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MAGNETOSTRATIGRAPHY OF KAMCHATKAN HOLOCENE FORMATIONS OF SOIL AND PYROCLASTICS

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An account is given of magnetostratigraphic studies of Kamchatkan Holocene formations: the cover of soil and pyroclastics and the rocks of the cinder cones from the flank eruptions of Klyuchevskoi Volcano. A study was made of seven sections of the soil and pyroclastics and of samples from 17 cinder cones. A detailed account is given of the data processing procedure. Consideration is given to the reasons for the established incompleteness of the paleomagnetic record in the sections and it is demonstrated that adequately detailed reconstruction of the history of the geomagnetic field is possible only provided that a study is made of a series of parallel sections. The trajectory of the geomagnetic field vector over the last 4000 years is determined on the basis of the material on radiocarbon datings. Seven cycles of paleosecular variations are distinguished in the age range investigated; each of these cycles has individual features by which they can be recognised and used for stratigraphic correlation. The features taken were the direction of rotation of the vector, the shape and size of its loops, and the length of the cycles. Correlation of the sections based on paleomagnetic data was found to be in good agreement with the tephrostratigraphic correlation and enabled corrections to be made to the age of some horizons, including the archeological layers of the primitive settlement at Zhupanovo and the cinder cones. The metachronous magnetization present in some tephra layers was found to be an obstacle to any improvement in the accuracy and detail of magnetochronological reconstructions.

Introduction

A study of the history of the geomagnetic field is of interest both for its bearing on the internal structure of the Earth, and for stratigraphy and geochronology. One of the main tasks in both cases is to construct a chronostratigraphically based scale of the variations of the geomagnetic field. This imposes certain requirements on the geological objects used in the construction of such a reference scale. First, the rocks investigated must possess sufficient paleomagnetic stability to retain the direction of the geomagnetic field at the time of formation of the rocks as primary remanent magnetization. Second, there must be paleontological, paleoclimatic or geochronological age correlations for the sections investigated. Third, the sections investigated must exhibit a fairly complete and, if possible, continuous record of the history of the geomagnetic field over the period under consideration.

As regards the Holocene, during which there were no inversions and excursions of the geomagnetic field, the task amounts to no more than a study of the paleosecular variations, the parameters of which are the only basis of paleomagnetic reconstructions for that time.

The research was conducted on the deposits of the Holocene cover of soil and pyroclastics that occurs widely in Kamchatka, and that has previously been shown in [5] to be promising for paleomagnetic research. The cover of soil and pyroclastics may be described as a "layercake", consisting of alternating layers of tephra and buried soils represented by variously humified sandy loams. The thickness of this cover of the foot of active volcanoes is on average 3-5 m, with a maximum thickness of 15-17 m. Periods of intensified volcanic activity are recorded in the cover by the accumulation of tephra - lapilli and bombs of pumice or cinders, coarse ash (volcanic sand and gravel) and fine ash (volcanic dust). Each tephra layer corresponds to a large eruption lasting for between a few hours and a few months, while a series of such layers or a packet of weakly stratified tephra record cycles of volcanic activitylasting tens or hundreds of years. At times when volcanic activity weakens the sandy loam horizons that form contain traces of ash or indistinct ash layers, while true soil horizons begin to form when volcanic manifestations temporarily cease. The formation of layers between ash lasts for periods ranging from tens or hundreds of years to 1000-1500 years for soils up to 15-20 cm thick.

Excellent examples of the cover of soil and pyroclastics are preserved in watershed areas at the foot of volcanoes, where the sequence of deposits is not disturbed by any outwashing, even locally. In such cases they may be regarded as, in a sense, a geological chronicle recording in succession the entire history of the region in the Holocene.

The presence of horizons of buried soils and of buried timber in the sections of soil and pyroclastics makes it possible to obtain quite detailed radiocarbon datings. Up to ten or so ^{14}C dates quite uniformly distributed throughout the section may be obtained in sections in which there are many buried soil horizons. This provides a good basis for paleomagnetic research in deposits the age of which has been reliably established.

Previous analysis [1] of the suitability of the cover rocks for paleomagnetic research has shown them to possess sufficient paleomagnetic stability for determination of the primary remanent magnetization. It has been concluded that such magnetization is created in layers of sandy loam and ash in the course of compaction during the first few months after their formation.

It has been found in the laboratory that atmospheric water percolating through tephra plays an important role in the formation of remnant magnetization.

All the above considerations justified extensive, planned magnetostratigraphic study of the cover of soil and pyroclastics in Kamchatka.

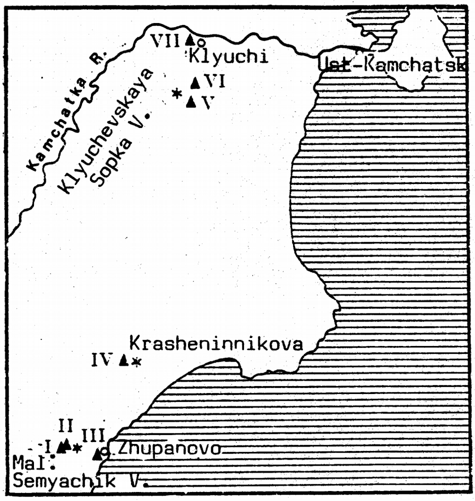

Fig. 1. Position of sections investigated. I - Semyachik-8, II - Semyachik-5, III - Zhupanovo, IV - Krasheninnikova, V - Apakhonchich, VI - Kirgurich, VII - Klyuchi.

Production of a generalized curve.

A total of seven sections were investigated (Fig. 1). The results obtained for two of them in the vicinity of Malyi Semyachik Volcano (Semyachik-5 and Semyachik-8) have already been published [11]. A similar procedure for the collection and initial processing of the data to that described in [11] was used in the other cases. Sampling layers 4-5 cm thick were taken as close together as possible. Between four and eight samples were taken from each layer. Samples were not however taken from deposits of cinders (with rare exceptions) and of coarse-grained volcanic sand (< 1 mm), and areas of soil horizons heavily permeated by a presentday system of plant roots.

All samples were magnetically cleaned either in variable fields of 150 and 300 Oe, or at temperatures of 100 and 200 $^{\circ}$C, maintaining them at these temperatures for 8-12 h in the nonmagnetic space of permalloy screens. Preliminary investigations had shown that such cleaning almost entirely eliminated the secondary viscous magnetization that accounts on average for 50% in the rocks under investigation. The mean direction of stable remanent magnetization and the Fisher parameters of its reliability (α_{95} and K) were calculated for each layer sampled. One direction of the two obtained as a result of the magnetic cleaning of each specimen was included in the averaging so as to minimize the parameters of the spread. This procedure was chosen because it is not only unstable remanent magnetization that is destroyed in each stage of cleaning; the result is also increasingly affected by perturbing factors: (a) the total remanent magnetization is reduced against the background of permanent inductive magnetization, which increases the measurement error in the astatic magnetometer; (b) the viscous magnetization arising in the course of measurement begins to have an effect; (c) the sample may contain large magnetostable inclusions with randomly oriented magnetization. Consequently, there is an optimum depth of cleaning for each sample, the effectiveness of which may be assessed by the clustering density within the layer.

In the next stage of statistical processing the directions of remanent magnetization obtained for each section from two or more adjacent sampling layers were averaged if the directions were similar, i.e. if their circles of confidence (when $P = 0.05$) were appreciably overlapping. This yielded a series of successive directions of stable remanent magnetization for each section, with each direction separated from the adjacent directions by more than the radius of the circle of confidence. Following this processing the data of all the sections were used to plot a composite curve of the variations of the geomagnetic field. We confined ourselves to the last 4000 years[1], for which sufficient material has been assembled.

The whole of this interval and the corresponding parts of the sections were first divided into several parts, using for that purpose ash marker horizons of Shiveluch Volcano: Sh_2 (1000 years), Sh_3 (1400-1500 years), Sh_4 (2000 years) and Sh_5 (2500-2600 years) [6]. These horizons are clearly distinguishable in three of the seven sections investigated, while in the four southern sections (Semyachik-5, Semyachik-8, Zhupanovo, Krasheninnikova) deposits synchronous to them may be established with sufficient accuracy thanks

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[1] Here and subsequently the reference is to the radiocarbon age uncorrected for the variation of radiocarbon concentration in the atmosphere.

to the large number of radiocarbon datings and to the detailed reciprocal tephrostratigraphic correlation [2-4, 7].

Trajectories of the geomagnetic field vector obtained from the sections investigated were compared for each age interval. This comparison revealed appreciable differences in the trajectories in addition to elements of similarity; in some instances the differences complicated correlation of the sections. On more detailed examination of the results obtained it was, however, still possible to solve this problem and to reconstruct the actual trajectory of the geomagnetic field vector in the past. In so doing we were guided by four main rules.

1. All successive directions of stable remanent magnetization obtained from the sections were considered as reflecting actual directions of the Earth's magnetic field. The preliminary analysis of the magnetic stability of the rocks investigated, to which reference has already been made, provided sufficient basis for so doing. The only exception to this rule will be considered below.

2. The stratigraphic sequence of the distinguished directions of residual magnetization observed in each section were equated by us to their chronologic sequence. While conceding, in principle, the possibility of "inversion" of the paleomagnetic record in the sections, we did not accept its reality in any specific case without weighty proof.

3. Irrespective of the apparent lithologic completeness of the sections we conceded the existence of unverifiable gaps in the paleomagnetic record. The existence of such gaps was the cause of the differences referred to above in the form of the vector trajectories in some parts of sections of the same age.

4. In the reconstruction of the composite generalized trajectory of the vector its minimum perimeter was a stipulated requirement.

We took as the input data for each of the provisionally desig-

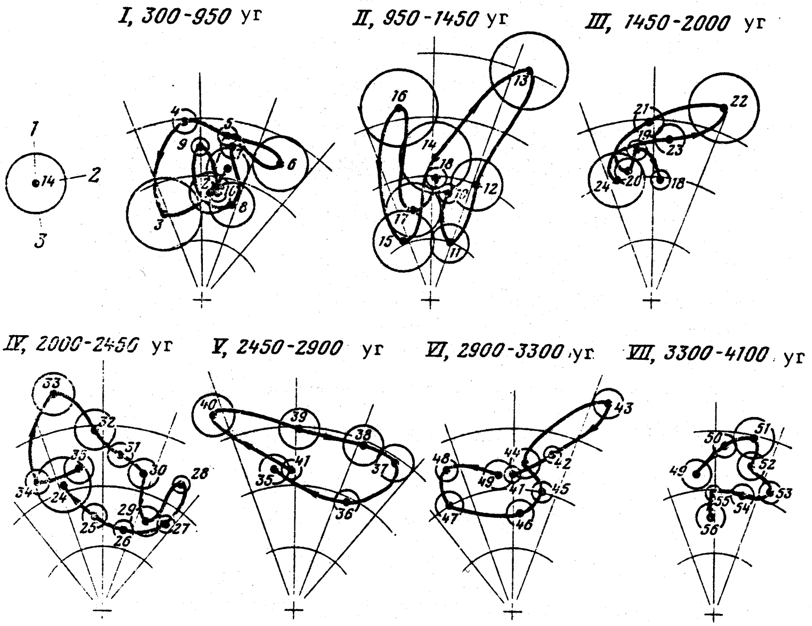

Fig. 2. Trajectory of the geomagnetic field vector over the last 4000 years. 1 - direction of the vector; 2 - numbers of the corresponding PMH; 3 - circles of confidence (at P=0.05); I-VII - cycles of paleovariations; Arrows - direction of passage of time.

nated time intervals data on the section in which this interval was represented by the largest number of horizons. Thus, the interval Sh_2 - Sh_3 was most fully represented in the Kirgurich section (six horizons), the interval Sh_3 - Sh_4 in the Apakhonchich section (five horizons), the interval Sh_4 - Sh_5 in the Krashenikova section (six horizons) and so on. Subsequently these input data for each interval of the vector trajectory were successively supplemented by data from other sections, once again beginning with the data most fully characterizing that interval. As a result it was already possible to derive the main elements of the required trajectory from the first two-three sections, and later to supplement and correct them by the data of the other sections.

We succeeded in obtaining a composite trajectory of the vector for each interval that combined the paleomagnetic data obtained for all sections and maintained the stratographic sequences of the directions of magnetization distinguished (Fig. 2). For ease of examination they were divided to some extent provisionally into seven cycles of paleovariations. As is evident from Fig. 2, there are 56 successive directions of the geomagnetic field distinguishable in the time interval investigated, and they are correlated with particular parts of the sections, which we have termed paleomagnetic horizons - PMH.

By PMH we understand coeval layers in which the direction of stable remanent magnetization differs by more than the radius of the circle of confidence from the direction of stable remanent magnetization of the layers above and below it. It follows from this definition that the rocks of PMH are regarded by us as having been formed synchronously as accurately as can be determined from the detail of sampling and the error of determination. The table that follows sets out the data of the generalized curve of paleovariations, indicating the combined sampling layers, the mean directions of stable remanent magnetization and the parameters of their scattering and information on the age of the rocks.

Allowance for data on cinder cones

As is evident from the Table, data obtained by studying the remanent magnetization of the rocks of the cinder cones that occur widely on the slopes of Klyuchevshoii Volcano were used in the compilation of this trajectory in addition to the seven sections of the cover of soil and pyroclastics referred to above. The stratographic position of the greater part of these formations relative to the ash marker horizons of Shiveluch was known from the tephrochronological research. Their stratographic position was established in greater detail from the paleomagnetic data.

We sampled a total of 17 cinder cones on the eastern slopes of Klyuchevskoi. On average some 15 oriented samples of cinders or agglutinate were taken from each. The samples were taken from the upper rim of the craters, where their setting had not been disturbed since the time of the eruption. The correctness of this assumption was confirmed by the fact that the overwhelming majority of the samples yielded quite satisfactory clustering (K_{mn} = 115; $\alpha_{95\ mn} = 4.5^{\circ}$).

Regarding the cinder cones it was known from tephrostratigraphic data that Perreya cone belongs to the stratigraphic interval Sh_2 - Sh_3, the Shmaleva, Ochki, Peshchernyi and Stellera cones to the interval Sh_3 - Sh_4, the Beringa, F, Nezametnyi, Levashova and Karpinskogo cones to the interval Sh_4 - Sh_5, and the J, Bulochka and Lepeshka cones to the interval Sh_5 - Sh_6. In most of the cones the direction of the mean vector of one of the PMH was found to be close to the direction of the remanent magnetization of the rocks in the corresponding stratigraphic interval. Data for such cones were included in these PMH (see the Table). In only two cones - Perreya and D - did the direction of remanent magnetization differ by more than the radius of the circle of confidence from the direction already obtained on the composite curve of paleosecular variations, on which basis they were distinguished as separate PMH-13 and PMH-30 that supplemented the trajectory of this curve. All this enabled us to correct the age sequence of the cones investigated within the known stratigraphic intervals.

There were no tephrostratigraphic data on age for three cinder cones, namely Mal'enkii, K and M, and paleomagnetic data were used to relate them to the stratigraphic scale. With respect to the direction of remanent magnetization the Mal'enkii cone was comparable to PMH-33, the K cone to PMH-37, and the M cone to PMH-43. The cinders of the M cone also have a direction of remanent magnetization differing markedly from that of the general group, as does a lava flow from Malyi Semyachik, which lies beneath a layer with a dating of 3000 years.

The oldest cone investigated is Lepeshka, shown by tephrostratigraphic data to belong to the interval Sh_5 - Sh_6. The paleomagnetic data support this conclusion and are the basis for according

Direction of Stable Remanent Magnetization of the Rocks of the Soil and Pyroclastics Cover and Cinder Cones of Kamchatka

No. of PMH	Sections or cinder cones	*N*	*D*°	*J*°	$\overset{\circ}{\alpha_{95}}$	*K*	^{14}C dating, yr
1	III (1—9), VI (189—190)	46	12,6	67,9	3,6	35	320 (III)
2	VI (191—194)	23	7,1	72,3	3,6	70	—
3	II (1), III (10), V (1)	16	338,4	75,2	6,1	37	—
4	I (1)	30	355	61	2	175	380—410 (I)
5	I (2), II (2. 3), V (2—7)	151	10,1	62,3	1,7	46,6	—
6	II (4), III (12, 13), V (8—10)	33	30,2	63,8	4,5	32	—
7	VI (195—197), VII (1—3)	39	11,8	64,3	2,1	113	—
8	I (3), IV (4, 5)	18	18,1	73,5	3,8	83	580—640 (I) 650 (IV)
9	I (4), IV (6, 7)	20	1,2	64,8	1,3	662	—
10	II (5 : 6), V (11—15), VI (198—202). VII (4)	68	9,9	72,3	1,6	116	900—1000
11	III (14—17), VI (203—205)	33	19,1	80,1	3,0	72	
12	III (18), V (16—18)	15	23,3	69,8	4,3	80	—
13	*1*	14	24,4	48,9	6,1	43	—
14	VI (206, 207)	12	3,9	66,6	5,9	55	—
15	II (7), III (19), VI (208)	12	336,3	79,2	5,2	48	—
16	I (5), II (8), III (20), VI (209)	15	352,5	58,3	6,2	39	—
17	VI (209—I)	6	349,9	75,4	4,6	217	—
18	III (21—24), IV (8—10), V (19—22), VII (5), *2*	75	3,1	70,0	1,8	82	1300—1450, 1550 (III), 1400—1500
19	I (6), VI (210—212), VII (6), *3, 4, 5*	80	354,0	65,0	1,5	111	1400—1500
20	V (23—25), VI (213—217)	40	350,0	68,6	2,2	102	—
21	II (9), V (26—28)	15	359,1	60,8	2,4	251	—
22	I (7), III (25, 26)	15	19,3	56,2	5,6	48	—
23	III (27—30), V (29—30)	25	5,3	63	2,4	146	—
24	V (31), VII (7, 8)	13	343,5	69,5	4,5	88	2000 (III_1)
25	V (32, 33), VI (218—222)	38	357,6	75,5	1,9	147	2000 (III_1)
26	II (10), IV (11, 12), V (34, 35), VI (223—225)	42	17,9	77,0	1,6	197	—
27	III (31), IV (13—15)	20	37,2	72,8	1,4	513	2240 (III)
28	III (32), IV (16—18)	22	34,2	66,4	1,5	428	—
29	IV (19—22)	22	29,7	74,5	2,7	134	—
30	*6*	10	16,8	67,9	2,2	503	—
31	II (11, 12), III (33—38), *7*	53	7,8	65,6	2,1	85	—
32	I (8), *8*	20	358,1	61,9	3,4	93	—
33	IV (23), *9, 10, 11*	52	347,1	54,6	3,7	29	2440 (IV)
34	I (9)	13	332	68	2	123	—
35	I (10), II (13—18), III (40, 41), IV (24)	44	352,0	67,3	2,4	78	2630 (I)
36	V (36—37), VI (226—227), VII (9—10)	31	26,3	70,7	2,0	177	2500—2600
37	V (38, 39), *12*	14	35,3	60,7	3,0	171	2500—2600
38	IV (25), *13*	27	23,6	61,3	3,3	74	—
39	IV (26)	8	1,9	61,0	3,5	246	2990 (IV)
40	II (19, 20), *14*	26	337,5	56,4	3,3	75	—
41	I (11), II (21—26), III (42, 43), *15*	78	358,1	67,9	1,5	109	—
42	I (12), III (27, 28), III (44)	19	14,8	63,6	1,5	533	3000 (I)
43	I (13), *16*	52	24,6	52,8	2,1	90	—
44	II (29—34)	22	5,7	65,3	2,4	162	—
45	VI (38, 39), VII (11—13)	33	15,0	69,7	1,8	181	—
46	IV (27), VI (40, 41)	24	5,6	74,0	1,9	234	3070 (IV)
47	VI (42, 43)	15	329,4	70,4	2,2	299	—
48	VI (44, 45)	15	335,1	64,7	2,0	376	—
49	II (35—41), IV (28, 29)	41	354,8	67,1	2,4	86	3290 (IV)
50	II (42, 43)	9	4,8	62,6	2,1	548	—
51	II (44, 45)	7	13,7	60,5	3,2	347	—
52	I (14), II (46, 47)	11	15,2	65,5	2,1	490	—
53	I (15)	28	25	68	1,8	110	4000 (I)
54	I 16), IV (29, 30)	23	14,0	70,2	1,8	296	4000 (I)
55	III (45), VI (46—57), *17*	105	1,8	70,2	0,9	243	—
56	VI (58, 59)	12	358,1	74,2	2,3	347	—

Note. N - number of samples in PMH, D and J - mean declination and inclination values of the stable remanent magnetization of the PMH, α_{95}- radius of the circle of confidence at P=0.05, K - clustering of the PMH. Sections: I - Semyachik-8, II - Semyachik-5, III - Zhupanovo, IV - Krasheninnikova, V - Apakhonchich, VI - Kirgurich, VI - Klyuchi, the figures in brackets after the number of the section are the numbers of the horizons sampled (see Fig. 5 for their location) combined this cone with respect to the direction of magnetization to PMH-55 preceding layers of the deposits of Malyi Semyachik with an age of about 4000 years.

It should be noted that very stable remanent magnetization of a thermoremanent nature is formed in cinders at the time of eruption and thereafter remains practically unaltered [10]. In contrast to the other rocks of the cover of soil and pyroclastics, which have orientational magnegization averaging the direction of the magnetic field over some period of time, cinders provide us with "instantaneous" values of the elements of the geomagnetic field at the time of their formation. This increases the probability that directions of remanent magnetization very far removed from the mean direction of the geomagnetic field for the Holocene will be obtained from objects of this type. This conclusion is also confirmed by our data. Thus, the scatter of the directions of remanent magnetization of all 17 cinder cones (treated by us as unit vectors) yielded K = 49.9 and $\alpha_{95} = 5.3^{\circ}$. These figures may be compared with the parameters calculated for eight random samples of 17 of the total of 106 PMH obtained in all seven tephra sections. The mean values of these parameters were K - 74.5, $\alpha_{95} = 4.4^{\circ}$. The clustering obtained in all the samples was greater, and the radius of the circle of confidence less than in the cinders.

The reasons for the incompleteness of the paleomagnetic data

Of the 56 consecutive directions of remanent magnetization in the Table approximately two-thirds were obtained by averaging data for two or more sections. A third of the directions were established in only one of the sections or in cinder cone deposits. It

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in this PMH, Cinder cones: 1 - Perreya, 2 - Shmaleva, 3 - Ochki, 4 - Peshchernyi, 5 - Stellera, 6 - D, 7 - Beringa, 8 - F, 9 - Nezametnyi, 10 - Levashova, 11 - Mal'enkii, 12 - K, 13 - Karpinskogo, 14 - Bulochka, 15 - J, 16 - M, 17 - Lepeshka. The Roman numerals in the final column indicate the sections in which datings were obtained. See [2, 3, 4] for the positions of the dated layers for sections I and III; see [7] for section IV. Dates labelled (Sh_2) - (Sh_5) correspond to rounded off values of the age of marker ashes of Shiveluch V [6].

follows from the Table that on average less than one-third of all the directions of the composite curve of geomagnetic field variations was established in each of the sections investigated. In order to clarify the reasons for this it is first necessary to examine the specific features of the cover of soil and pyroclastics as a subject for paleomagnetic research.

One significant feature is that the rate of formation of such cover may differ by several orders, in connection with the regime of volcanic activity in volcanoes close at hand, which are the main sources for the supply of the material in the section. The lack of tephra layers or a sharp reduction in their thickness may be connected with the failure of some given layer of ash to be deposited in this sector of the foot of the volcano because carried by the wind in a different direction, or maybe due in general to temporary cessation of the activity of the volcano. In the latter case we should expect a layer of sandy loam or soil to form, but even it is sometimes very thin or is not accumulated at all owing to the development of eolian processes (especially in coarse cinders or pumices of preceding eruptions).

Therefore, there are two established reasons for the development of paleomagnetic incompleteness of the data in the section, reasons connected with the regime of volcanic activity. The first is the actual absence in the time interval under consideration of deposits incorporating any information, including paleomagnetic information, while the second is the very low rate of sedimentation at some periods. In the latter case the incompleteness of the data is connected with the limited resolution of the sampling procedure. Our method of continuous sampling throughout the section incorporated and averaged data on magnetization in a portion of the section some 5 cm thick. Even in sectors where there are thin alternating layers of ash and sandy loam (often 1-2 mm thick), the direction obtained for stable remanent magnetization yields the mean direction of the geomatic field over some

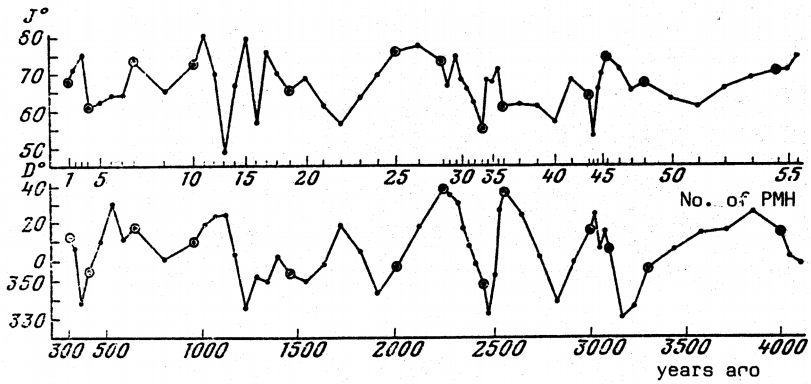

Fig. 3. Generalized diagram of the variation of D and J with age. The circles denote values of D and J for those PMH in which the age of the rocks was reliably determined and related to the age of the remanent magnetization.

interval of time. Should the averaging interval be sufficiently large (of the order of hundreds of years), a part of the information on the history of the geomagnetic field will naturally be lost. Consequently a gap in the paleomagnetic record in the section is to be expected in periods of reduced explosive activity of a volcano.

In addition to these two characteristics of the object investigated, we should also note one further source of incompleteness of the paleomagnetic record of sections. That, as will be demonstrated below, is inadequate paleomagnetic stability of the rocks of individual portions of the sections and stable metachronous magnetization arising in them. The combined effect of these factors is probably the reason why considerably less than a half of the directions of the composite trajectory of paleovariations is represented in each of the sections investigated (even in the Kirgurich section, the one that is thickest and has been investigated in the greatest detail).

Let us now give more detailed consideration to the completeness of the composite scale of paleovariations. Fig. 3, which depicts the variations of the declination D and the inclination J of the geomagnetic field may conveniently be consulted for this purpose. It gives the D and J values of those PMH whose age is well known; they occupy the appropriate position on the x-axis. Intermediate values of the elements of the geomagnetic field are uniformly distributed between them, although the unevenness in the formation of the cover of soil and pyroclastics does not exclude the possibility that the actual distribution was slightly different.

It is evident from Fig. 3 that the mean interval between observation points is 70 years, but that it ranges on different parts of the scale between 25 and 150 years. The least investigated range proved to be 640-950 years ago, a period for which there is only one intermediate direction of the vector. The need for correction is evidently to be anticipated in this interval, which corresponds to points 8-10 of the trajectory on Fig. 2. A correction is also possible in the range 3300-4000 years ago, for which the mean time interval of observations between PMH-49 and PMH-54 is 140 years. For the rest of the scale, where the mean observation interval is less than 60 years, there is evidently no need for further detail, at all events not for stratigraphic purposes, since cycles of variations lasting for less than 100 years are rather too small as magnetostratigraphic subdivisions even for the Holocene and cannot be given a sufficiently accurate chronologic basis.

Characteristics of the Paleovariations

Let us return to the vector trajectory in Fig. 2. The first cycle of variations (counting backwards from the most recent) covers the period between 950 and 300 years ago, i.e. a period lasting approximately 650 years. This cycle of variations is charactized by the predominant anticlockwise rotation of the vector, and its commencement coincides with the time of formation of the Sh_2 marker horizon of Shiveluch ash. The second cycle of variations is confined in the section to the Sh_3 and Sh_2 ash layers and has a duration of about 500 years. It is a dual cycle characterized by a single fluctuation of the vector with respect to declination and two with respect to inclination. During the first half cycle the vector rotated anticlockwise, and clockwise during the second.

The duration of these halfcycles was apparently similar, 200-300 years. The third cycle of variations is confined to the section of Sh_4 and Sh_3 ash and lasted for about 550 years. During the time of this cycle the vector described an intricate trajectory in which the direction of rotation varied from right to left. The fourth cycle of variations is confined in the section to the Sh_4 and PMH-35 ash layer, for which the age of the rocks is 2630 years in the Semyachik-8 section. Consequently, the length of this cycle was about 450 years. It is evident from Fig. 2 that this cycle is characterized by clockwise rotation of the vector. Similar rotation is also to be found in the fifth cycle of variations, which lasted for about 450 years. In the last two (sixth and seventh) cycles of variations the rotation of the vector is again anticlockwise, and the cycles lasted for about 400 and 800 years.

Consequently, levorotation was slightly predominant,taking up roughly 2200 years as against approximately 1600 years for gyrorotation. The distribution of the cycles by duration has a practically continuous spectrum of values from 400 to 800 years with a mean value of about 550 years. Since each cycle is characterized by nine points on average, we applied nine-point running averaging to the data in the Table. The result (Fig. 4) was quite clearly revealed fluctuations with a duration of the order of 1000 years on average. This result is similar to that obtained by Zagnii [9], who studied the paleovariation of the Ukraine and Moldavia over the last 5500 years. He distinguished a 1200 year period as the basic period in spectral analysis of the variations, with variations lastin 500-600 years superimposed on it.

The slow variations of the elements of the geomagnetic field (see Fig. 4, in which the trend is indicated) are a gentle increase of inclination at a rate of 0.8° per 1000 years and an increase of easterly declination at a rate of 2.3° per 1000 years. In all probability, these variations are long-period variations of the geomagnetic field having a period of at least 10,000 years.

In order to identify the cycles of variations revealed in the sections it is important to know their individual characteristics for their discrimination one from the other. Let us consider which parameters may be used to solve this problem. The clearest qualitative characteristic of the cycles of variations is the direction of rotation of the vector. Four key moments characterized by a change in the direction of rotation may be distinguished in the history of the geomagnetic field over the last 4000 years by applying this character. Two of those moments, 1000 and 1800 years ago, are characterized by a change in rotation from right to left, and two, 1200 and 3000 years ago, by a change in the opposite sense. It is evident that these moments of change in the rotation of the magnetization vector may be used as chronological markers for the region in which the pattern of paleovariations established by us is maintained.

Duration is another parameter that varies greatly from cycle to cycle. As has been indicated, it may vary between 400 and 800 years. Unfortunately, only very limited use may be made of this parameter for those geologic objects in which, as in the case of tephra, the rate of formation is extremely irregular, but we can rely on effective use of the parameter for the identification of cycles of paleovariations for geologic formations of the type of deepwater sediments with a constant sedimentation rate.

The next individual character of the cycles of variations is the shape and amplitude of the loops described by the vector. Let us turn to Fig. 2. It is evident that the double loop II of the cycles of variations (PMH 10-17) differs most from the others; it is characterized by a change in the direction of rotation of the vector, as well as by the largest amplitude ratio of the variations of inclination and declination. Cycles III-VI are typified by a slightly lesser ratio of these amplitudes, and it is the change in the direction of rotation of the vector that is the distinguishing feature of cycles III and VI. Cycle VII is typified by low ampli-

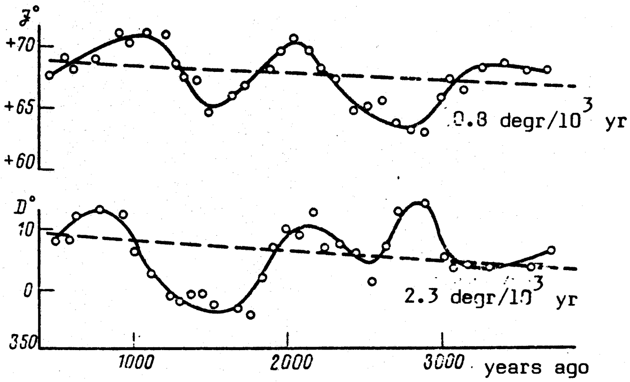

Fig. 4. Variation of D and J as indicated by a 9-point sliding average (geomagnetic field trend indicated by dashed line).

tude of the variations of declination and inclination. In addition, the cycles of variations in the sections may be identified by their fine structure, for example the type of complex trajectory of slight amplitude described by the vector at the beginning of cycle I of the variations (see points 7-10 on Fig. 2).

Magnetostratigraphy of the sections and cinder cones

Data on paleovariations in a section for which there are no chronostratigraphic reference points may be used to compare it with the reference scale of paleovariations and to apply the age markers of the reference scale to the section. As the number of cycles of variations detected in the section increases so also will the accuracy and reliability of its magnetochronological dating.

The correlation of the sections yielded by paleomagnetic data is depicted in Fig. 5 which gives lines of correlation corresponding to the synchronous levels separating the cycles of variations depicted in Fig. 2. It is obviously possible to make a far more detailed correlation with an accuracy reaching the PMH shown on the sections at the right, tracing each PMH in the table from section to section. Such correlation enables the stratigraphic position of layers dated in one section to be determined in all sections.

We may take as an example an estimate of the age of the archeological levels in the section of Cape Pamyatnik (Zhupanovo).

Thus, according to the data in Figs. 3 and 5 and in the Table, the age of the roof of archeological level II may be put at 1000-1100 years, and the age of the base of archeological level III at approximately 2400 years. Consequently, despite the fact that this section has been studied in detail by the tephrostratigraphic method, drawing upon a great many radiocarbon datings [4], paleomagnetic data, used in conjunction with the data referred to above, do enable further corrections to be made to the chronology of these formations.

Dobretsova [8] has attempted to use this method to determine the age of archeological levels of the section near the settlement of Avacha. She found that the inclination of remanent magnetization was systematically understated in the rocks of the archeological levels. It was not until an empirically selected formula had been used to make corrections to the inclinations that the paleovariations obtained in the Avacha section became comparable to the data of the Malyi Semyachik reference section. We found a similar abnormally low inclination in the Zhupanovo section only at the very bottom of archeological level III (sampling horizon 39). Because this result was the only one of its type it was discarded; this was the one case of the scrapping of data referred to in the introduction.

Interpolated values of the age of each of the PMH distinguished may be readily determined from Fig. 3. In particular, using it and applying the data in the Table it is possible to estimate the time of formation of the cinder cones already considered. Thus, the oldest of the cones investigated, namely Lepeshka (PMH-55) was formed approximately 4100 years ago, cone M (PMH-43) about 3000 years ago, and the Nezametnyi, F, Beringa and D cones (PMH 30-33) in succession in the interval 2350-2200 years etc.

Metachronism of the remanent magnetization of tephra

Let us now turn to the synchronism of the magnetization that we have isolated. This is a question that acquires particular importance when studying paleosecular variations, since a discrepancy of several hundred years between the time of formation of the rocks and the "age" of the direction of the geomagnetic field that they record may appreciably distort the nature of the paleovariations obtained, especially when the degree of such delay differs in different parts of the section. The question of the synchronism of magnetization has not previously arisen with such acuteness in paleomagnetic research because in most instances there is sufficient basis for taking into consideration metachronism measureable in thousands or even tens of thousands of years.

Let us now consider which out of our data may cast some light on this matter. The presence in three of the sections investigated of ash horizons of Shiveluch Volcano formed absolutely synchronously may be of some assistance. If the remanent magnetization in these deposits is synchronous it should have the same direction and belong to the same PMH. It may readily be verified from Fig. 5 and the Table that the Sh_2 deposits present in two sections do in fact belong to the same PMH-10. The Sh_3 deposits in two sections belong to PMH-18, and those in the Kirgurich section to PMH-19. The Sh_4 deposits in two sections belong to PMH-25, and in the third section (Klyuchi) to PMH-24. Finally, Sh_5 deposits belong to PMH-36 in two sections and to PMH-37 in the third (Apakhonchich).

Consequently, in addition to the fact that the directions of stable remanent magnetization coincide in synchronously formed horizons, there are instances of discrepancy suggestive of metachronism. These discrepancies are on average 9° of arc of the great circle, which (to judge by the data in Fig. 3) is evidence that the formation of remanent magnetization was delayed on average by 60 years.

The fact that fairly large sectors consisting of a succession of differing lithologic layers in the sections are found to belong to the same PMH in a whole number of instances may be another indication of the metachronism of remanent magnetization in the rocks. This suggests that the formation of the rocks of these sectors occ-

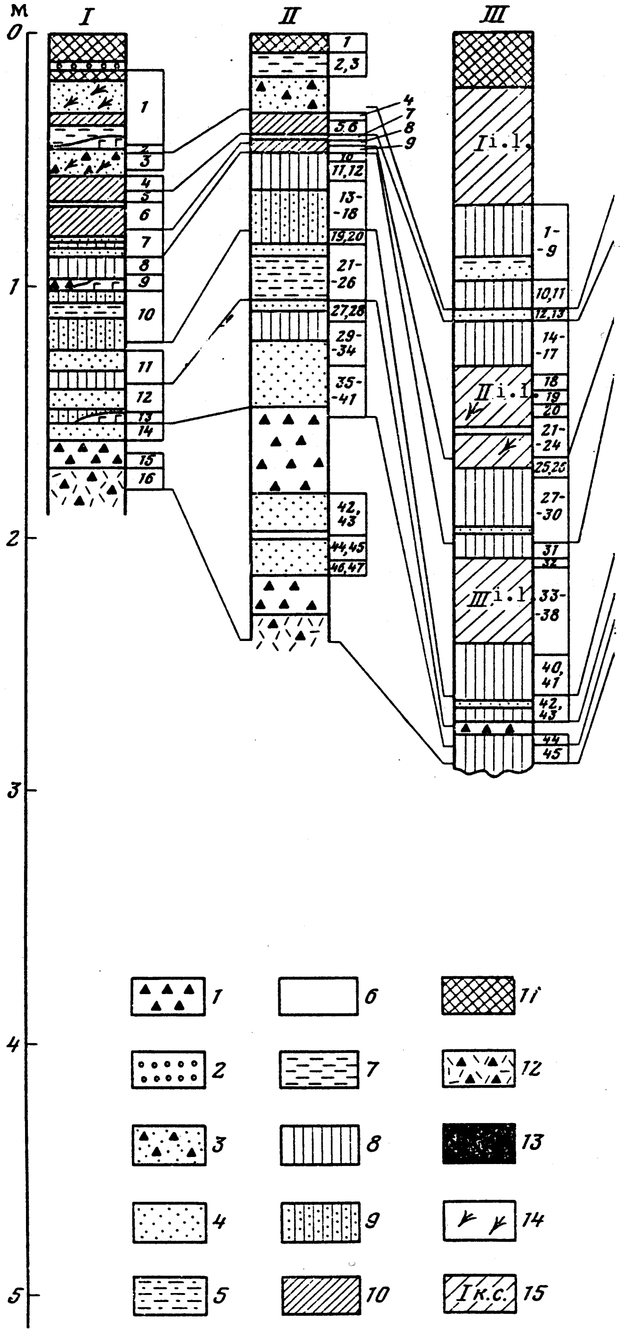
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Fig. 5

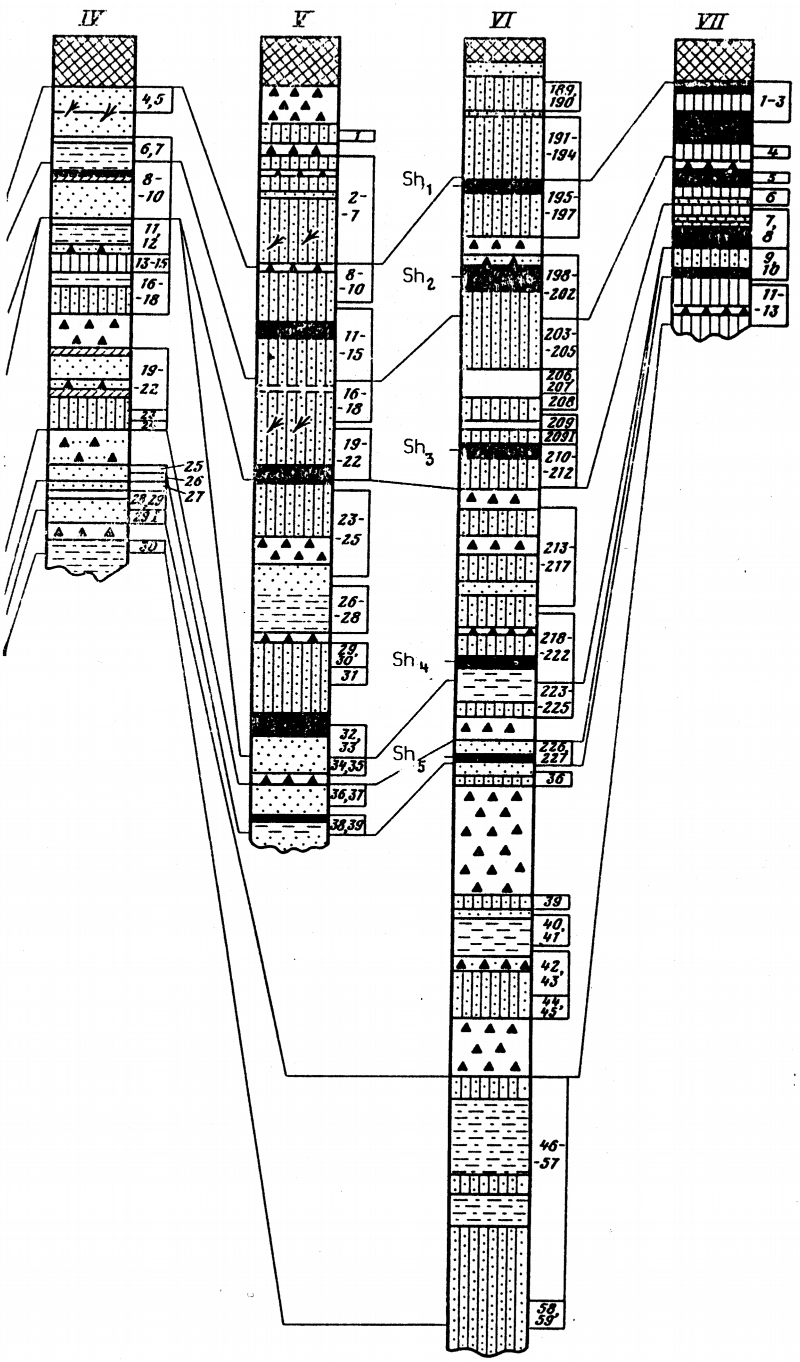

Fig. 5. Paleomagnetic correlation diagram of the sections investigated. 1. - volcanic gravel and cinder lapilli, 2 - volcanic gravel of pumice, 3 - volcanic gravel and cinder lapilli with traces of volcanic sand,m 4 - volcanic sand, 5 -

urred over quite a long interval, possibly of the order of a few hundred years. At the same time, the direction of remanent magnetization of the rocks of these sectors obtained after cleaning remains constant, which was the basis for according them to the same PMH. The clearest example of this is to be seen in the lower parts of the Kirgurich section (see Fig. 5), where there are 12 sampling layers in PMH-55 taking in a portion of the section up to 90 cm thick. The orientational magnetization of the rocks of such sectors most probably reflects the direction of the geomagnetic field in the concluding stage of their formation or even later. The isolated remanent magnetization of the rocks of the greater (lower) part of these portions should be regarded as metachronous. On the other hand, if a different direction of stable remanent of magnetization is noted in synchronously formed layers of the type of the Shiveluch ash horizons, the difference between the age of the rocks and the age of this magnetization will be less in layers in which the direction of the stable remanent magnetization relates to earlier portions of the trajectory of the paleovariations.

Consequently, it should be borne in mind in analyzing the data obtained that the age of the rocks and the age of their stable remanent magnetization may differ and that the difference may be as much as 100 years and, in some instances, more. Strictly speaking, Fig. 5 correlates not coeval rock horizons, but stable remanent magnetizations formed at the same time. In all probability, owing to the presence in the sections of rocks that have recorded the remanent magnetization with differing degrees of metachronism, the paleomagnetic correlation in Fig. 5 does not agree in a number of

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stratified volcanic sand, 6 - fine ash interlayers, 7 - fine stratified ash, 8 - sandy loam, 9 - sandy loam with traces of volcanic sand, 10 - buried soils, 11 - turf, 12 - pyroclastic flow tuff, 13 - ash marker interlayers of Shiveluch Volcano, 14 - organic remains, 15 - inhabited layers. See the key to Fig. 1 for sections I-VII. The numbers to the right of the columns are the horizons sampled. Sh_1 - Sh_5 - ash of Shiveluch Volcano; correlation lines constructed along the boundaries cycles.

instances with available tephrostratigraphic and geochronologic data. It follows that metachronous magnetization sets a limit on improvement of the accuracy in detail both of magnetochronological reconstructions and of the age correlation of geologic sections. However, as regards the subject of our research, the error introduced by metachronism is similar to the error of radiocarbon datings. As regards the scale of paleovariations given in Fig. 3, we have sufficient grounds for the assertion that it is the age of the stable remanent magnetization of the rocks that is plotted on the x-axis, i.e. that it is the history of the geomagnetic field with which we are concerned, since allowance may be made for metachronism in a whole number of instances. This possibility of making partial allowance for the metachronism of stable remanent magnetization arises from the detailed tephrostratigraphic and chronometric investigation of the materials investigated.

Conclusions

1. A scale of paleosecular variations of the geomagnetic field for the last 4000 years has been produced from the study of a series of sections of Kamchatkan deposits of soil and pyroclastics in the course of combined paleomagnetic and tephrostratigraphic research employing radiocarbon dating.

2. The scale consists of 56 consecutive directions of the geomagnetic field vector describing an intricate trajectory divided up into seven cycles of paleovariations. Each cycle has individual characteristics: the direction of rotation of the vector, the form and amplitude of the loops described by the vector, and the duration of the cycle. Correlation of sections of soil and pyroclastics on the basis of the isolated cycles of variations has shown them to be in good agreement on the whole with correlation on the basis of tephrochronologic data.

3. The scale produced may be used to solve the converse problem, the dating and correlation of deposits whose age is unknown. Paleomagnetic data have been used to correct the age of the archeo-

logical levels of the reference settlement at Zhupanovo and the age of the flank eruptions of Klyuchevskoi Volcano.

4. The main difficulties encountered in such research have been analyzed. The incompleteness of the paleomagnetic records in the sections, which has a whole number of causes, makes it necessary to study several parallel sections to reconstruct a sufficiently complete history of the geomagnetic field. The metachronous magnetization present in some horizons limits the degree of detail and accuracy achievable in magnetochronologic reconstructions and stratigraphic correlation. This metachronism does not, as a rule, exceed 50-100 years in the deposits investigated between the time of formation of the rocks and the time of the formation of stable remanent magnetization in them.

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