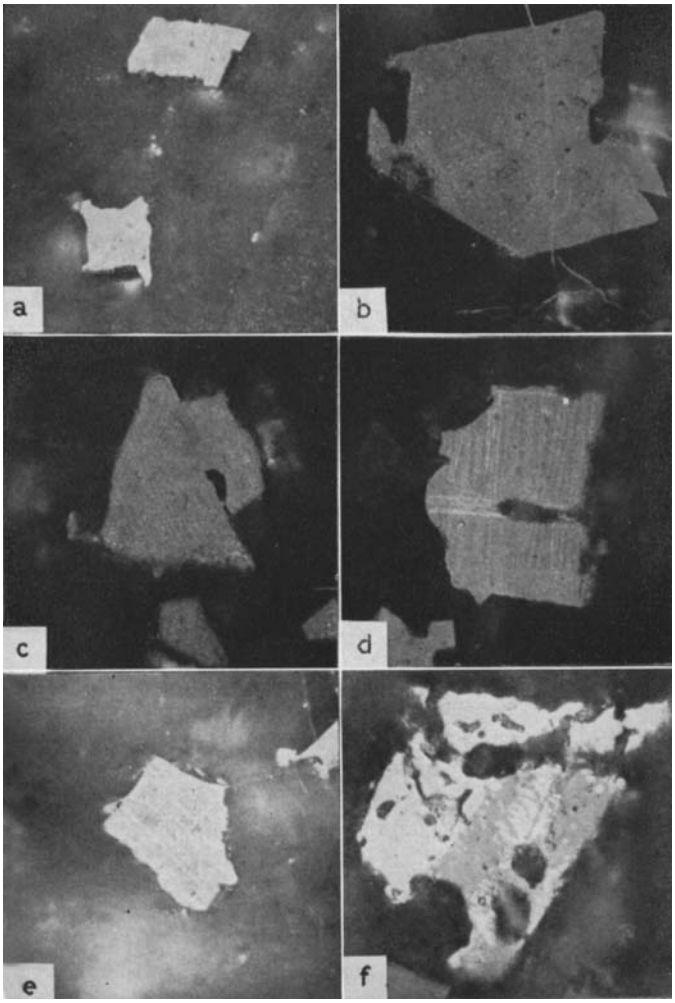
Olivine, if present, has a highly reflecting opaque material growing in cracks, and around the rim; and sometimes exsolved on a fine scale with orientation controlled by the olivine lattice. This opaque material is sometimes called hematite, but the powdered olivine has both hematite and magnetite X-ray lines, and is strongly magnetic enough to be easily separated from rock powder using a bar magnet.

Coloured photographs of these oxidation states may be seen in an article by Wilson & Haggerty (1966). Black and white photomicrographs are reproduced here in Plate 1.

We have classified not single grains, but the overall state of a polished surface of the specimen. In the majority of cases, there was little difficulty in placing the whole specimen in a unique petrological class, although we recognize the subjective nature of the judgment involved. For the cases where there was doubt about classification, we made rules to make the definitions more rigid. For example, if the specimen fell between any two classes defined above, it was deliberately put into the lower of the two classes, except that those between I and II were *raised* into Class II. This procedure made the end classes I and V (least and most oxidized) sharply defined.

Objectivity was also increased in two ways. First, we did not read the specimen code number (and hence did not know its polarity) until *after* petrological classification. Second, the two authors independently assessed many of the specimens petrologically. Their results are compared in Fig. 1. The numbers in each square represent

## Plate 1




(a) Class I—homogeneous titanomagnetite grains (some maghemitization in whiter areas). Specimen B25–1 (i) at ×1200 under oil in plane polarized light.

(b) Class II—incipient creation of fine ilmenite lamellae at one end of the titanomagnetite grain. Specimen J18–1 (ii) at ×1200 under oil in plane polarized light.

(c) Class III—a titanomagnetite grain filled with fine ilmenite lamellae. They do not contrast highly with the host. Specimen G15–1 (iii) at ×1200 under oil in plane polarized light.

(d) Between classes III and IV—the beginning of hematization (bright thin lines) in a class III grain. Specimen G15–1 (iii) at ×1200 under oil in plane polarized light.

(e) Class IV—the completion of (d) showing bright streaks of hematization throughout the grain. The class III structure is still present. Specimen G15–1 (iii) at ×1200 under oil in plane polarized light.

(f) Class V—lamellar structure has broken down and larger irregular areas of hematite (bright) and pseudobrookite (dull) have replaced the original titanomegnetite grain. Specimen G7–2 (i) at ×1200 under oil in plane polarized light.

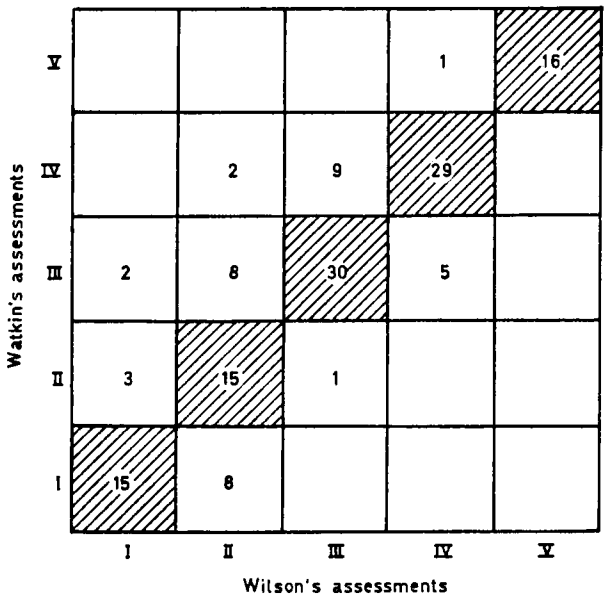



FIG. 1. Comparison of Watkin's petrological assessments of oxidation class with Wilson's independent assessments. Diagonal squares mean agreement between two observers. Off diagonal squares indicate the extent of disagreement. Numbers of specimens observed are written into each square.

the numbers of specimens observed by both authors. A specimen in a diagonal square means that the two observers agreed on petrological classification. Off-diagonal squares represent disagreement. Disagreement by *one* class was treated by the above rules concerning borderline cases. Greater disagreement (four cases in Fig. 1) caused us to review a polished surface together until we agreed on a final classification. A very few slides were so 'mixed' (M in Tables 1 and 2) that we were not willing to classify their overall state of oxidation.

A further test of consistency was as follows. Ten of the polished sections were duplicated by producing ten more from about one inch away in the same oriented core. These pairs are bracketed together in Table 1. They were independently assessed. Assessments of nine pairs agreed precisely. The tenth pair from core J 17–1, were in Classes I and II, which made J 17–1 a Class II specimen according to our rules. The extent of experimental agreement seems to ensure adequate objectivity, at least when a very clear correlation is later found.

The five classes defined here extend an original threefold classification (Ade-Hall *et al.* 1964), in which the third class grouped together Classes III, IV and V of this paper. Five classes of titanomagnetite is not the ultimate in classification of overall oxidation state. A larger scheme should be invented which will include separate ilmenite grains and the states of olivine as oxidation indicators. The scheme should also become more quantitative, especially where correlations are weaker than for these Columbia Plateau basalts.

## Investigation of the ten sections A to J

Watkins (1965a) has demagnetized, in fields as high as 800 oersteds, each of the specimens used from sections A to J. Our specimens were chosen randomly, except to provide about equal numbers of $N$ and $R$ specimens. Each specimen then had a sell-defined polarity, $N$ or $R$. Fig. 2 shows, for those specimens which were analyzed petrologically, five histograms of natural intensity ($J_0$), one histogram for each class

## Table 1

*Data on rocks from the ten sections A to J*

| Specimen | Polarity | $J_0$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | Petr. class. | $T_c$ class |
|---|---|---|---|---|
| A1–6 | R | 6·0 | 5 | — |
| A2–2 | R | 2·91 | 5 | 6− |
| A3–2 | R | 1·40 | 4 | — |
| A4–3 | R | 2·92 | 3 | 6− |
| A5–3 | R | 8·1 | 3 | 6− |
| A6–1 | R | 1·91 | 2 | 5+ |
| A7–7 | R | 1·13 | 4 | 6− |
| A8–2 | R | 3·50 | 3 | 5+ |
| A9–1 | R | 9·4 | 4 | 6− |
| A10–2 | R | 4·8 | 3 | 6− |
| A12–2 | R | 2·90 | 3 | 6− |
| A14–2 | R | 1·97 | 2 | 6− |
| A16–2 | R | 2·94 | 4 | 6− |
| A18–3 | R | 2·79 | 4 | 5+ |
| A19–1 | R | 1·05 | 4 | 5+ |
| A20–1 | R | 6·6 | 3 | 6− |
| B8–1(i) | R | 5·4 | 5 | 6− |
| B8–2(i) | R | 3·80 | 4 | 5+ |
| B25–1(i) | N | 1·01 | 1 | 6− |
| B25–2(i) | N | 0·93 | 2 | 5+ |
| B26–1(i) | N | 1·27 | 2 | X |
| B26–2(i) | N | 1·89 | 1 | 5+ |
| C9–1(i) | R | 3·94 | 5 | 6− |
| C10–1(i) | R | 1·06 | 4 | 6− |
| C32–1(i) | R | 0·83 | 2 | 5+ |
| C39–1(i) | R | 2·14 | 3 | 6− |
| D5–1(i) | R | 6·4 | 5 | 5+ |
| D5–2(i) | R | 5·8 | 4 | 5− |
| D20–1(i) | R | 16·7 | 5 | 5+ |
| D20–2(i) | R | 18·0 | 5 | 5+ |
| E27–1(i) | R | 1·62 | 2 | 6− |
| E27–1(ii) | R | 1·66 | 2 | (1+, 5+) |
| F1–1 | N | 3·48 | – | — |
| F2–2(i) | N | 2·20 | – | 6− |
| F3–1(i) | N | 1·77 | 1 | X (see text) |
| F5–1(ii) | N | 1·65 | 1 | 3+ |
| F6–2(i) | N | 3·32 | 2 | X |
| F8–1(i) | N | 0·80 | 1 | (4−, 6−) |
| F9–1(ii) | N | 2·44 | 1 | X |
| F10–1(ii) | N | 2·45 | 1 | X |
| F11–1(ii) | N | 4·5 | Mixed | X |
| F12–1(i) | N | 2·98 | 1 | X |
| F12–2(ii) | N | 2·58 | 1 | X |
| F13–1(i) | N | 1·31 | 1 | X |
| F14–1(i) | N | 3·42 | 2 | X |
| G7–2(i) | R | 18·2 | 5 | 6− |
| G21–2(i) | R | 18·4 | 5 | 5+ |

The meaning of code numbers is exemplified by G21–2(i). G=section of lavas, 21=lava number, 2=second oriented core, (i)=first one-inch specimen sliced from core.

The letters here are original field numbers. For correlation with Fig. 1 (p. 1380) and Table I of Watkins 1965a, the following conversion is necessary: A=SB, B=SG, C=SD, D=SA, E=SC, F=SE, G=SI, H=SF, I=SH, J=SJ, L=L.

**Table 1** (continued)

| Specimen | Polarity | $J_0$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | Petr. class | $T_c$ class |
|---|---|---|---|---|
| H2–1(i) | N | 6·3 | 4 | — |
| H2–1(ii) | N | 6·4 | 4 | — |
| H2–2(i) | N | 3·72 | 3 | 6− |
| H2–2(ii) | N | 2·71 | 3 | 6− |
| H3–1(i) | N | 4·8 | 5 | 6− |
| H3–2(i) | N | 5·1 | 4 | — |
| H4–1(i) | N | 0·59 | 2 | — |
| H4–2(i) | N | 0·24 | 2 | — |
| H5–1(i) | Intermediate | 54·0 | 3 | — |
| H5–1(ii) | Intermediate | — | 3 | — |
| H5–2(ii) | Intermediate | 12·4 | 3 | — |
| H6–1(i) | R | 14·9 | 5 | — |
| H6–1(ii) | R | 14·9 | 5 | — |
| H6–2(i) | R | 12·9 | 5 | 5+ |
| H6–2(ii) | R | 13·1 | 5 | 5+ |
| H7–1(i) | R | 2·85 | 4 | — |
| H7–2(i) | R | 7·3 | 5 | — |
| H8–1(i) | R | 5·7 | 4 | — |
| H8–2(i) | R | 2·06 | 4 | — |
| H9–1(i) | R | 1·26 | 3 | 6− |
| H9–2(i) | R | 1·33 | 3 | — |
| H9–2(ii) | R | — | 3 | 5+ |
| H10–1(i) | N | 4·5 | 3 | — |
| H10–1(ii) | N | 4·4 | 3 | 6− |
| H10–2(ii) | N | 4·2 | 3 | 6− |
| I4–1(i) | R | 0·93 | 3 | 6− |
| I5–2(i) | R | 0·71 | 3 | 6− |
| I18–1(i) | R shallow | 1·43 | 4 | 6− |
| I18–2(i) | R shallow | 1·13 | 4 | 6− |
| J2–2(i) | N | 5·1 | 2 | (1+, 5+) |
| J3–2(ii) | N | 6·4 | 4 | 6− |
| J4–1(i) | N | 6·0 | 3 | 6− |
| J4–2(i) | N | 4·5 | 3 | 6− |
| J5–1(ii) | N | 53·5 | 3 | 6− |
| J5–2(i) | N | 5·5 | 3 | 6− |
| J6–2(i) | N | 5·6 | 1 | 6− |
| J8–2(ii) | N | 5·2 | 2 | (2−, 6−) |
| J9–2(ii) | N | 3·96 | 3 | (2−, 6−) |
| J10–2(ii) | N | 2·96 | 1 | 2+ |
| J12–1(ii) | N | 4·3 | 2 | 6− |
| J12–2(i) | N | 3·56 | 1 | 6− |
| J13–1(ii) | N | 2·56 | 4 | 6− |
| J14–1(ii) | N | 3·28 | 4 | 6− |
| J15–1(ii) | N | 5·6 | 4 | 6− |
| J16–2(i) | N | 4·9 | 3 | 6− |
| J17–1(i) | N | 4·8 | Mixed | 6− |
| J17–2(i) | N | 2·77 | 1 | 5+ |
| J17–2(ii) | N | 2·65 | 2 | 6− |
| J18–1(i) | N | 3·43 | 2 | 5+ |
| J18–1(ii) | N | 3·27 | 2 | 5+ |
| J20–2(ii) | N | 3·74 | 2 | (2−, 6−) |
| J21–1(ii) | N | 6·8 | 4 | 5+ |
| J22–1(ii) | N | 3·22 | 1 | (2−, 5+) |
| J19–2 | N | 3.01 | Not polished | 6− |

## Table 2

*Data on rocks from polarity transition section L*

*Data concerning natural magnetization, petrology and Curie points of each specimen. Curie points are placed within 50 °C intervals; thus 2+ means 200 to 250 °C, 6— means 550 to 600 °C, and so on. (See also Table 3.)*

| Specimen | Polarity | $J_0$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}/J_0$ | Petr. class | $T_c$ class |
|---|---|---|---|---|---|---|
| L43–1 | N | — | 0·24 | — | 4 | 2+, 5+ |
| L43–2 | | 0·74 | 0·55 | 0·74 | 4 | 6— |
| L43–4 | | 0·48 | 0·32 | 0·67 | 4 | — |
| L43–5 | | 0·72 | 0·55 | 0·76 | 4 | 6— |
| L44–1 | N | 0·51 | 0·34 | 0·67 | 4 | 6— |
| L44–2 | | 0·69 | 0·45 | 0·65 | 3 | 6— |
| L44–4 | | 1·52 | 0·61 | 0·40 | 3 | 6— |
| L44–6 | | 0·83 | 0·47 | 0·57 | 2 | 6— |
| L45–2 | N | 3·37 | 2·10 | 0·63 | 1 | — |
| L45–3 | | 3·36 | 0·55 | 0·16 | 2 | — |
| L45–6 | | 1·70 | 0·32 | 0·19 | 2 | 2—, 6— |
| L45–8 | | 2·72 | — | — | 2 | 2—, 6— |
| L46–1 | N | 0·72 | 0·48 | 0·67 | 4 | 6— |
| L46–4 | | 1·25 | 0·89 | 0·71 | 3 | — |
| L46–5 | | 1·36 | 0·99 | 0·73 | 3 | 6— |
| L46–6 | | 1·17 | 0·76 | 0·65 | 4 | 6— |
| L47–1 | N | 1·99 | 0·96 | 0·48 | Mixed | 6— |
| L47–3 | | 1·47 | 0·74 | 0·50 | 5 | 6— |
| L47–5 | | 1·64 | 0·80 | 0·49 | 4 | 6— |
| L47–6 | | 1·45 | 0·75 | 0·52 | Mixed | 6— |
| L48–1 | N | 1·25 | 1·28 | 1·02 | 3 | 6— |
| L48–3 | | 0·98 | 0·59 | 0·60 | 3 | 6— |
| L48–4 | | 0·58 | 0·57 | 0·98 | 3 | 6+ |
| L48–6 | | 3·32 | 0·49 | 0·15 | 4 | 6— |
| L49–1 | N | 1·57 | 0·70 | 0·45 | 3 | (2—, 6—) |
| L49–2 | | 0·98 | 0·53 | 0·54 | 4 | 6— |
| L49–4 | | 2·78 | 0·32 | 0·12 | 1 | 6— |
| L49–6 | | — | 11·20 | — | 3 | 6— |
| L50–1 | N | 1·89 | 0·77 | 0·41 | 3 | 6— |
| L50–2 | | 2·10 | 0·61 | 0·29 | 2 | 2—, 6— |
| L50–3 | | 2·68 | 0·56 | 0·21 | 2 | — |
| L50–6 | | 1·32 | 0·53 | 0·40 | 3 | 6— |
| L51–1 | N | 2·87 | 0·11 | 0·04 | 2 | (2+ to 5+) |
| L51–2 | | 3·16 | 0·15 | 0·05 | 1 | 2+, 5+ |
| L51–4 | | 3·31 | 0·25 | 0·08 | 2 | 2—, 5+ |
| L51–6 | | 1·45 | 0·82 | 0·57 | 3 | 6— |
| L52–1 | N | 1·56 | 0·27 | 0·17 | Mixed | 6— |
| L52–2 | | 0·92 | 0·51 | 0·55 | 4 | 6— |
| L52–3 | | 1·18 | 0·52 | 0·44 | 5 | 6— |
| L52–4 | | 1·11 | 0·42 | 0·38 | 4 | 6— |
| L53–1 | N | 0·60 | 0·37 | 0·62 | 4 | — |
| L53–2 | | 0·70 | 0·37 | 0·53 | 3 | 6— |
| L53–4 | | 0·88 | 0·45 | 0·51 | 2 | (2—, 6—) |
| L53–5 | | — | 0·51 | — | 5 | 6— |
| L54–1 | N | 0·96 | 0·40 | 0·42 | 1 | 5+ |
| L54–2 | | 1·31 | 1·05 | 0·80 | 2 | 6— |
| L54–3 | | 0·97 | 0·62 | 0·64 | 1 | — |
| L54–7 | | 0·96 | 0·75 | 0·78 | 3 | 5+ |

**Table 2** (continued)

| Specimen | Polarity | $J_0$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}/J_0$ | Petr. class | $T_c$ class |
|---|---|---|---|---|---|---|
| L55–2 | N | 1·49 | 0·82 | 0·55 | 2 | — |
| L55–3 | | 2·20 | 0·66 | 0·30 | 2 | — |
| L55–4 | | 1·97 | 0·81 | 0·41 | 2 | 6− |
| L55–6 | | 2·32 | 1·34 | 0·58 | 2 | 6− |
| L56–1 | N | 2·12 | 1·45 | 0·68 | 3 | (1+, 6−) |
| L56–3 | | 2·10 | 0·64 | 0·30 | 2 | (2−, 6−) |
| L56–5 | | 2·21 | 1·59 | 0·72 | Mixed | 6− |
| L56–6 | | 2·07 | 1·61 | 0·78 | 3 | (2−, 6−) |
| L57–1 | R | 3·88 | 2·81 | 0·72 | 5 | 6− |
| L57–2 | | 4·60 | 3·61 | 0·78 | 5 | — |
| L57–5 | | 5·55 | 4·86 | 0·87 | 5 | 6+ |
| L57–6 | | 3·60 | 2·44 | 0·68 | 5 | 6− |
| L58–1 | R | 0·75 | 0·61 | 0·81 | 5 | 6− |
| L58–3 | | 3·58 | 2·97 | 0·83 | 5 | 6− |
| L58–5 | | 4·36 | 3·44 | 0·79 | 5 | 5+ |
| L58–6 | | 5·64 | 4·12 | 0·73 | 5 | 6− |
| L59–2 | R | 0·67 | 0·43 | 0·64 | 5 | 6− |
| L59–3 | | 0·91 | 0·54 | 0·59 | 5 | 6− |
| L59–4 | | 0·84 | 0·59 | 0·70 | 5 | 6− |
| L59–7 | | 1·73 | 1·38 | 0·80 | 4 | 6− |
| L60–2 | R | 1·09 | 0·90 | 0·82 | 3 | 6− |
| L60–3 | | 1·14 | 0·96 | 0·84 | 3 | 6− |
| L60–4 | | 1·23 | 1·12 | 0·91 | 3 | 6− |
| L60–7 | | 1·65 | 1·38 | 0·84 | 3 | 6− |
| L61–1 | R | 1·05 | 0·91 | 0·87 | 2 | 6− |
| L61–3 | | 0·91 | 0·86 | 0·94 | 4 | 6− |
| L61–5 | | 1·14 | 1·08 | 0·95 | 2 | (2−, 6−) |
| L61–6 | | 2·13 | 1·93 | 0·91 | 2 | 5+ |
| L62–3 | R | 1·85 | 1·46 | 0·79 | 5 | 6− |
| L62–4 | | 1·26 | 1·01 | 0·80 | 3 | 6− |
| L62–5 | | 1·73 | 0·98 | 0·57 | 4 | 6− |
| L62–6 | | 1·88 | 1·47 | 0·78 | 5 | 6+ |
| L63–1 | R | 2·42 | 1·98 | 0·82 | 5 | 6− |
| L63–4 | | 2·66 | 1·87 | 0·70 | 4 | 6− |
| L63–5 | | 2·78 | 2·13 | 0·74 | 3 | 6− |
| L63–7 | | 3·07 | 2·29 | 0·75 | 5 | 6− |
| L64–1 | R | 1·61 | 1·49 | 0·93 | 4 | 6− |
| L64–2 | | 1·48 | 1·04 | 0·70 | 5 | ? |
| L64–4 | | 1·38 | 0·95 | 0·69 | 4 | — |
| L64–6 | | 2·96 | 3·04 | 1·03 | 4 | 6− |
| L65–1 | R | 3·08 | 2·27 | 0·74 | Mixed | 6− |
| L65–2 | | 4·50 | 3·32 | 0·74 | 2 | 6− |
| L65–4 | | 3·94 | 3·02 | 0·77 | 3 | 6+ |
| L65–6 | | 12·42 | 10·21 | 0·82 | 5 | 6− |
| L66–1 | R | 6·99 | 6·25 | 0·89 | 4 | 6− |
| L66–3 | | 2·94 | 2·37 | 0·81 | 3 | 6− |
| L66–4 | | 3·04 | 2·16 | 0·71 | 3 | 6− |
| L66–6 | | 5·48 | 4·78 | 0·87 | 4 | — |
| L67–1 | R | 5·36 | 4·50 | 0·84 | 4 | 5+ |
| L67–3 | | 2·20 | 1·72 | 0·78 | 4 | 6− |
| L67–5 | | 2·57 | 2·17 | 0·84 | 3 | 6− |
| L67–8 | | 3·14 | 2·39 | 0·76 | 3 | 6− |

**Table 2** (continued)

| Specimen | Polarity | $J_0$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}$ $\frac{\text{e.m.u.}}{\text{cm}^3} \times 10^{-3}$ | $J_{200}/J_0$ | Petr. class | $T_c$ class |
|---|---|---|---|---|---|---|
| L68–1 | R | 8·03 | 5·91 | 0·74 | 4 | 6− |
| L68–2 | | 3·78 | 2·63 | 0·70 | 3 | 6+ |
| L68–4 | | 4·62 | 4·08 | 0·88 | 3 | 6− |
| L68–6 | | 7·35 | 5·86 | 0·80 | 4 | 6− |
| L69–1 | R | 6·68 | 5·67 | 0·85 | 3 | — |
| L69–4 | | 4·40 | 3·41 | 0·77 | 2 | 6− |
| L69–7 | | 4·16 | 3·15 | 0·76 | 4 | — |
| L69–8 | | 4·48 | 3·02 | 0·67 | 3 | 6− |
| L70–1 | R | 3·26 | 2·65 | 0·81 | 4 | 6− |
| L70–3 | | 5·59 | 4·69 | 0·84 | 4 | 6− |
| L70–4 | | 4·15 | 3·38 | 0·81 | 4 | 6− |
| L70–6 | | 5·74 | 3·50 | 0·61 | 4 | 6− |
| L71–1 | R | 2·18 | 1·85 | 0·85 | 4 | 6− |
| L71–4 | | 3·72 | 3·33 | 0·90 | 4 | 6− |
| L71–6 | | 5·55 | 4·61 | 0·83 | 4 | 6− |
| L71–7 | | 3·35 | 2·67 | 0·80 | 4 | 6− |

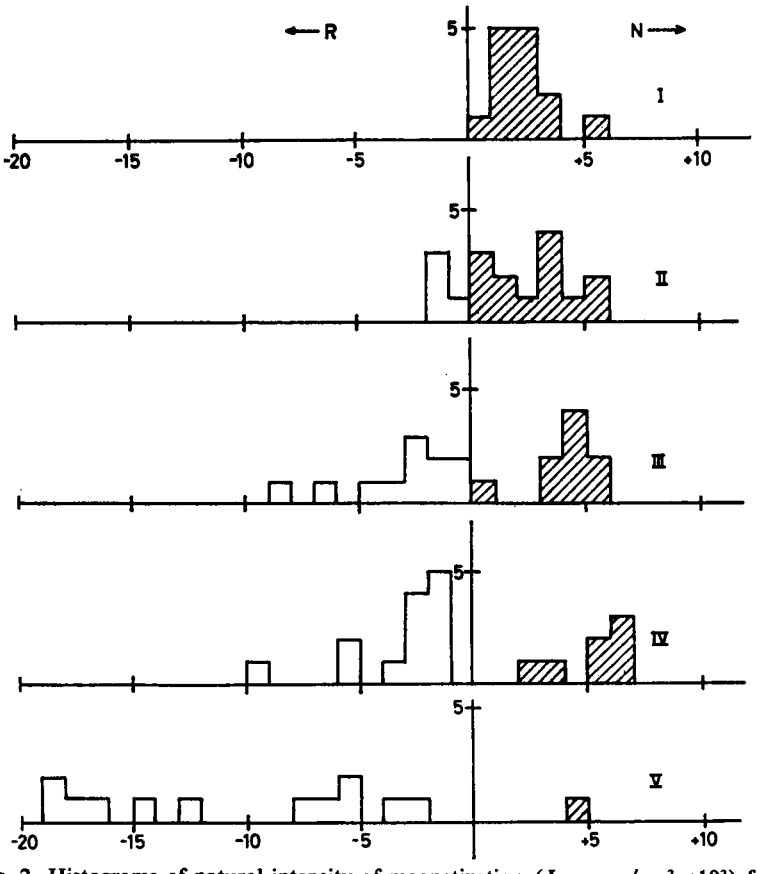



FIG. 2. Histograms of natural intensity of magnetization ($J_0$ e.m.u./cm$^3 \times 10^3$) for each state of oxidation in lava spections A to J.

of oxidation of titanomagnetite grains. It is clear that the proportion of reversed specimens increases regularly with oxidation and that the reversed specimens tend to be more strongly magnetized. The percentage of reversed specimens in each oxidation class is plotted in Fig. 5, as open circles. The correlation of oxidation state with natural magnetic polarity is clear, but only statistical. There are exceptions to the trend, in that some highly oxidized specimens are normally magnetized; and intermediately oxidized specimens are of both polarities.

Five reversed lavas were sampled along with associated baked rocks beneath them. The five baked zones also had reversed polarity (Watkins 1965a). This has been shown to be strong evidence for field reversal as a cause of reversed magnetization (Wilson 1962, Irving 1964).

## Investigation of section L, containing transition lavas

We concern ourselves now with a sequence of 29 lavas from section L in Steens Mountain (Watkins 1965b). From each lava six to eight separately oriented specimens were collected, using geographical orientation.

### Table 3

*Directional data from section L*

| Lava No. | No. of samples | Before a.c. demag. Decl. | Incl. | $k_0$ | After a.c. demag. in 200 oe Decl. | Incl. | $k_{200}$ | Δ (degrees) | $\frac{k_{200}}{k_0}$ |
|---|---|---|---|---|---|---|---|---|---|
| L 43 | 6 | 287° | +60° | 67·0 | 282° | +58° | 122 | 3 | 1·82 |
| L 44 | 6 | 349° | +64° | 5·5 | 293° | +52° | 28·5 | 30·5 | 5·21 |
| L 45 | 8 | 340° | +55° | 7·0 | 306° | +54° | 24·5 | 19·7 | 3·50 |
| L 46 | 6 | 313° | +55° | 205 | 307° | +55° | 142 | 3·25 | 0·69 |
| L 47 | 7 | 321° | +49° | 71·0 | 298° | +45° | 84·3 | 15·5 | 1·18 |
| L 48 | 6 | 331° | +77° | 4·3 | 267° | +68° | 23·0 | 19·5 | 5·38 |
| L 49 | 6 | 255° | +70° | 2·7 | 187° | +71° | 2·3 | 21·0 | 0·85 |
| L 50 | 7 | 95° | +73° | 22·4 | 133° | +40° | 20·0 | 37·5 | 0·89 |
| L 51 | 6 | 51° | +72° | 5·4 | 126° | +34° | 11·7 | 53·0 | 2·15 |
| L 52 | 6 | 105° | +59° | 24·0 | 122° | +31° | 19·1 | 30·0 | 0·79 |
| L 53 | 7 | 111° | +56° | 59·0 | 130° | +29° | 83·5 | 30·5 | 1·41 |
| L 54 | 7 | 117° | +59° | 10·8 | 127° | +29° | 26·5 | 31·0 | 2·45 |
| L 55 | 6 | 104° | +58° | 13·2 | 131° | +25° | 136 | 37·5 | 10·3 |
| L 56 | 6 | 114° | +46° | 12·8 | 131° | +16° | 42·4 | 33·0 | 3·30 |
| L 57 | 6 | 191° | −16° | 53·7 | 195° | −19° | 40·4 | 4·5 | 0·75 |
| L 58 | 6 | 192° | −20° | 32·0 | 194° | −23° | 166 | 4·0 | 5·20 |
| L 59 | 7 | 194° | −13° | 185 | 194° | −18° | 104 | 5·0 | 0·56 |
| L 60 | 7 | 185° | −21° | 3·0 | 202° | −24° | 37·2 | 16·0 | 12·4 |
| L 61 | 7 | 209° | −34° | 3·8 | 213° | −36° | 15·8 | 3·0 | 4·19 |
| L 62 | 7 | 200° | −28° | 32·2 | 199° | −31° | 29·4 | 3·5 | 0·91 |
| L 63 | 7 | 162° | −66° | 91·8 | 170° | −66° | 93·9 | 3·5 | 1·02 |
| L 64 | 6 | 163° | −70° | 72·6 | 168° | −69° | 12·4 | 2·5 | 0·17 |
| L 65 | 6 | 210° | −62° | 166 | 209° | −61° | 1612 | 1·0 | 9·6 |
| L 66 | 6 | 203° | −60° | 500 | 201° | −60° | 757 | 1·0 | 1·5 |
| L 67 | 8 | 215° | −71° | 220 | 211° | −69° | 273 | 3·0 | 1·23 |
| L 68 | 6 | 237° | −70° | 375 | 228° | −72° | 149 | 3·5 | 0·39 |
| L 69 | 8 | 224° | −71° | 700 | 221° | −72° | 362 | 1·5 | 0·51 |
| L 70 | 6 | 224° | −73° | 156 | 212° | −73° | 375 | 3·5 | 2·40 |
| L 71 | 7 | 223° | −74° | 103 | 229° | −75° | 495 | 2·0 | 4·8 |

Declination in degrees east of true north
Inclination in degrees below horizontal
} mean for each lava.

$k_x$ = precision factor after demagnetization in $x$ peak oersteds.

Δ = angles between means for lava before and after alternating field demagnetization.

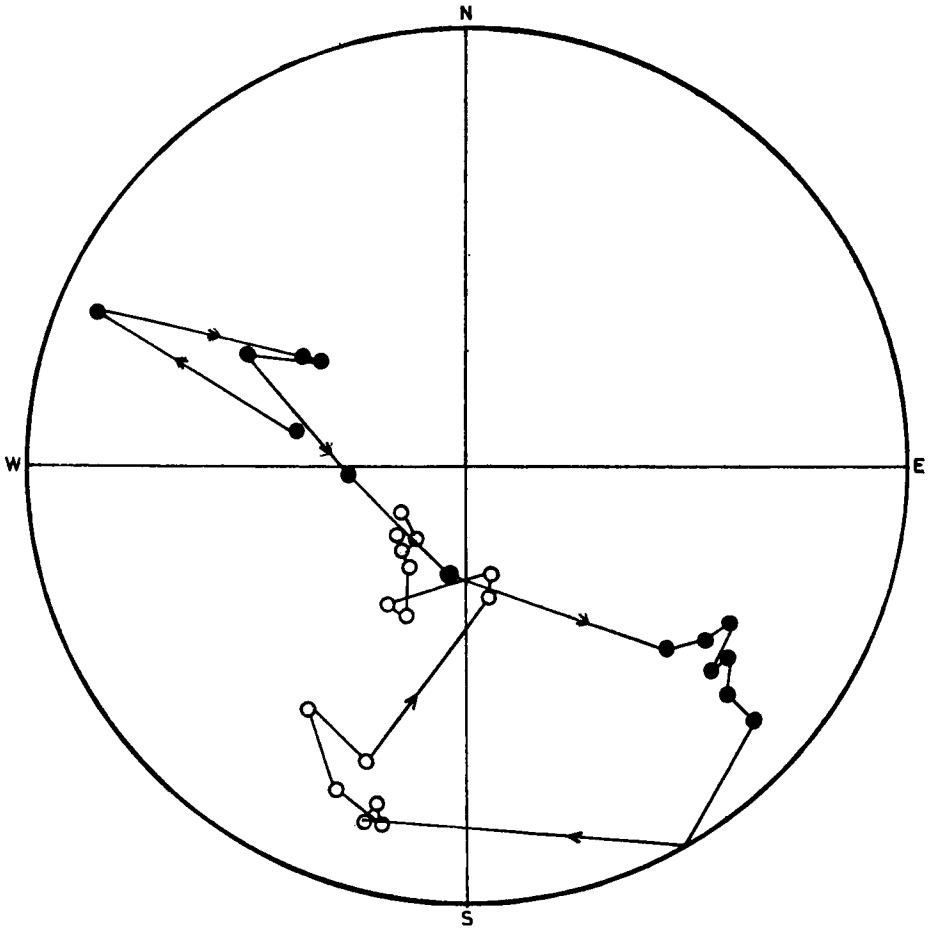



FIG. 3. Mean directions of magnetization for each lava in section L, which contains transition or intermediate directions. ○, dips up; ●, dips down.

Table 3 lists the mean direction of magnetization for each lava before and after demagnetization of all specimens in a 200 oersted alternating field. The mean directions after demagnetization are plotted in Fig. 3. There are several lavas with directions intermediate between true normal and reversed polarity. This phenomenon has been observed before in lavas by Brynjolfsson (1957), Momose (1963), and van Zijl *et al.* (1962a, b). It has been interpreted as a record of a magnetic transition period during which the Earth's magnetic field was changing polarity.

The break between lavas L56 and L57 was chosen as the natural horizon to divide 'reversed' lavas (negative inclination) from 'normal' lavas (positive inclination). This was decided prior to petrological investigation.

Four separately oriented specimens from each lava were analysed petrologically by the method of Section 2. Fig. 4a contains histograms of these specimens' natural magnetizations for each of the five oxidation states. Fig. 4b shows analogous histograms of the magnetization after demagnetizations in 200 oersted alternating fields.

Fig. 5 shows (solid circles) how the percentage of reversed specimens increases regularly with increasing oxidation state. The mode of increase is very similar to the curve for sections A to J, and was, of course, derived absolutely independently.

The apparent 'magnetic hardness' of the normal specimens also differed from that of the reversed specimens, statistically. This is shown in two ways.

First, the rate of decrease of natural magnetization with alternating field demagnetization may be indicated by the ratio $J_{200}/J_0$ of the natural magnetization before and after demagnetization in a 200 oersted field. Fig. 6 shows that reversed specimens apparently resisted the alternating field more than the normal specimens (all L section specimens, not just the petrologically analysed ones).

Second, although the grouping of directions within each lava did not differ too drastically from normal to reversed lavas, the shift of the *mean direction* of each lava did differ after alternating field demagnetization. Fig. 7 and Table 3 show that the mean directions of many of the normal lavas swung through large angles upon demagnetization, while the mean directions of the reversed lavas remained remarkably stable.

Both the above evidences and Figs. 6 and 7 indicate greater overall magnetic stability in the reversed lavas than in normal lavas. One might feel that this indicates a link between petrology and magnetic hardness as first suggested by Graham (1953), and subsequently observed by Watkins & Haggerty (1965) and Larson *et al.* (1966a). But, strangely, this apparent stability is *not* strongly related to the observed petrology. Fig. 8 shows the ratio $J_{200}/J_0$ as a function of oxidation state *and* polarity. The normal specimens seem to increase somewhat in resistance to alternating fields as their oxidation state increases, but the reversed specimens maintain their apparent resistance in all oxidation states in which they were observed (as low as Class II). This may be due to the magnetic history of the lavas rather than to their internal magnetic properties. For example, if the reversed lavas were by chance magnetized

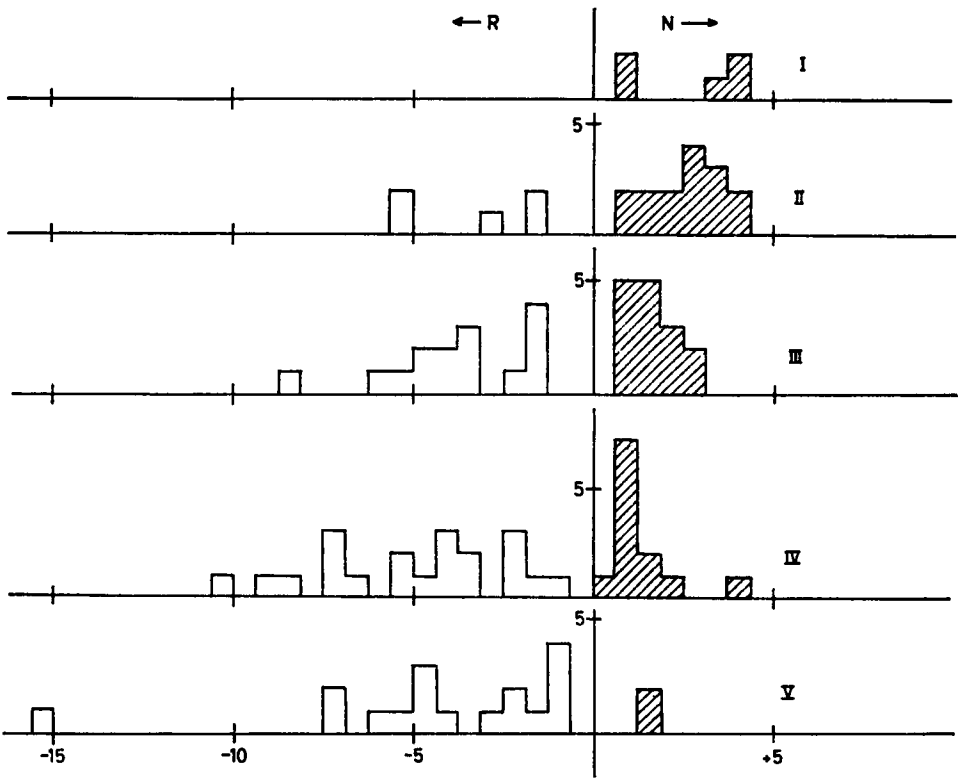



FIG. 4a. Histograms of natural intensity of magnetization ($J_0$ e.m.u./cm$^3$ $\times 10^3$) for each state of oxidation in lava section L.

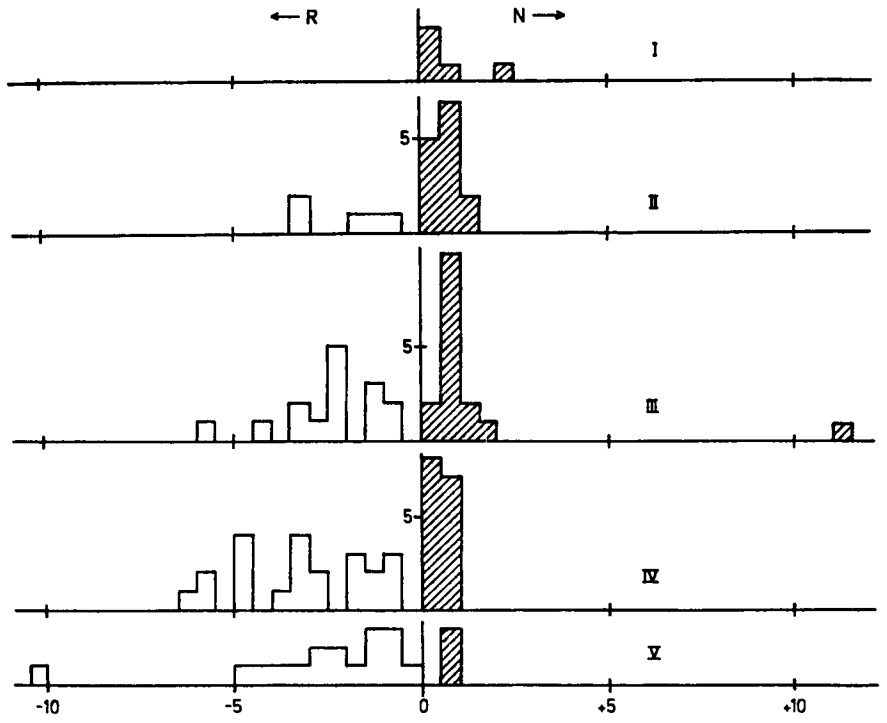



FIG. 4b. Histograms of intensity of magnetization ($J_{200}$ e.m.u./cm$^3 \times 10^3$) after demagnetization in 200 oersted peak alternating field. One histogram for each oxidation state in lava section L.

in a stronger magnetic field than the normal ones, then this could explain their relative stability (Fig. 7) and apparent magnetic hardness (Fig. 6); because given identical normal and reversed materials, secondary magnetizations will be less important in the more strongly magnetized specimens. This would cause less angular change and less intensity change at first during a.c. demagnetization. If these 'properties' are due to the relative *N* and *R* field strengths (external), then they cannot be regarded as showing real differences (internal) between *N* and *R* specimens. An independent indication that this is the correct explanation of the apparent differences is that the original *and* a.c. demagnetized specimens separately are, *in any given petrological state*, more strongly magnetized when reversed than when normal [Figs. 4(a) and (b)]. Smith (1966) has shown that Tertiary dipole field strengths may fluctuate by a factor of 5 to 10 so that the above hypothesis is physically quite possible. We therefore hypothesize that L section may have recorded a transition from a weak normal field to a relatively strong reversed field.

The evidence therefore indicates (a) that there are obvious (but only statistical) petrological differences between *N* and *R* specimens, and (b) that the reversed field may have been significantly stronger than the normal field immediately before and after the moment of polarity transition.

## Curie points and heating curves

Heating curves on these specimens revealed (Tables 1 and 2) that the only specimens with single Curie points below 500 °C were the least oxidized lavas in sections J and F. Their Curie points were measured in 1000 oersteds in air as described by Ade-Hall *et al.*

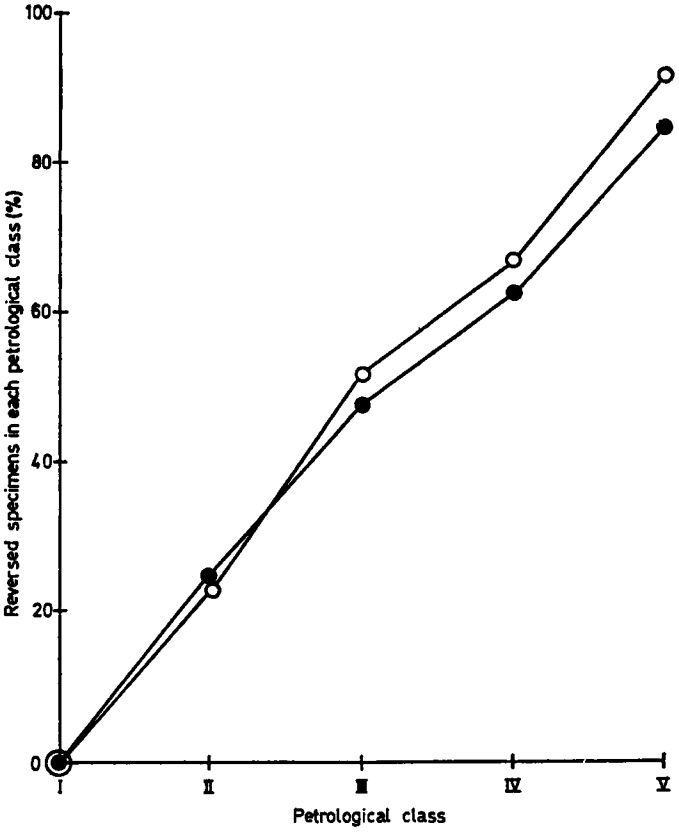



FIG. 5. Percentage of reversed specimens in each oxidation state. Ten sections A to J combined; L—section alone.

(1964). The low Curie point curves marked 'X' in Table 1 began to change the shapes of their heating curves before the Curie point was reached, in the manner described by Parry (1957). We believe this is due to oxidation of titanomagnetite during heating (Akimoto & Katsura 1959, Havard & Lewis 1965).

Otherwise some double Curie point specimens were observed in Classes I and II, but in Classes III, IV, and V the Curie points were very high, between 500 and 600 °C, and heating curves were similar in shape, as exemplified in Fig. 9. This verifies earlier results concerning petrology and Curie points (Ade-Hall *et al.* 1964).

It is rather odd that despite the enormous difference in the appearance of opaque minerals in (for example) Classes II and V, nevertheless their heating curves are often quite similar in shape although the Class V specimens are more strongly magnetic in 1000 oersteds. It may be sheer coincidence that they are similar, for the titanomagnetite seen in Class II no longer exists in Class V, certainly not enough to account for a *stronger* magnetization in Class V.

## Discussion and conclusions

It is abundantly clear that there is a statistical correlation of petrology with polarity in these Columbia Plateau basalts. Fig. 5 demonstrates that the more highly oxidized the specimen, the greater the percentage of reversely magnetized samples in that state of oxidation.

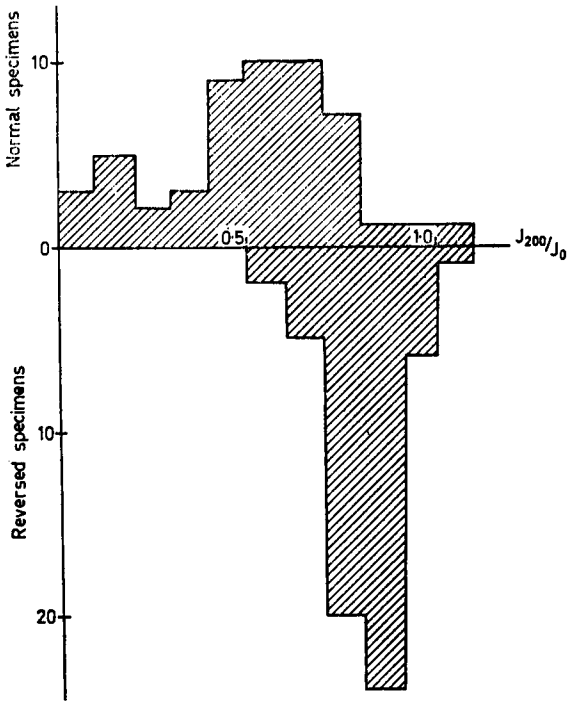



FIG. 6. Histograms of $J_{200}/J_0$, the 'magnetic hardness', for normal and reversed specimens from L section.

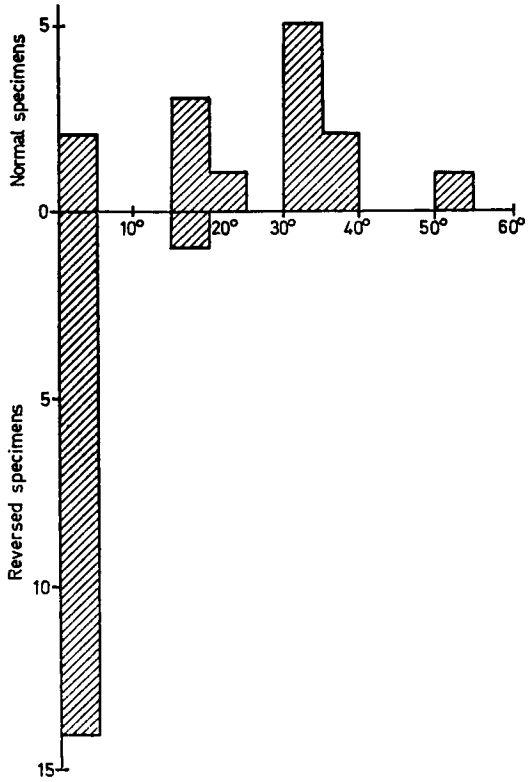



FIG. 7. Histograms of angular change of *mean* direction of each lava in L section during alternating field demagnetization.

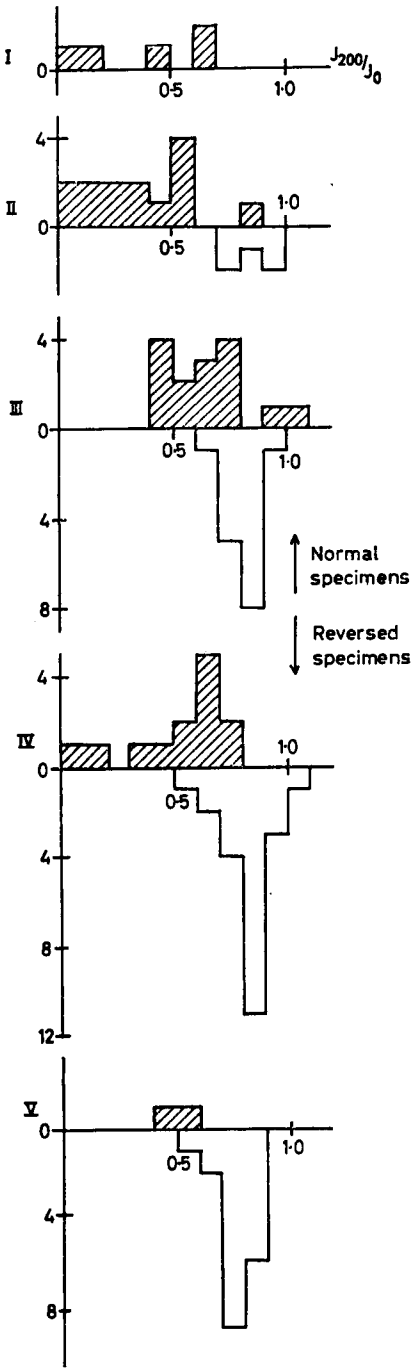



FIG. 8. Histograms of $J_{200}/J_0$ for each petrological class in L section. Normal specimens are upright, reversed specimens inverted histograms.

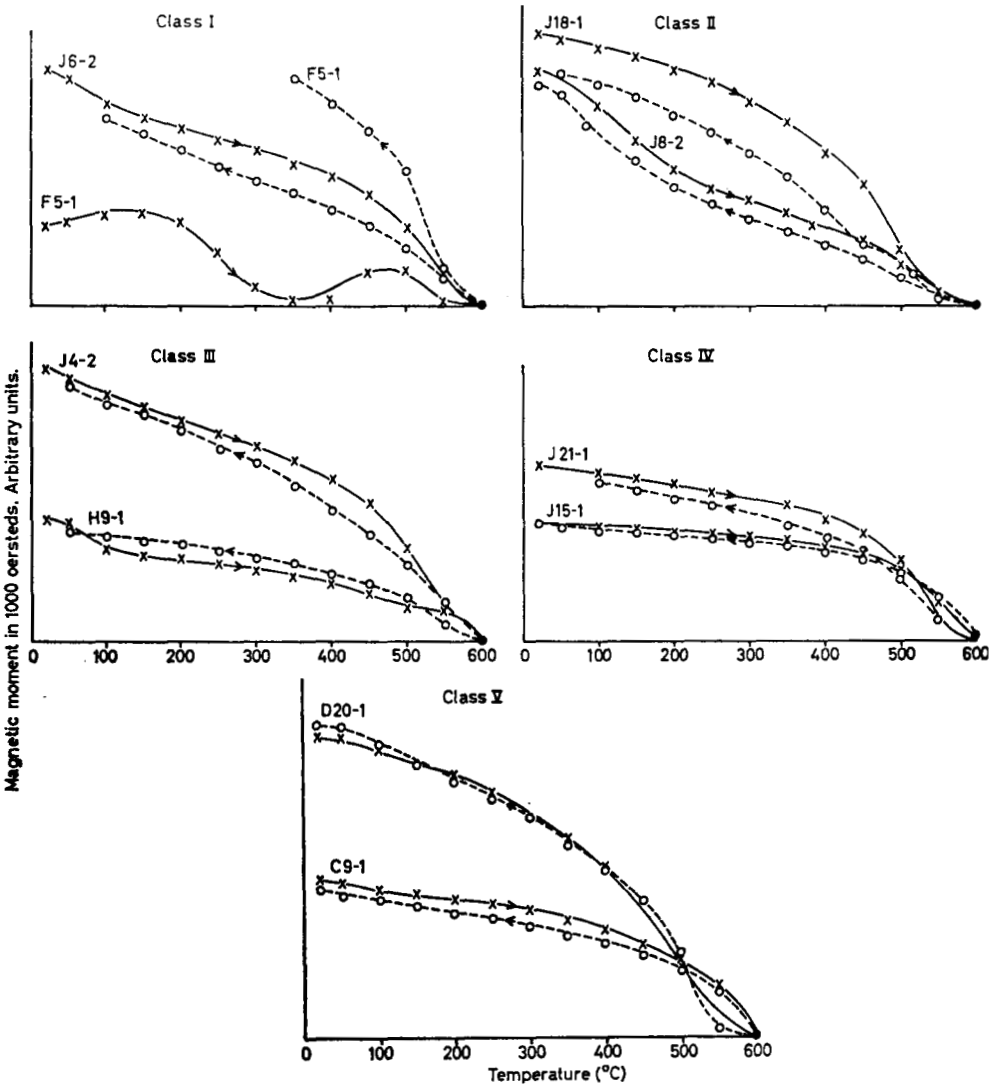



FIG. 9. Typical heating curves of magnetization in 1000 oersteds versus temperature for each of the five petrological classes.

The reversed samples are also more intensely magnetized, and harder to demagnetize in alternating fields (Figs. 6 and 8 and Section 5), although this may indicate that the reversed field following the transition was stronger than the normal field just prior to the transition.

Two classical tests indicating that the ancient magnetic field did reverse its polarity are:

(a) Five baked zones under five different reversely magnetized lavas all have reversed polarity.

(b) There are several lavas in L section which have intermediate polarities leading from normal to reversed states progressively. This has only so far been interpreted as a record of the Earth's magnetic field gradually reversing its polarity.

Both of the above evidences (a) and (b) occur in the same lava sequences which show a correlation between polarity and petrology. There are three possible interpretations of all the evidence:

Either (1) the petrology–polarity correlations are purely accidental and the evidence for field reversal is correctly interpreted. In view of the amount of petrological data and the separate duplication of results in different sections, accidental petrology correlation seems unlikely. The wide geographical separation of these lavas precludes the possibility of the same lavas being repeatedly collected, although they might be fairly contemporaneous and therefore have accidentally the observed chemistries due to common sources.

Or (2) the evidence for field reversal is misinterpreted, and the petrology–polarity correlation means that some of these lavas are self-reversed. This also seems unlikely, since the intermediately magnetized lavas in L-section cannot be explained by a self-reversal mechanism.

There also exist here many lavas of both polarities in the same oxidation state, which means that the polarity depends on petrology only statistically and not with a unique one-to-one relationship. If it were a question of a normal magnetic component and another self-reversing component contending for domination in the same specimen, then the lava specimens with intermediate oxidation states ought to be most weakly magnetized since they would contain nearly balanced normal and reversed components of natural magnetization. They are not relatively weakly magnetized as Figs. 2, 4(a) and 4(b) show.

Finally, there exists the classical test of baked rocks agreeing with lavas.

Therefore, self-reversal seems to be an unlikely explanation of the magnetic states of these lavas.

Or (3) the field reversal evidence is correctly interpreted as supporting the reality of field reversal, and for an unknown and perhaps very indirect reason the oxidation state of these lavas is related (statistically) to the polarity of the Earth's magnetic field. The ' unknown reason ' for the correlation of oxidation state of lavas with polarity of the external field is, however, not satisfactory.

There are in the literature at least twelve other reported cases of differences between normally and reversely magnetized sequences of rocks. They often involve oxidation, and in each case the reversely magnetized specimens tend to be the more highly oxidized ones, as we have found here. The special references below refer to all the papers of which we are aware on this subject.

Larson & Strangway have suggested (1966b) that correlations of oxidation state with polarity are probably fortuitous, due to instability (and hence to viscous normal remagnetization) being connected with low oxidation states of titanomagnetite. All of our specimens have been a.c. demagnetized so that instability is not likely to be the source of our correlations. Larson & Strangway also suggest that correlations are fortuitous because of ' limited sampling '. As proof, they present observations of 90 specimens from five locations in the U.S. and Japan, and find no correlation. They reject 18 of these because of instability, whereas we retain all of our samples, which, though some are ' unstable ', give satisfactory polarities on a.c. demagnetization. By rejecting low stability (and presumably low oxidation state) specimens, their sampling is biassed. They do not state that their specimens were a.c. demagnetized at all. As for ' limited sampling ', the numbers of specimens presented in this paper exceeds 200 from one general location, which, judged by Larson & Strangway's own criteria, should be quite adequate to establish a local correlation if it exists.

The problem, therefore, is how to reconcile our experimentally founded belief in field reversal with the obvious petrological differences between normal and reversed lavas from these Columbia Plateau basalts, and with those differences generally found, which suggest at first sight self-reversal. A causal connection, however indirect,

between field polarity and oxidation state in lavas would permit the evidence to be reconciled.

**Acknowledgments**

We should like to thank Miss Carolyn Reeves and Miss Alice Crosbie for typing this manuscript; and Miss Nina Olsson and Miss Gladys Lewis for help in producing the diagrams and some of the data.

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1966 *August.*

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