PROSPECTS FOR THE STUDY OF REGIONALLY METAMORPHOSED STRATA BY THE PALEOMAGNETIC METHOD

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Abstract

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PROSPECTS FOR THE STUDY OF REGIONALLY METAMORPHOSED STRATA BY THE PALEOMAGNETIC METHOD

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The objects of paleomagnetic studies are, as a rule, minimally altered rocks. Mute metamorphic strata, whose age determination requires primary attention, are considered poorly suited for paleomagnetic investigations. It is assumed that metamorphic processes, by destroying either the ferromagnetic mineral itself or its initial remanent magnetization, must inevitably change the direction of the latter, if not destroy it altogether. It is also assumed that metamorphism gives rise to a new magnetization and that in this case there is no plane with which the direction could be related (^{1}). The complex tectonic setting characteristic of metamorphic strata gives rise to doubts concerning the correct reconstruction of the original bedding of the layers. At the same time, a distorting influence of stress effect and magnetic anisotropy is admitted.

However, the results of many years of paleomagnetic studies of metamorphic strata on the western slope of the Polar Urals fundamentally change the established view of the problem in question. These studies were carried out from 1959 to 1966 on the basis of the fully equipped magnetic laboratory of the Pechora Geophysical Expedition.

The stimulus for work that at first glance appeared unpromising was the discovery of a fairly rigid relationship between the directions of I_n and the bedding planes of metamorphic and metamorphosed pre-Ordovician rocks. This relationship, established initially by a formal calculation of the angles between I_n and the bed surface for arbitrarily selected specimens, was subsequently confirmed by direct tracing of the direction of I_n along fold bends and by comparing the clustering of vectors in the modern and ancient coordinate systems. Moreover, I_n in specimens of coeval green schists collected in different areas showed good agreement of directions.

The very fact of the convergence of the directions of I_n in the ancient coordinate system over a large area makes it possible to conclude that: a) the hinges of folds at the sampling sites are approximately horizontal; b) the blocks making up the folded region did not undergo appreciable rotational movements; c) the schistosity planes, along which bedding elements of relict stratification or contacts were often measured, correspond in these areas to the primary bedding.

The uniformity of the directions of I_n in rocks that are folded and schistose to varying degrees excludes any noticeable influence of stress effect and magnetic anisotropy. The difficulty of determining the facing side of an isoclinal fold is easily eliminated by comparing the results of unfolding folds with different strikes.

The spatial relationship of I_n with the bedding surfaces of paleomagnetically stable rocks can and should be widely used for structural constructions, examples of which are given, in particular, by Irving

(2). On the other hand, proof of paleomagnetic stability specifically by Graham' s fold method also has a direct bearing on the age of the magnetization under study.

Indeed, the basic condition for the applicability of this method—the pre-folding origin of I_n—for metamorphic rocks means that their I_n, regardless of its nature, must have formed within a definite time interval: from the formation of the rock to the nearest tectonic inversion, i.e., during the period of sediment accumulation. Consequently, any a priori assumptions about a substantial age gap between the metamorphogenic I_n and the epoch of rock formation are untenable where its stability has been proved by the unfolding (fold) method. Further experiments also cast doubt on the very genetic dependence of stable I_n on metamorphism.

Table 1

Mean directions of I_n of paleomagnetically stable metamorphic rocks of Ordovician age
(greenschist facies)

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Mangutskaya	Mt. Borzova	1	5	45	233	6			16	19	0	15	50	70

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Nyarkheyskaya	Khaytalouskaya depression	1*	5	45	232	−10			50	11	5	15	55	60

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	[illegible]	[illegible] depression	2	6	45	277	4			15	18	−20	40	50	80

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Nyarkeyskaya	Khaytalouskaya depression	3	10	41			333	7	20	11	−30	65	30	80

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees, azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Kokpel.	Pelskaya Lemba	4	3	70			332	7	200	9	30	65	50	65

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Kokpe.	Relskaya Lemba	5	11	70	239	5			12	14	0	80	40	80

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, *D*	Direction, group I, *I*	Direction, group II, *D*	Direction, group II, *I*	*K*	α_{95}	Range of variation in degrees, azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Green orthoschists of albite-epidote-actinolite composition, basic effusives, porphyritoids, metadiabases	Kokpelskaya	R. Lemba	5*	4	70	294	−11			60	12	0	80	35	75
Tuffs, tuffolavas, tuffoschists	Nyarkveyskaya	Khaytalouskaya depression	6	5	18	303	16			50	11	0	40	45	85

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Tuffs, tuffolavas, tuffoschists	Nyarkveyskaya	Kheytalouskaya depression	7	2	18			333	−8	50		−30	65	40	60
Tuffs, tuffolavas, tuffoschists	Nyarkveyskaya	Kheytalouskaya depression	7*	3	18			341	18	29	23	25	30	50	85
Paraschists: mica-quartz-carbonaceous, aleurolitic, quartz-sericite phyllite-like schists	Kol[illegible]	Pelskaya Lemba	8*	12	44			324	−8	12	13	−5	80	25	85

Rock	Suite	Sampling area	No. of plane I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, *D*	Direction, group I, *I*	Direction, group II, *D*	Direction, group II, *I*	*K*	α_{95}	Range of variation in degrees azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees dip angle, from	Range of variation in degrees, dip angle, to
Paraschists: mica-quartz-carbonaceous, aleurolitic, quartz-sericite phyllite-like schists	Kolsk.	Pelskaya Lemba	9	3	44	289	12			50	17	−5	25	60	90
Paraschists: mica-quartz-carbonaceous, aleurolitic, quartz-sericite phyllite-like schists	Kolsk.	Pelskaya Lemba	9*	4	44	278	−9			23	19	0	65	45	85

Rock	Suite	Sampling area	No. of I_n	Number of outcrops included in calculation, abs.	Number of outcrops included in calculation, %	Direction, group I, D	Direction, group I, I	Direction, group II, D	Direction, group II, I	K	α_{95}	Range of variation in degrees, azimuth of strike, from	Range of variation in degrees, azimuth of strike, to	Range of variation in degrees, dip angle, from	Range of variation in degrees, dip angle, to
Paraschists: mica-quartz-carbonaceous, aleurolitic, quartz-sericite phyllite-like schists	[illegible]	[illegible] Lemba	10	12	59	297	4			16	12	−15	40	35	60
Sandstones, siltstones	[illegible]	[illegible] of Mt. Paypudynskiy	11	3	25	266	3			18	29	−40	50	5	65
Metamorphosed albitophyres	[illegible]	Mt. Borzova	12	14	64	259	8			15	11	−45	10	60	85
Metamorphosed albitophyres	[illegible]	Mt. Borzova	12*	7	64	260	2			20	14	0	10	60	80

Note. Mean directions of I_n whose numbers are marked with an asterisk have here been reversed by 180° for ease of comparison.

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

Table 1 gives the results of paleomagnetic studies in a greenschist belt 350 km long. Mean directions, concentrations, and confidence radii were calculated at the outcrop level. Directions of I_n for outcrops were obtained from 2-3 individually measured specimens. The sole criterion used in rejecting initial data was the scatter of vectors within an outcrop. All outcrops with within-site concentration $K_\mathrm{v} \geqslant 4$ were included in the calculation. The initial directions of I_n selected according to this principle agree satisfactorily in the ancient coordinate system without magnetic cleaning and without corrections for partial paleomagnetic instability. The magnitude and direction of I_n with stability established by the field method do not change appreciably in demagnetizing alternating fields with a maximum amplitude of 400 Oe.

On the other hand, I_n of specimens from rejected outcrops ($K_\mathrm{v} \leqslant 3$) changes sharply in both magnitude and direction in an alternating magnetic field. According to the method of comparing stability characteristics developed by G. N. Petrovaya, the isothermal nature of the unstable I_n was established. Repeated measurements of the rejected specimens after 3-4 months showed a wide occurrence of the viscous component.

In Table 1 and in Fig. 2 it is easy to see that, for the same petrographic varieties, the directions of I_n form two separate groups of mutually opposite vectors. Such a difference in directions in identical rocks, often observed in the same sections of a monofacial sequence, in the absence of mechanical causes such as tectonic displacements, can be attributed only to the age factor. It follows from this that the I_n under consideration is not obliged in its origin to the processes of metamorphism, which, having obscured the primary lithological differences of the rocks, could not level out their initial remanent magnetization. A study of its nature by the method of comparing stability characteristics showed that it may be either thermoremanent or chemical (Fig. 1b). In the first case, the syngenetic character of I_n with the rock is obvious, considering its independence from regional metamorphism. For the same reason, chemical magnetization could have occurred only at the stage of diagenetic changes—again, simultaneously with the formation of the rock.

Fig. 1. Demagnetization in an alternating magnetic field of specimens of albitophyres of the Manya suite.
a—specimen from a rejected outcrop; *b*—paleomagnetically stable specimen; 1—natural magnetization; 2—ideal; 3—thermoremanent.

Fig. 2. Mean directions of I_n of metamorphic rocks of the green-schist facies. 1—projection of I_n onto the lower hemisphere; 2—onto the upper. The numbers of the groups and points correspond to Table 1. The group boundaries are drawn taking account of the radii of confidence.

From this point of view, the elongation of the directions of group I along the circumference of the stereographic projection (Fig. 2) is hardly due to statistical scatter alone: here the stratigraphic sequence of the rocks studied is probably also involved, which can be established by resolving the disputed question of the direction of migration of the geomagnetic dipole in pre-Silurian time (3). However, this uncertainty does not prevent the solution of problems of a correlational nature. In particular, from the distribution of the mean directions of I_n (Fig. 2, Table 1) it may be concluded that the Nyargovei and Kokpel suites are of the same age and that each is characterized by two time intervals (groups I and II), one of which (I) corresponds to the period of accumulation of the Manya suite.

The observed resistance of primary ferromagnetic minerals to metamorphic processes is rather difficult to explain on the basis of mineralogical and geochemical data, since, as M. I. Abdulla acknowledges, we have very scant data on the nature and distribution of iron and titanium oxide phases in metamorphic rocks (⁀4). The preservation of the initial remanent magnetization may be explained as follows. Under the microscope, in effusive rocks and schists, the coexistence of two ore fractions is often noted: adiagnostic ore dust impregnating the groundmass, and comparatively large grains of titanomagnetite, usually developed along microfractures. It must be assumed that the carriers of the primary I_n are the finest grains of the finely dispersed fraction, which possess a large coercive force, whereas unstable components are inherent in large grains, often clearly of secondary origin. The quantitative ratio of these two phases in the rock apparently determines the stability of its I_n.

The resistance of the initial magnetization to heating at the greenschist stage of metamorphism—if, even following V. S. Sobolev, its lower limit is taken to be 400-450° (⁀5)—is readily explained by the experiments of M. A. Grabovskii and G. N. Petrova, which showed that repeated heating of a rock to 450-500° cannot substantially alter its thermostable magnetization (⁀6).

Important indications of the reliability of the results presented here are the similarity of the directions of I_n in rocks of different genesis, as well as the presence of normally and reversely magnetized varieties.

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Note: Figure translations are in progress. See original paper for figures.