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PROBLEMS WITH THE INTERPRETATION OF PALEOMAGNETIC MEASUREMENTS DUE TO STUDIES OF BASALTS FROM THE PALEOVOLCANO VOGELSBERG IN HESSEN

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PROBLEMS WITH THE INTERPRETATION OF PALEOMAGNETIC MEASUREMENTS DUE TO STUDIES OF BASALTS FROM THE PALEOVOLCANO VOGELSBERG IN HESSEN*

E. Schenk**

Summary. The palaeomagnetic parameters of more than 5000 samples of cores taken from 33 drilling holes through innumerable basalt units of the Vogelsberg Paleovolcano in Hessen were measured. Measurements of specimens of thin and thick layers without any gap proved that inclination, natural remanence, susceptibility and Königsberger factor are dependent on their distance from the surface of units, layers, lamelles, etc. Therefore, representative data for the evaluation of palaeomagnetic measurements can be expected only in the interior part of lava flows, intrusions, a.s.o. The statistic method which encloses all values of measurements gives significant data which are not appropriate for the interpretation of palaeomagnetic and geological events. /359***

Purpose of the Study

It is well known that the parameters of magnetic samples from volcanic rocks, for instance, from lava flow, show a scatter, and that for this reason statistical methods are required to obtain significant data. Since correlations of such significant values with radiometric age determinations were often successful, it is generally believed that the history of the migration and of the exchange of the magnetic poles of the earth as well as the physical foundations of a description of the stratification of rock formations, in particular, of volcanic origin, can be dated. This claim /360

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is even extended to geotectonic events, such as the continental drift.

Many of the contradictions that become obvious, when the ages on the basis of paleomagnetic data from rocks from all parts of the world were compared, are not affected by geological uncertainties and by uncertainties of the limited amount of physical measurements. This is especially true since the conditions for the reverse magnetization of rocks and minerals are physically as well as mineralogically defined [Neel, 1951 and 1955, Blackett/Irving, 1964] with the possibilities for the appearance of this effect and of a secondary heating with resulting change in magnetization being apparently limited by the physical processes and, thus, accessible to evaluation.

In view of these statements, the idea of discussing the geological and, in particular, the volcanic events on the basis of a global prespective appears important and interesting. This involves the collection of the data on the geomagnetic history of the planet earth.

Studies in this direction had been taking place with respect to the paleovolcano Vogelsberg and its surroundings [Angenheister, 1956; Hahn, 1956; Turkowski, 1963; Schult, 1963; Nairn, 1961, 1962; Murawski, 1965]. Especially the results of the study by Angenheister (1956) which is excellent in its statistical methodology appeared to bear witness for the applicability of the paleomagnetic methods in order to obtain an organization of the basalt complex of this volcanic mountain with the aid of paleomagnetic data. The results were based on a study of the core drillings that had been conducted since 1960 for the purpose of hydrogeological studies. However, already the first few series of measurements made it clear [Turkowski, 1963] that there was a significant scatter in the remanence and inclination. In addition, a certain regularity in the distribution of the magetization in the various basalt layers became obvious.

Similar observations with respect to the remanence exist for the lava rocks of the Stormberg [J. S. V. Zijl, K. W. T. Grahmm, and A. L. Hales, 1962] and for the Patetere ignimbrites of Waipapa [New Zealand; Hatherton, 1954]. There is so far no explanation [Irving, 1964]. In order to be sure about the interpretation of paleomagnetic measurements, however, it is necessrry to know whether this more or less regular scatter is an exception, happens rather often, or whether it may even be a hidden regularity. After all, it is conceivable that the paleomagnetic data of a sample that has been taken at some arbitrary location of a lava flow are characteristic for the specific location, but not for stratigraphic correlation, and for the paleomagnetic location of the terrestrial poles.

In order to clarify this point and to obtain a secured basis for the discussion, we have studied the distribution of the magnetization, that is, of the remanence, of the inclination, and /361
of the volume susceptibility along the vertical axis of basalts (such as found in lava flow, deposits, etc.).

Method of Study

The method recognized as valid by all paleomagneticists is to obtain oriented samples from rock layers and to cut the samples into specimens for which values prior to, and after demagnetization are then determined and averaged [Creer, 1957; Runcorn, 1955; Irving, 1964; Cox and Deoll, 1960; and others]. This results in a major importance for the statistical treatment.

It is typical to remove samples from a rock layer (with orientation) near some boundary layer; the reason is that only boundaries, surfaces, warpings, etc., make it easy to cut off edges and to start the drills. It is probably a rare occasion that the central portion of a rock layer offers itself naturally for the sample-taking. The authors usually do not mention the technique of this sample taking. Hence, from the literature we do not obtain information on the exact location of the samples, for instance, how close they were to the upper or lower boundary of a layer, and how the layer was located, etc. This is a highly significant uncertainty for all previous paleomagnetic data.

A possibility ot obtain samples in a continuous sequence across not only single rock layers, but also across thick layers of basalt was offered by the core drillings in the Western part of the Vogelsberg. In the framework of our study program, 80 core drillings were carried out so far, each having about 4000 m depth (Figure 3). They were studied paleomagnetically along the entire depth range. More than 5000 specimens resulted whose length was made mostly equal to the diameter of about 7 - 11 cm. Thus, we obtained a continuous sequence of data across the basalt layers. The measurements were done with the aid of a fluxgate magnetometer [Turkowski, 1973; Fromm, 1967] and yielded inclination (i), remanence (r_n), and susceptibility (k).

Some samples were checked in the Institute for Geophysics of the University of Göttingen, in collaboration with Mr. Fromm, to whom I would like to express my gratitude at this time. We used a fluxgate magnetometer and an astatic magnetometer and found the results in agreement. The demagnetization in the a.c. field was also carried out at this Institute; thermal demagnetization was done with a large number of specimens in our own laboratory. The measurements of single specimens which were cut off from large samples showed negligible scatter, so that we may consider the values obtained for the large samples as correct.

The demagnetization has shown that tuff, tuffite, and laterite contain a soft component [Schenk, 1968], whereas the magnetization of the basalts always is hard and stable (see Table 1). In the case /362
of the basalts we found to our surprise that samples that had a reverse magnetization and formed a closed series of identical inclination with continuously increasing depth yield a scatter after demagnetization which, in a graphical representation, shows up as an arc and might even reach the range of normal magnetization (Figure 4). This is a sign of a magnetization reversal. In most

TABLE 1. DRILLING NUMBER 31. RAINROD. THERMAL DEMAGNETIZATION AT 220 °C

Sample no.	Rock	Depth (m)	Inclination before	Inclination after	J_{rn} before	J_{rn} after
			heating			
4	Tholeite	96,30	48	45	0,71	0,48
5		96,50	49	48	0,75	0,74
6		96,70	47	56	0,86	0,82
7		96,90	45	52	0,81	0,72
8	Alkaline basalt	131,50	51	70	4,65	5,50
9		136,30	56	75	3,98	3,30
10		134,90	60	68	3,33	5,00
11		135,40	73	77	4,47	3,55
12	Alkaline basalt	290,20	−40	73	2,72	13,30
13		290,30	−15	70	3,90	10,20
14		290,36	9	−67	3,85	8,44
15		290,90	6	−64	3,03	6,00
16	Tholeite	261,50	−90	30	1,03	0,30
17		261,60	−61	11	1,09	0,62
18		261,70	−66	69	1,22	1,62
19		261,90	−65	52	1,18	0,62

cases we found inclinations after demagnetization that were only a little less than the inclinations prior to the demagnetization step. In no case was the scatter of the inclinations reduced to zero; instead, their regularity was enhanced (Table 1). These results were verified by means of specimens that had been cut off with orientation from large samples.

The scatter of the measured values from the samples from one layer has been noted in practically all studies. Even if maximum accuracy is achieved, there remains some subjective and sytematic measuring errors. Their elimination is securely achieved by statistical methods. These methods have been used previously to remove even larger deviations as they have appeared in the case of measurements on the basis of samples from the same layer or geological unit. Our study was aimed at finding out whether it is permissible to average over such larger scatters, or whether this procedure is not permissible.

In order to show the basic importance of the method, we quote the results of various authors. For instance, Angenheister (1968) found an average inclination of 57° and -59.8°, Turkowski (1963) 64° and -70°, Nairn (1961, 1962) 43° and 63°, Schult (1963) 66.63° and -63°. By contrast, the averaging of the inclinations from the about 5000 core samples of the Western Vogelsberg yields only about 55° (see Table 2, Figure 2). /363

TABLE 2. FREQUENCY OF INCLINATIONS AMONG 4107 CORE DRILLING SAMPLES, OBTAINED FROM 27 DRILLINGS IN THE WESTERN PART OF THE VOGESLBERG.
(The sign of the inclination is disregarded)

Inclination in degree (Class)	Number of samples	Frequency in %	%	
0—5	53	1,29		
6—10	70	1,70		
11—15	74	1,80		
16—20	68	1,66		
21—25	78	1,89	32,89	
26—30	118	2,87		
31—35	120	2,92		
36—40	145	3,53		
41—45	230	5,60		
46—50	395	9,63		
51—55	570	13,89	27,50	
56—60	559	13,61		
61—65	407	9,91	19,11	73,33
66—70	378	9,20		
71—75	366	8,91	17,09	
76—80	336	8,18		
81—85	121	2,95	3,41	
86—90	19	0,46		
	4107	100,00	100,00	

The Geology of the Area of Our Study

The samples for the paleomagnetic measurements were taken from basalt effusion and intrusion bodies in the Western part of the paleovolcano Vogelsberg (Figure 1). The paleovolcano originated in the miocene in the Hessische Senke on one of the large terrestrial N-S continental geofractures. The central volcano appeared at the crossing of the NE-SW and NW-SE old geofractures while crossing

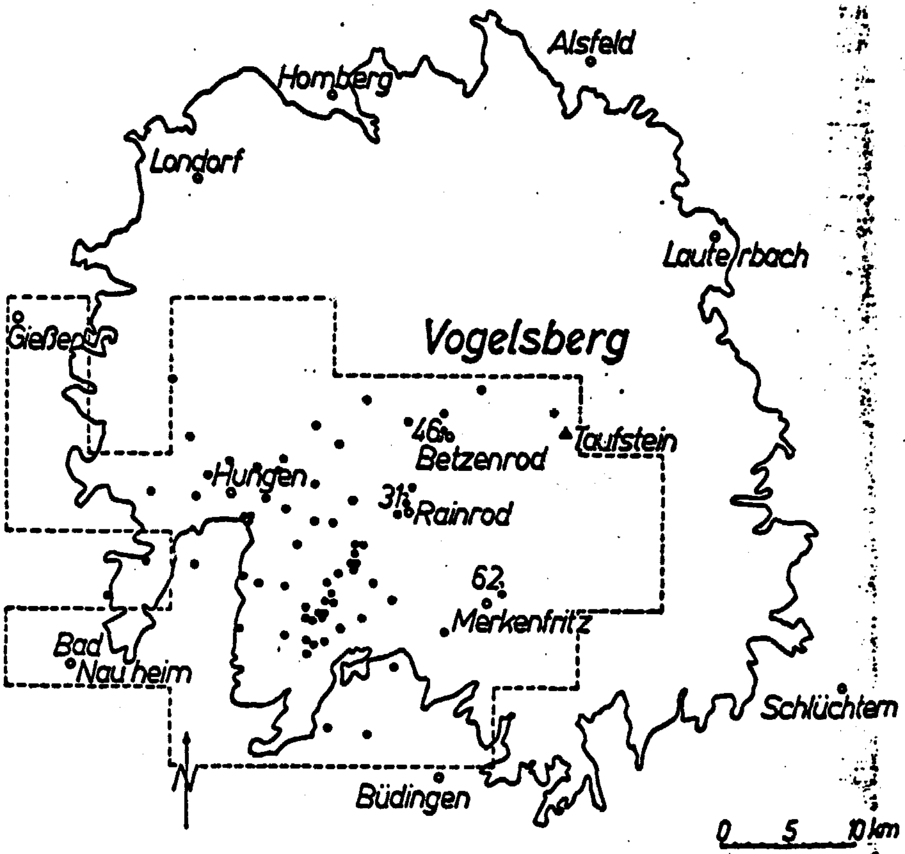

Figure 1. Map showing the limits of the continuous volcanic cover, the recorded geomagnetic field, and the location of the core drillings that were used for the paleomagnetic measurements.

the N-S fracture zone which is the continuation of the Rheingraben [Rhine river depression].

The erosion during the pleistocene period caused the volcanic mountain whose form was almost completely reduced to the core during the pliocene [see Schenk, 1968] to appear over a height of almost 700 m between peak and base area. Some particularly deep drillings yield additional data for another 322 m of the central portion of the volcano between the locations Schotten and Rainrod. As a result, /366 it was possible to obtain, on 38 maps with a scale of 1:10,000, making use of geological maps and measurements of the geomagnetic field, and covering the Western rim of the volcano toward the Taunus

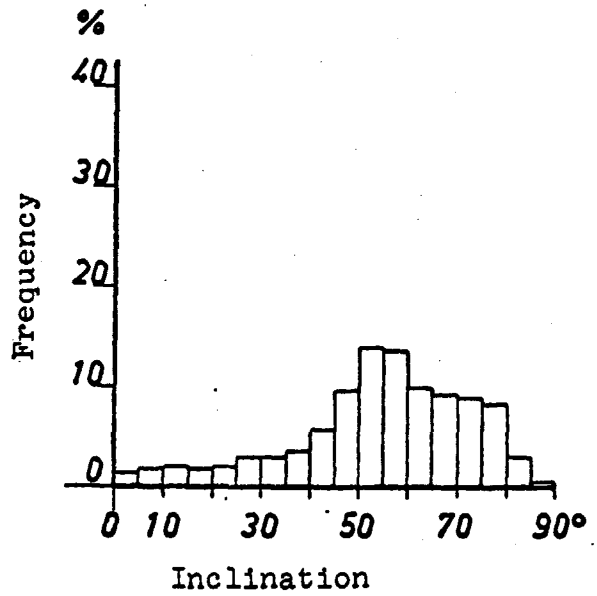

Figure 2. Histogram of the more than 4100 samples from 27 core drillings with the measured paleomagnetic inclination angle.

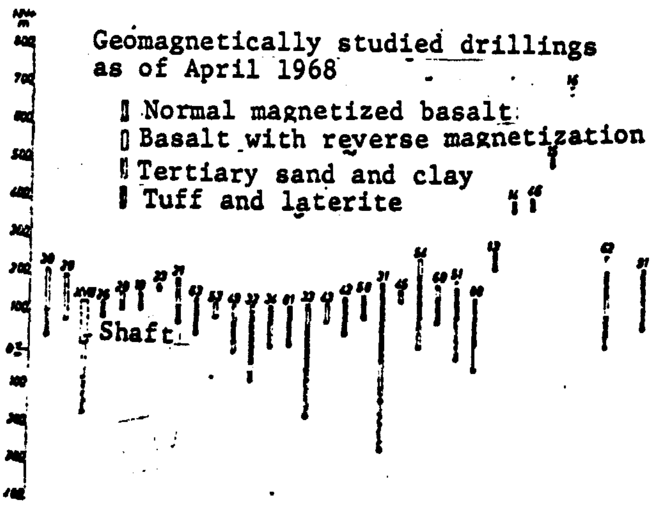

Figure 3. Normal and inverse magnetization of the core samples from 31 drillings in the Western part of the Vogelsberg

area all the way to the central portion (the radius of the paleovolcano was 30 km), a good impression of its structure, containing tuffites, tuff, with lateritic floors, basalt effusion as well as horizontal and vertical intrusion bodies [Schenk, 1968].

The first deposits were tuffites containing lime. They filled the depression of the ocean in the aquitaneous period between the Schiefergebirge and the central portion of the Vogelsberg. On the high shoulder of the depression, that is, the Eastern slope of the volcano, tuff was deposited. The lava flow in the late aquitan and burdigal periods consisted of tholeite which has been described as "trappbasalt" in the literature [Schottler, 1937]; the individual layers are usually separated by thin layers of tuff. Alkaline basalt deposits already started in the burdigal and helvet periods. Also present were alkaline basalts in the torton and sarmat periods as evidenced by the fauna. The volcanic activity probably terminated in the late upper miocene [Schenk, 1968] with deposits of highly basic melts, that is, basanites [Schottler, 1937]. It is not yet clear whether this sequence which has been disturbed and complicated significantly by horizontal intrusions (sills, subfusions, [Schenk, 1964]) has covered the entire area uniformly or whether simultaneously different types of lava were deposited. A definitive decision in this respect will probably have to await radiometric dating.

In comparison with recent volcanoes, the paleovolcano Vogelsberg, as many others, confronts us with the difficulty to separate and evaluate the various rock formations in the form of effusion and intrusion bodies in a volcanic base system [Schenk, 1964]. The Vogelsberg rests on the layers of the variegated sandstone and of tertiary (oligocene and aquitaneous) sediments. Several drillings actually reached into this foundation with the result that the study covers the entire height of the volcano (see Figure 3).

The map of Figure 1 shows the location of the drillings and the samples. The boundaries of the area with geomagnetic measurements are indicated. A detailed report with the entire body of results will be published elsewhere. The current paper presents selected examples for the distribution of the inclination in the various basalt layers. The number of these examples could be increased easily; they are certainly not special cases.

Drilling 31, Rainrod I

Thermal demagnetization at 220°C
- • Before heating
- + After heating

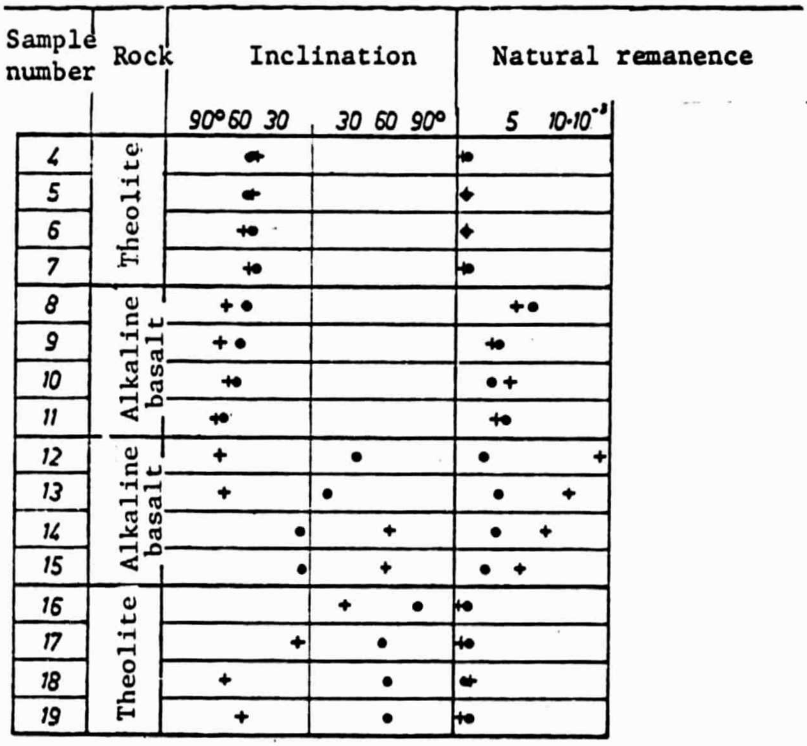

Figure 4. Effect of thermal demagnetization at 220°C. 19 core samples from drilling 31, Rainrod. Four highly complete data sets.

The Global Picture of the Distribution of the Magnetization in the Vertical Direction

The Paleomagnetic Structure of Drilling 62: Merkenfritz

Drilling 62 will be used to show a typical vertical distribution of the magnetic parameters through the profile of the volcano. This drilling is in Merkenfritz (see Figure 5). The graphical representation of the inclination (i), the amount of natural remanence (J_{rn}), the susceptibility (k), and the Königsberger factor (Q) shows three large basalt units below almost 50 m of top layer. The /369 sign of the inclination varies. The upper complex reaches down from about 50 m to almost 110 m. There is a central complex with inverse

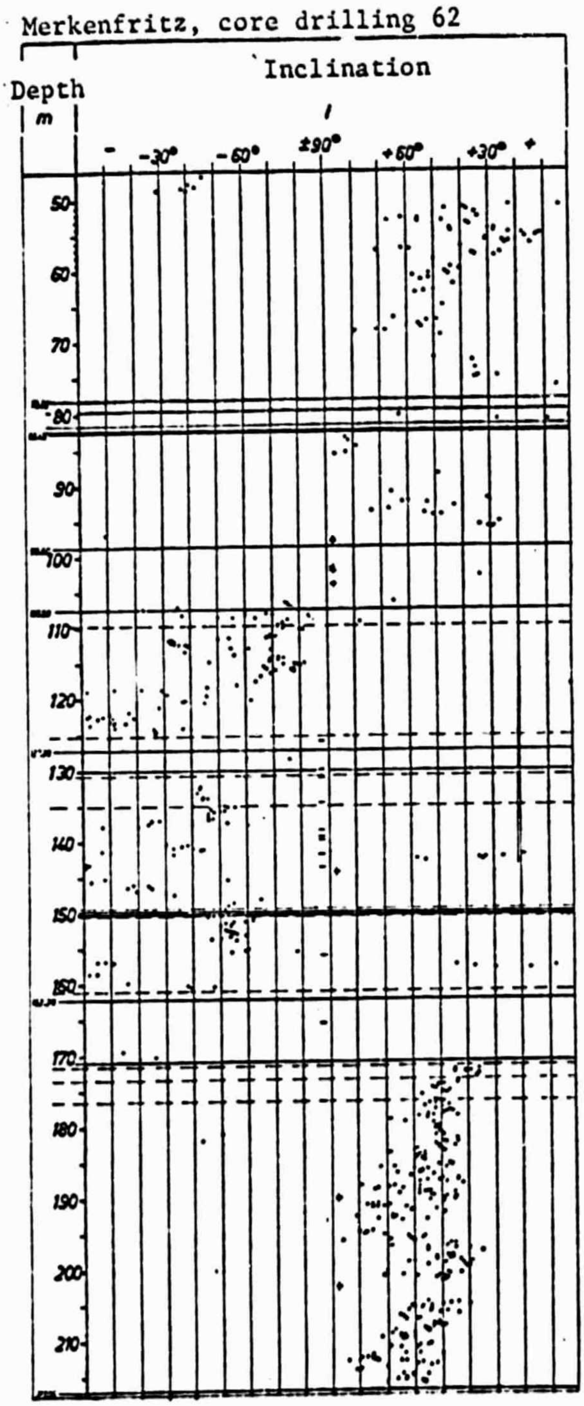

Figure 5. Graphic representation of the inclination in the basalt from drilling 62 near Merkenfritz. Western part of the Vogelsberg (also see Figure 16, p. 25).

magnetization down to about 170 m. Finally, the lower complex with normal magnetization reaches to the lower boundary of the basalt at a depth of about 220 m. The three complexes have almost identical thickness (about 50 - 60 m). The structuring is obvious from the sign change of the inclination and the small values of the inclination in the boundary layers where the remanence is large. The volume susceptibility in the boundary layers is significantly reduced by comparison with the interior parts of the complexes. Also large is the Königsberger factor in the boundary layers. On the basis of these characteristic variations of the paleomagnetic data, substructures of the major complexes can be defined, and they correspond exactly to the geological and petrographical data.

The Geological Profile

Down to about 10 m there is a surface layer from late tertiary. Then follow decayed tuff with clay, tuffite, and basalt rocks, and a multicolored detritus which is formed from erosion products; this layer stretches to about 20 m. Below, down to about 50 m, we have fine and coarse tuff with basalt inclusions, breccias, and laterite. It is not clear whether in the range between 39 m and 48 m, or roughly 50 m, there is a strongly eroded intrusion breccia or debris from the surrounding volcanic material.

At a depth of about 50 m, a layer of compact, blue-grey alkaline basalt starts, with fine grains and a lot of olivine. There are layers in this unit, down to 78 m depth, which are compact, practically free of bubbles, and with little distortions. We shall call in the following the subunits of a major unit, consisting of effusive and intrusive basalt, the "layers" of this unit. A second similarly compact layer occupies the range between 82.25 and 97.50 m. It is separated from the first layer by tuff and soft-coal sediments. At its base, compact molten slags are present. They are deposited on reddish, lateritically eroded and on yellow-grey tuff which reaches down to 107.50 m.

The central complex starts at a depth of about 108 m. It consists of compact alkaline basalt of a dark blue-black color, practically free of bubbles and distortions. It is very rich in olivine. Its lower boundary is at 161 m; below are about 10 m of breccias and grey-green tuffs.

The central complex consists of an upper, central, and lower part. These three parts are separated at the depths of 127.00, 149.00 and 162.00 m, respectively, by layers of tuff with the corresponding thickness of 10, 8, and 10 m. Further subdivisions are easily defined by means of breccias and bubble zones. The entire complex is bounded above and below by large breccias which consist of a mixture of compact, dense basalt, tuff, laterite, and montmorillonite. It is suggestive to identify the complex with intrusion; however, this statement requires further specific studies.

The basalt in the lower part (between 171.5 and 217.0 m) is at first grey (uppermost 5 m), largely decayed, oxidized with a reddish color and spotted, with many large small bubbles with zeoliths, often foamy and porous and rich in slags. Below this layer, however, /370 it is again of a black-blue color, massive, compact, with few distortions. It sits on a 4 m-base of laterite and tuffite on top of aqueteneous clays and sand and clay from the oligocene.

There is tholeite between 171.5 and 177.0 m. The basalt down to the base is highly alkaline with Sonnenbrenner spots. It is magmetized in the normal mode as is the entire complex. No layers can be defined here by means of bubble zones or breccia deposits. However, there are indications of flow patterns. This basalt deposit, the deepest one, looks much more as an intrusion or subfusion than an effusion structure. However, the question is not solved yet.

Inclination

The large scatter of the values in the graphic representation of the inclination data of Figure 5 is immediately obvious. The values scatter uniformly across the entire scale between 0 and 90°, both in the range of normal and of inverse magnetization. Only in the lower reaches do values in the intermediate range between 30 and 60° take over.

The statistical investigation shows the scatter width between 0 and 90° even more clearly. Let us begin by discussing the global picture disregarding the signs (Table 3, Figure 9), since we have not found any basic differences in the relationships among the magnetic /371 parameters between the various units. The relative frequencies of of the small angles (< 45°) and of the large angles (> 60°) outside of the range of dominance reaches 7% in the various classes, even 11.3% in the upper complex, 7% in the central, and 9 and 10% in the lower complex. The sum of these frequencies of the small angles reaches 15% in the upper complex (0 - 25°), 53% for the range 0 - 45°; the corresponding figures for the central and lower complexes are about 48 and 13%. The frequencies of the large angles are almost 20%, more than 23%, and almost 30% in the upper central and lower complexes, respectively. By contrast, we find for the dominant angles in the three classes between 45° and 60° the following percentages: 30, 60, and again 60% in the upper central and lower complex, respectively. The significant class is between 51 and 55°.

TABLE 3. FREQUENCY DISTRIBUTION OF THE INCLINATION IN THE SECTION BETWEEN 48 AND 217 m OF DRILLING 62, MERKENFRITZ
The sign has not been taken into account

Inclination in degree Classes	Number of samples	Frequencies in %	
0–5	14	2,42	
6–10	13	2,24	
11–15	11	1,90	
16–20	12	2,07	
21–25	11	2,24	
26–30	22	3,80	
31–35	25	4,32	
36–40	34	5,88	
41–45	43	7,43	63,98
46–50	86	14,87	
51–55	100	17,30	
56–60	66	11,41	
61–65	40	6,92	
66–70	35	6,05	
71–75	34	5,88	
76–80	23	3,97	
81–85	7	1,21	
86–90	2	0,34	

The frequency diagram of the upper complex (Figure 6) shows, with the significance of the data only marginally different, the classes with 26 - 30 - 35°, and 46 - 50° as prominent. There is no good reason to disregard the group with the small inclination angles, and there is neither one to prefer the group with 46 - 50°, or to follow either one of these paths singly. This is true on the basis of statistics, the representation with the aid of depths, and the geological differentiation (Figure 5).

The central complex does not show a markedly increased significance (51 - 55°) with respect to the upper complex. According to the figure, the class with 46 - 50° should actually be included. This would result in an average of 50°.(Figure 7).

The classes between 46 and 60° are dominant in the lower complex. The significant (17%) inclination angle here is 53° (Figure 8).

Drilling 62 Merkenfritz
Section 51.07 to 106.55 m

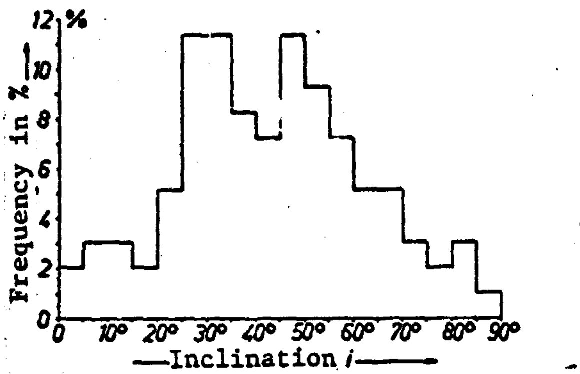

Figure 6. Histogram for the inclination data from the core samples of the section between 51.0 and 106.5 m. Drilling 62 near Merkenfritz.

Drilling 62 Merkenfritz
Section 107.30 to 170.65 m

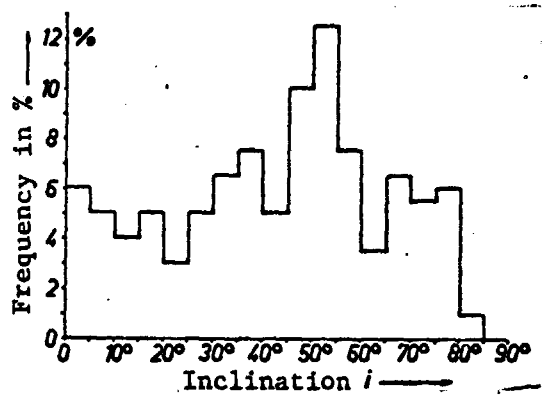

Figure 7. Histogram for the inclination data from the core samples of the section between 107.3 and 170.6 m. Drilling 62 near Merkenfritz.

Drilling 62 Merkenfritz
Section 172.30 to 216.66 m

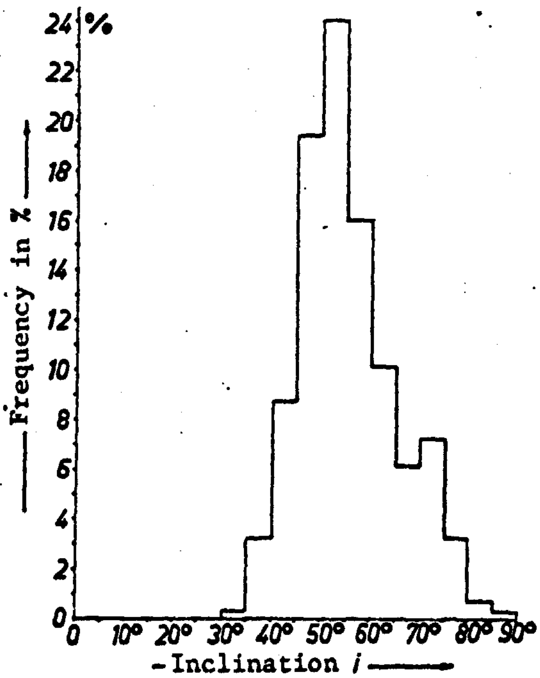

Figure 8. Histogram for the inclination data from the core samples fo the section between 172.3 and 216.6 m. Drilling 62 near Merkenfritz

Drilling 62 Merkenfritz

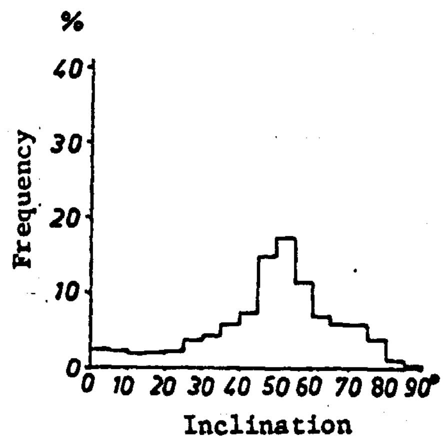

Figure 9. Histogram for the inclination data from all core samples of drilling 62 near Merkenfritz

The global picture shown in Figure 9 corresponds to these partial analyses. We find significance for the class 45 - 60°. This would result in an average inclination angle of 52 - 53° for the entire basalt profile of the Merkenfritz drilling. We have already noted that this value is significantly different from data on the inclination of the basalts of the Vogelsberg (55 - 70°) as published by Angenheister (1956), Turkowsky (1963) and Nairn (1961 and 1962), and by Schult (1963). The difference might be due to differences in age; however, there is no geological reason for this assumption. /373

If one takes a closer look at the representation which relates the inclination to depth, additional doubts as to the adequacy of the statistical method arise. It is clear that the particularly small angles occur at the boundary zones of the volcanic units. This is, for instance, especially obvious at the base and ceiling areas of the lower complex. Also, the corresponding areas of the central and upper complex show a similar behavior. The individual values show a large scatter; but even so, the small angles, according to the averages of the scatter, belong again to the geological boundary areas. That is, they characterize the base and ceiling zones of the subunits we have described in the discussion of the profile. By contrast, the respective central parts of a unit are characterized by the large and maximum angles. Other drillings show the same behavior. Finally, the statements are confirmed by the analysis of small areas, that is, of subunits which together make up the complexes, as well as the distribution of remanence, susceptibility, and Königsberger factor.

Remanence, Susceptibility, and Königsberger Factor

The investigations of Jaeger and Joplin (1955) and of Bull, Irving, and Willis (1962) have shown that the susceptibility and, correspondingly, the remanence change as a function of the distance from the upper boundary of a volcanic body. The same observation was made as far as the decrease of the remanence vs. depth is concerned in the case of the Vogelsberg basalts [Turkowsky, 1963; Angenheister and Turkowsky, 1964]. Hatherton (1954) even found a close correlation between the magnetization and layering of ignimbrites. The complete measurements of the core drilling samples from the Vogelsberg show the same problematic behavior of the basalts. /374

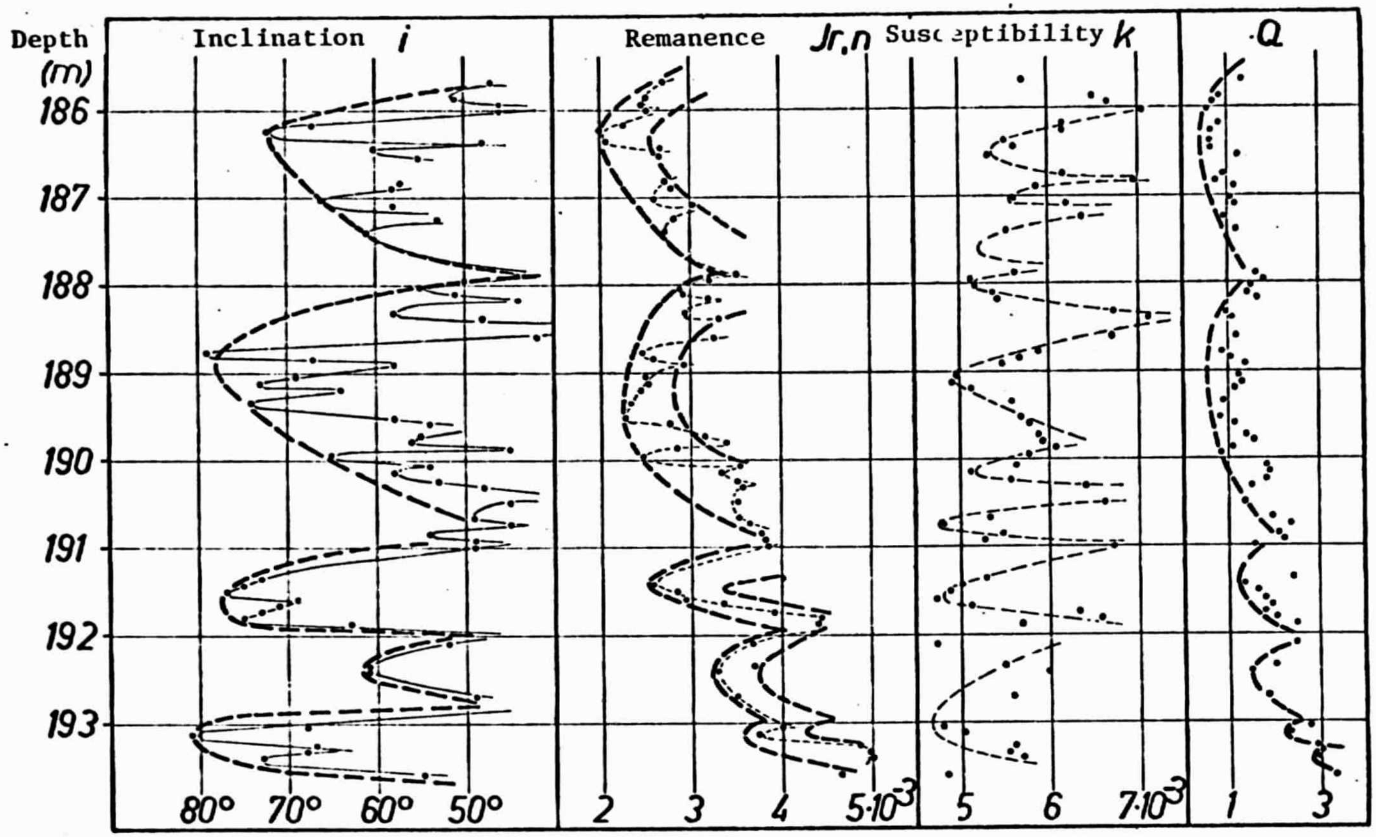

Figure 10. Distribution of inclination, remanence, susceptibility, and Konigsberger factor Q for a nearly complete set of data from the core samples in the section 185.6 to 193.6 m of the core drilling 62 near Merkenfritz

This is exemplified by Drilling 62, Merkenfritz, Section 185.6 to 193.0 m (Figure 10). Down to almost the smallest details we see that the remanence is inversely correlated to the inclination. If the inclination increases, the remanence decreases. The behavior of the Königsberger factor is parallel to that of the remanence. By contrast, it appears that the susceptibility is the smallest in the boundary areas (see Figure 16).

It is thus possible to talk about strong correlations. That is, the values of the magnetization represent very accurately the layer or lamellar structure of the volcanic strata.

The Inclination in the Compact Basalt Units

The graphic representation with the depth dependence of the inclination indicates that, for instance, the section between 185 and 191 m (Figure 10) belongs, according to the accpeted rules, to an area within the complex that yields a statistically clearly acceptable average (see Figure 5). The average is expected, so is the significance between 50 and 60°, and one is inclined to discard the extreme values of about 70°. Indeed, the statistics of Figure 11 show significance for the lower complex we have previously computed (Figure 8).

The basalt in this section does not show macroscopically clear boundaries of subunits by means of bubble and slag zones. However, there is an indication of flow patterns. The section is compact and barely distorted; thus, it was possible to take 58 cylindrical samples of a diameter of 11.3 cm and 11.3 cm height each. This section of 600 cm thus cannot yield more samples; it is essentially completely covered.

The scatter of the inclinations (Figure 10) is now between 42 and 79°. In the uppermost section of 40 cm, we find inclinations of 46, 47, and 51°. The next 25 cm show an increase of the inclination to 72°; at a depth of 15 cm below, the inclination is again at 48°.

Drilling 62 Merkenfritz
Section 185.6 to 193.6 m

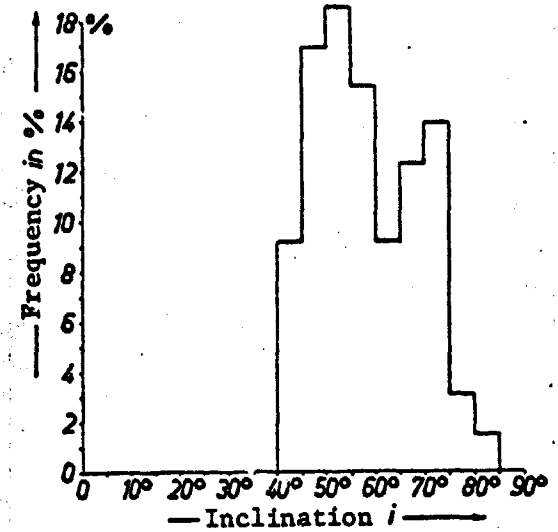

Figure 11. Histogram of the inclinations measured for the core samples of the section 185.6 to 193.6 m of drilling 62 near Merkenfrtiz

Drilling 62 Merkenfritz

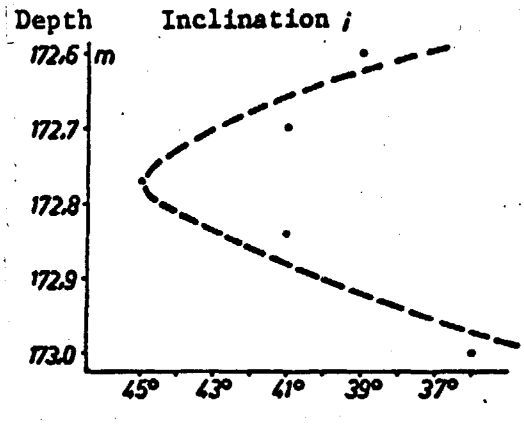

Figure 12. Graphic representation of the inclinations measured for the core samples from the section between 172.6 to 173.0 m of Drilling 62 near Merkenfritz

The next 2 m in depth show, in the same manner as before, "lamelles" of a thickness between 20 and 40 cm and inclinations in the range between 66 and 44°. It is easy to draw an average line through these measurements; one then obtains an arc which starts at about 185.8 m with an inclination of about 48°, reaches a maximum of about 70° at about 186.4 m, terminating again at about 47° at a depth of 187.9 m. At this point, another mean arc starts, reaching a maximum inclination of about 75° at 190.7 m, terminating again at 45° and joining the beginning of yet another arc. In this lower portion, the basalt clearly shows a lamellar flow pattern.

This free-hand construction of average lines results in two units in the compact basalt which on the outside does not show any structuring. Each of these units is about 2.5 - 3 m in depth, shows very small inclinations in the boundary layers, and very large values of the inclination in the center and the upper third of the depth range. There is a third arc-shaped unit between 191.0 and 192.5 m, and a fourth between 192.5 and 193.6. It also appears as if these subunits contain even smaller units. /377

In fact, the continuous sets of samples, covering only 25-40 cm, and showing more or less clearly flow structures, indicate a continuous regular change of the inclination between small and large angles. In the section between 172.60 and 173.00 m (Figure 12, but also Figure 5), the inclination varies between 39° at the upper edge, 45° in the center, and 36° at the base. In the section between 191.30 and 191.90 cm (Figure 10), we have two such lamelles over the depth range of 60 cm. However, here the inclination varies from 73° to 77° and back to 63°. The next sample, farther down at 192.10 m, shows only 52°, and the next lamelle above, only 49° (Figure 5).

These results require the acceptance of the back-and-forth of the scatter as a variation which is tied to the lamellar flow pattern even in ranges, where there are no continuous measurements. As a result, we conclude that each basalt layer which appears as a unit consists of a multitude of lamelles depicted by their inclinations.

Drilling 31 (Rainrod) cut through effusive as well as intrusive basalts. Intrusion breccias at the upper and lower boundaries differ from the flow slags and often mark intrusive layers, while the central parts are characterized by compact bubble-free basalt with flow patterns. The variation of the inclination in this pattern appears well established. In the slope and horizontal end zones appear (see the section between 141 and 145 m, Figure 13) the smallest angles (20 - 50°), while the central portion shows the largest angle with more than 60°.

If the distance between single specimens is small in a volcanic unit, the flow pattern becomes particularly well recognized. At the same time, the scatter of the inclinations increases.

The section between 59 and 73 m of the drilling 31 (Rainrod) given in Figure 14 barely shows the effusion slags. Here, liquid lava has filled all spaces and crevices. However, when the wetted

Drilling 31, Rainrod I

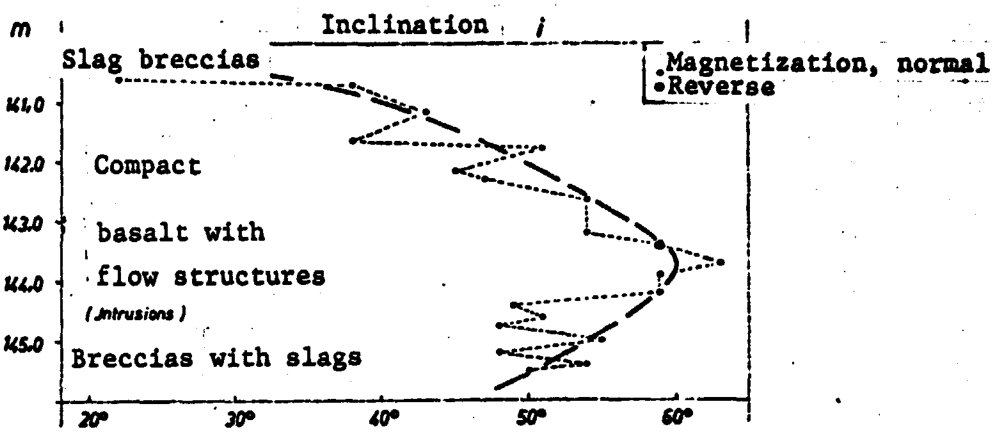

Figure 13. Representation of the geological profile and of the inclinations measured from the core samples obtained in the section between 140.5 and 145.5 m of drilling 31, near Rainrod

Drilling 31, Rainrod I

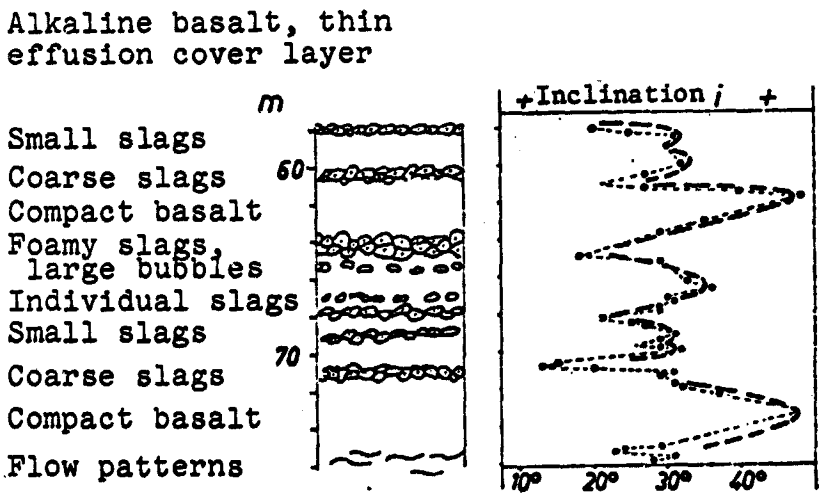

Figure 14. Geological profile and distribution of inclinations in the section between 59.0 and 73.0 m of the core drilling 31 near Rainrod

rock dried out, the boundaries of the single slag pieces became very distinct. Again we find a correlation between the inclination and the flow structure and the boundary layers. In the slag layer and immediately above and below we find the smallest values of the inclination, while the values are largest in the center portion. Figure 13 shows that this behavior is not restricted to alkaline basalts, but is also found with tholeite. Even if the data sets have large gaps, as is the case with drilling 46, Betzenrod II, /379 (Figure 15), with the highly distorted, broken, and slag-containing layers of the lava flow of Vockenhain [see Schottler, 1937 and 1924], it is easy to recognize that the inclination in the boundary layers even of large units is smaller than that in the center portions. Hence it is not clear in the case of measurements with gaps, whether the maximum, minimum, or average inclination has been found. The behavior appears the more regular, the smaller the experimental data set. The result of such an investigation similarly is much more questionable, or at least, uncertain.

<u>The Evaluation of the Paleo-Magnetic Measurements</u>

It is by now obvious that the extremely large scatter of the inclinations in massive volcanic units, as we have found in the case of the drilling near Merkenfritz, as well as the variability of remanence and susceptibility /380 show regularity and are caused by a multitude of thin laminar flow units with the inclination angle decreasing in the boundary zones. This requires to take into account the often large scatter that had been noted by all authors; it should not be eliminated. The separation of samples and the recording and averaging of specimens may secure the result, but it does not yield representative values for a volcanic unit.

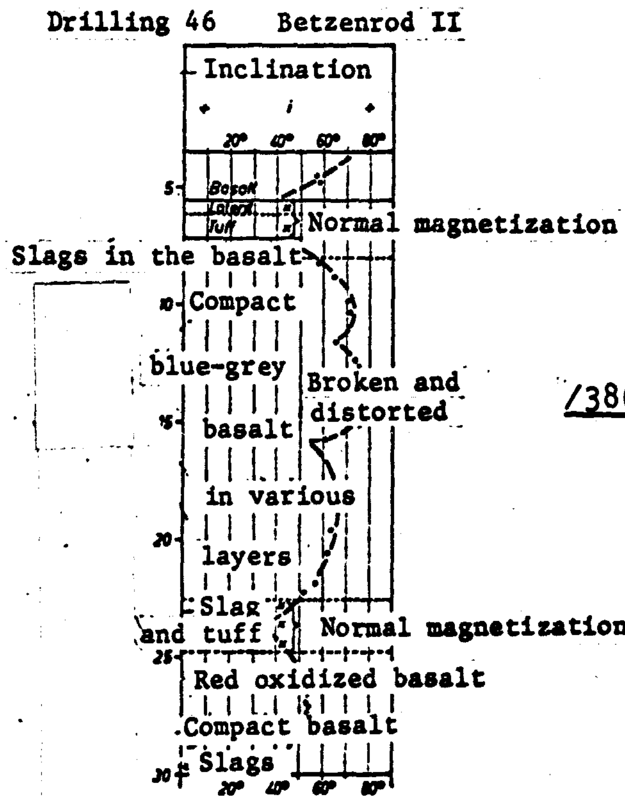

Figure 15. The distribution of the inclination in the basalt layers of the core drilling 46 near Betzenrod

The "decrease of the angle" decreases with increasing distance from the boundary layers. This is true for single lava lamelles as well as for their compounds in the form of a flow unit of a thickness of some decimeters. Such a flow unit, in turn, may be a subdivision of a larger unit with a thickness of several meters, and of a yet larger unit or an intrusion or subfusion body (sill). The angles are extremely small in the boundary zones of such super-units (see Figures 5 and 10). The largest values are always limited to, roughly, the center portions. It is important to realize that in smaller units even in their central portions the largest angles (with respect to the entire complex) may not be reached. Thus, the small and intermediate angles contribute significantly to the frequency of average values.

We have related the frequency of small and intermediate angles to the flow patterns on a purely phenomenological basis; this relation must also be present in the statistical data. The number of boundary layers and zones is twice as large as the number of flow units. Thus, the frequency of small and intermediate angles is a priori twice as large as the number of largest inclination angles. As a result, we find that the significant inclination of 55 - 60° (30% according to the frequency analysis; see Figure 9) is certainly not representative.

In order to obtain equal weights for the statistical elements, one would have to divide the frequency values of the small and intermediate angles by the number of units that enter the measurements. The result, however, can be obtained in a simpler manner by considering the group of maximum inclination angles, possibly discarding improbably extreme values, and then averaging arithmetically.

The clearest situation is presented by the graphic representation of the spatial and geomagnetic situation. An inclination angle of 75° (Figure 10) in this manner represents the volcanic unit between 185 and 191 m ' the drilling Merkenfritz in its magnetization direction better than a statistical procedure which contains all recordings. It is also clear from our analysis that a sample even from the central portion of a volcanite plate does not necessarily yield a representative value for the direction of the magnetization; after all, it may happen that the sample belongs to a boundary area between two flow zones of the same volcanic event. It is then necessary to investigate the entire volcanic unit. According to our experience, the same statement holds for the vertical intrusion bodies whose boundary layers show significant departures. If on the basis of the diagram for the drilling near Merkenfritz (Figure 5), one attempts to find the representative inclination of the single units, the following table ensues:

from	50— 78 m ~ + 70°
	80—100 m ~ + 80°
	100—125 m ~ + 80°
	130—160 m ~ − 60°
	170—185 m ~ + 60°
	185—200 m ~ + 80°
	200—205 m ~ + 70°
	205—210 m ~ + 65°
	210—215 m ~ + 70°
	215—220 m ~ + 80°

Space does not permit to discuss in detail the interpretation of these data; it would also be necessary to discuss the reasons why the small angles are not representative. These things will be evaluated elsewhere.

When volcanoes were active in the area of the drilling near Merkenfritz, the inclination in our geographical latitude should then have been larger than 60° and smaller than 80°, but certainly not 55° as follows from the usual statistical treatment of all values. The above quoted averages given by Angenheister, Nairn, Schult, Turkowsky, and others, too, are too small, not representative, and are just unsubstantiated statistical averages.

Merkenfritz, core drilling 62

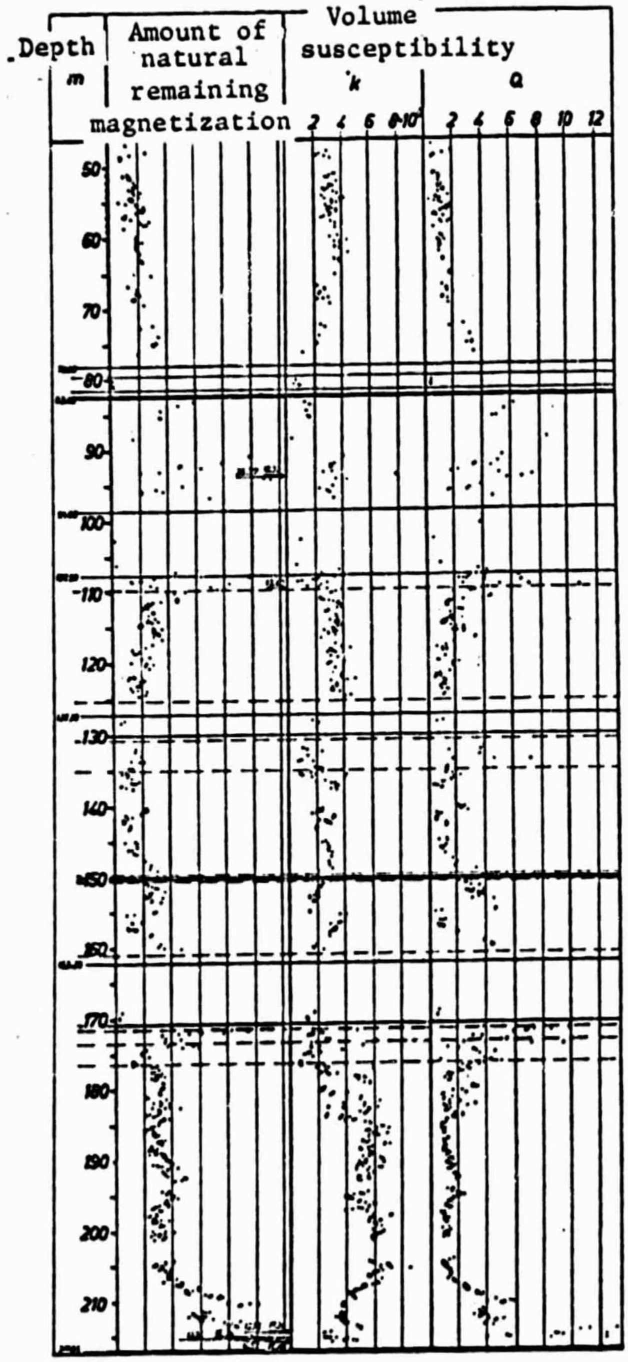

Figure 16. Graphical representation of remanence, susceptibility, and Königsberger factor in the basalts of drilling 62 near Merkenfritz in the Western portion of the Vogelsberg.

The position of the geomagnetic pole can only be determined if the declination is known. Drilling samples, as is well known, do not yield the declination. Measurements along a quarry wall which runs for about 100 m E to W on the Alten Berg near Lauterbach, carried out upon my suggestion by Mr. Turkowsky (1963), now show that the declination, too, presents a true geologically and petrographically caused scatter. This scatter appears both in the horizontal and vertical directions. The scatter covers the range between 16 and 22° [Turkowsky, 1963]. Angenheister's recordings show even larger differences (55 - 65°), similarly those of Nairn. The discrepancies should then be as meaningful for the interpretation as the scatter of the inclination values.

In view of our results, it is clear that samples taken at arbitrary locations in basalt layers are not useful for the determination of the geomagnetic poles on the basis of paleomagnetic measurements. Most of the determinations available to date, are, presumably, based on such faulty sample-taking. As a consequence, one might ...

question previous results of paleomagnetics for the determination of the positions of the poles. We do not have to explain in detail that at the same time the geotectonic evaluation of the available paleomagnetic data, as they are used, for instance, for verification of the theory of continental drift, is not based on reliable data either.

In view of our results it appears to be necessary at this time to work out the basis of reliable paleomagnetic data; after all, the connection between the scatter in the inclination and, possibly, declination and the laminar flow patterns is similarly questionable. Even with the clear phenomenological relationships no causality has been shown. It is obviously difficult to argue on the basis of an organization of the magnetite, since these tiny crystals belong to the regular system and have no reason for longitudinal stretching. It is conceivable that magnetic inhomogeneities in the basalt are the reason. It is also to be investigated whether the regular variability of the paleomagnetic parameters is due to a refraction of the force lines, or whether we have the striction phenomenon [see Irving, 1964]. There are then micromagnetic and petrographic problems to be solved before paleomagnetic conclusions can be drawn. /383

Summary

Core drillings in the basalt of the paleovolcano Vogelsberg in Hessen made it possible to obtain cylindrical samples for continuous data sets covering many decimeters and meters of effusion and subfusion (intrusion) units. Measured were inclination (i), remanence (J_{rn}), susceptibility (k), and Königsberger factor (Q).

The following results were obtained:

I. 1) The inclination may vary in a large unit of basalt across the entire scale from 0 to 90°, both in the case of normal and inverse magnetization. In the case of smaller subunits, lamelles of a thickness of up to 30 cm, the variation is

limited to smaller ranges which, too, are variable. The angles are largest in the center portions of the respective units, smallest in the boundary areas. Even if the global picture of a large, continuously recorded unit recognizes small scatters as irrelevant, we find larger scatters which are dominant.

2) The remanence J_{rn}, too, present significant variability. Absolute largest is this variability in the boundary zones of large units; the relative variability is largest in the boundary layers of the subunits. Thus, the variations are inverse to those of the inclination. Usually the remanence is less than 4×10^{-3} Gauss. Ten times as large values are observed in the boundary layers.

3) The susceptibility (k), too, shows variations which go parallel to those of the inclination: they increase and decrease together.

4) The variability of the Königsberger factor, too, is tied to the geometric and petrographic structures of the volcanic units. The depth variation equals that of the remanence with the relationships with the volcanic units often being even more pronounced.

II. 1) The variability of the parameters depends on the distance from the center of the magnetic basalt layer and the axis of the corresponding large or small unit of the volcanite. It often mirrors the lamellar flow pattern down to minute details. One might arrive at a reasonable geometric relation by equating half the depth of the unit with unity. /384

2) This regularity makes it possible to classify volcanite complexes more rapidly and with a finer grid than is possible on the basis of geological and petrographic methods.

III. 1) The commonly applied statistical method which uses the recordings of all samples results in average values which may be significant for a specific small section of the volcanite. They are, however, not necessarily representative for any unit, large or small.

2) Most authors do not give sufficiently precise data with respect to the location of the recorded samples within the volcanite unit; in many instances, such data cannot even be given. Hence, previously published interpretations of paleomagnetic data do not have a sound basis.

IV. We expect to find representative values of inclination and, probably, declination for paleomagnetic applications in the center portion of subunits in the middle of large center units. Such representative values are never obtained from boundary layers.

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