Izvestiya, Physics of the Solid Earth, Vol. 35, No. 5, 1999, pp. 402–412. Translated from Fizika Zemli, No. 5, 1999, pp. 61–71.

Magnetostratigraphy of the Polovinka Key Section, Midstream Lena River: Did the Geomagnetic Polarity Change in the Early Llandeilian?

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Received March 2, 1998

Abstract—Results derived from detailed magnetostratigraphic studies of an important Ordovician Siberia key section are discussed. The geomagnetic field in the early Llandeilian is shown to have had mostly reversed polarity with very rare or completely absent episodes of normal polarity. The inferred data indicate that the Late Ordovician–Early Silurian overprint is widespread in Ordovician deposits of the Lena River, and disregard of this component can invalidate interpretation of a magnetostratigraphic record. Comparison between Llandeilian paleomagnetic poles from the northern and southeastern Siberian platform with the help of the same methods and instrumentation confirms the earlier conclusion [Gurevich, 1984; Pavlov and Petrov, 1996] on the relative rotation of the Aldan and Anabar blocks at the post-Ordovician time.

INTRODUCTION

The most prominent and, at the same time, most enigmatic events in the history of the Earth's magnetic field are the so-called superchrons, i.e., time intervals during which development of the geomagnetic polarity transition process, ordinary for any other interval of the geological history, stopped, and the field "froze" in one of its two stable states for many millions or tens of millions of years. Presently, the existence of two superchrons has been reliably established. These are the normal polarity Cretaceous and reversed polarity Carboniferous–Permian Kiaman superchrons. Recently, strong arguments have been put forward in favor of the existence of a third, Early–Middle Ordovician superchron that began at the boundary between the Tremadocian and Arenigian and supposedly terminated in the mid-Llandeilian [Johnson *et al.*, 1995; Pavlov and Gallet, 1996, 1998; Gallet and Pavlov, 1996; Algeo, 1996].

Presently, a few alternative models explaining the existence of superchrons and quasi-periodic variations in the geomagnetic reversal frequency have been offered [McFadden and Merril, 1984; Loper and McCartney, 1986; Courtillot and Besse, 1987; Larson and Olson, 1991]. Each of the models suggests the essentially specific behavior of the geomagnetic field before and immediately after a superchron. Thus, the Llandeilian appears to be a crucial interval in the geomagnetic field history, and its detailed study should provide constraints on the termination time of the third Phanerozoic superchron and indicate a model most adequate to the real processes in the Earth's inner shells.

From the standpoint of magnetostratigraphy, the Ordovician is the best studied period of the Early Paleozoic, but the data available on the Llandeilian are rather contradictory (Fig. 1). According to the magnetostratigraphic scheme constructed by Torsvik and Trench [1991a], the lower Llandeilian correlates with a reversed polarity interval including a single magnetic zone of normal polarity, and the field of middle and upper Llandeilian had only normal polarity. On the other hand, Ordovician data from southern Sweden [Torsvik and Trench, 1991b] indicate that the Earth's magnetic field had reversed polarity during almost the entire Llandeilian, and only the second half of this stage included a short normal polarity interval. Data from the Ordovician Moyero River key section [Pavlov and Gallet, 1996; Gallet and Pavlov, 1996] confirm, on the whole, that a reversed polarity field dominated the lower Llandeilian. According to the Phanerozoic paleomagnetic scale of the USSR [Khramov *et al.*, 1982], the field had reversed polarity throughout the Llandeilian, and two relatively short intervals of normal polarity existed near the boundaries with the Llanvirnian and Caradocian.

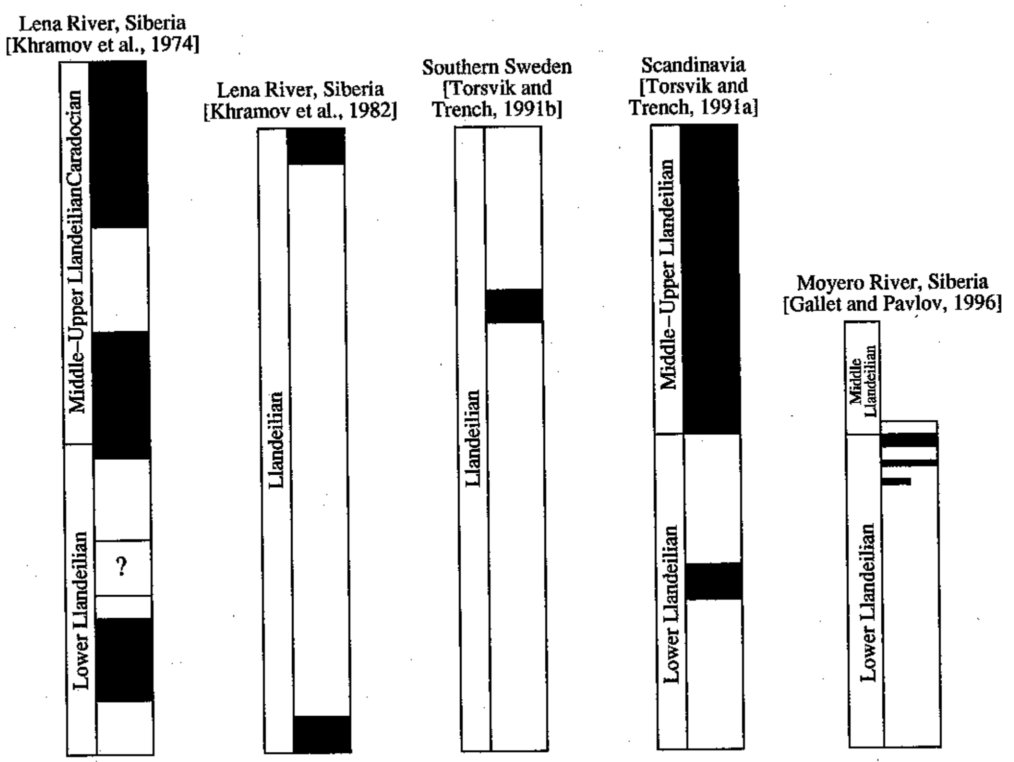

Fig. 1. Polarity variation of the geomagnetic field as inferred by various authors. Black and white areas are normal and reversed polarities, respectively.

Very interesting are unpublished results obtained by V.P. Rodionov in the early 1970s from a detailed (virtually on a bed level) study of the Kirensko-Kusdrinskii horizon (upper part of the lower Llandeilian) in an Ordovician key section near the Polovinka village, midstream Lena River, Siberia (φ = 60.1°N; λ = 113.7°E). Here, in rocks of the lower Llandeilian overlying a relatively thick interval of reversed polarity in the lower portion of the studied section, Rodionov discovered frequently alternating low-thickness zones of normal and reversed polarity (Fig. 2), which was preliminarily interpreted as evidence of a high reversal frequency in this time interval.

During the quarter century following the time of the first magnetostratigraphic studies of the Polovinka key section, the sensitivity of instrumentation in use and resolution accuracy of magnetization components considerably improved, and requirements to reliability of inferred results became much more stringent. If Rodionov's results could be reproduced on a modern level of studies, this would date the upper boundary of the Ordovician superchron and would provide a strong argument in favor of the McFadden–Merril, Besse–Courtillot, and Loper–McCartney models supposing that the reversal frequency was high immediately upon termination of superchrons.

Thus, the aim of this work is to perform a detailed magnetostratigraphic study of the Llandeilian Polovinka key section, based on up-to-date instrumentation and techniques, for the purpose of elucidating the geomagnetic field variation in the Llandeilian.

GEOLOGY AND SAMPLING

The Ordovician section represented by an exposure at the right-hand bank of the Lena River, 4–5 km upstream from the Polovinka village, is a key section of paramount importance for the Siberia Ordovician; it has been repeatedly described in stratigraphic literature [Tesakov *et al.*, 1975; Kanygin *et al.*, 1989]. Upper Tremadocian, Arenigian, Llanvirnian, and lower Llandeilian rocks outcrop here on a steep bluff over a distance of about 800 m.

The lower part of the section correlates with the Nyaiskii stratigraphic horizon (regional stage) and is mainly composed of gray sandstone and limestone. They are overlain by mostly gray-colored limestone (with interbeds of argillite and aleurolite) attributed to the Ugorskii and Kimaiskii regional stages (Arenigian). The Llanvirnian (only Mukteiskii stratigraphic horizon) of the exposure is represented by a thin (13 m)

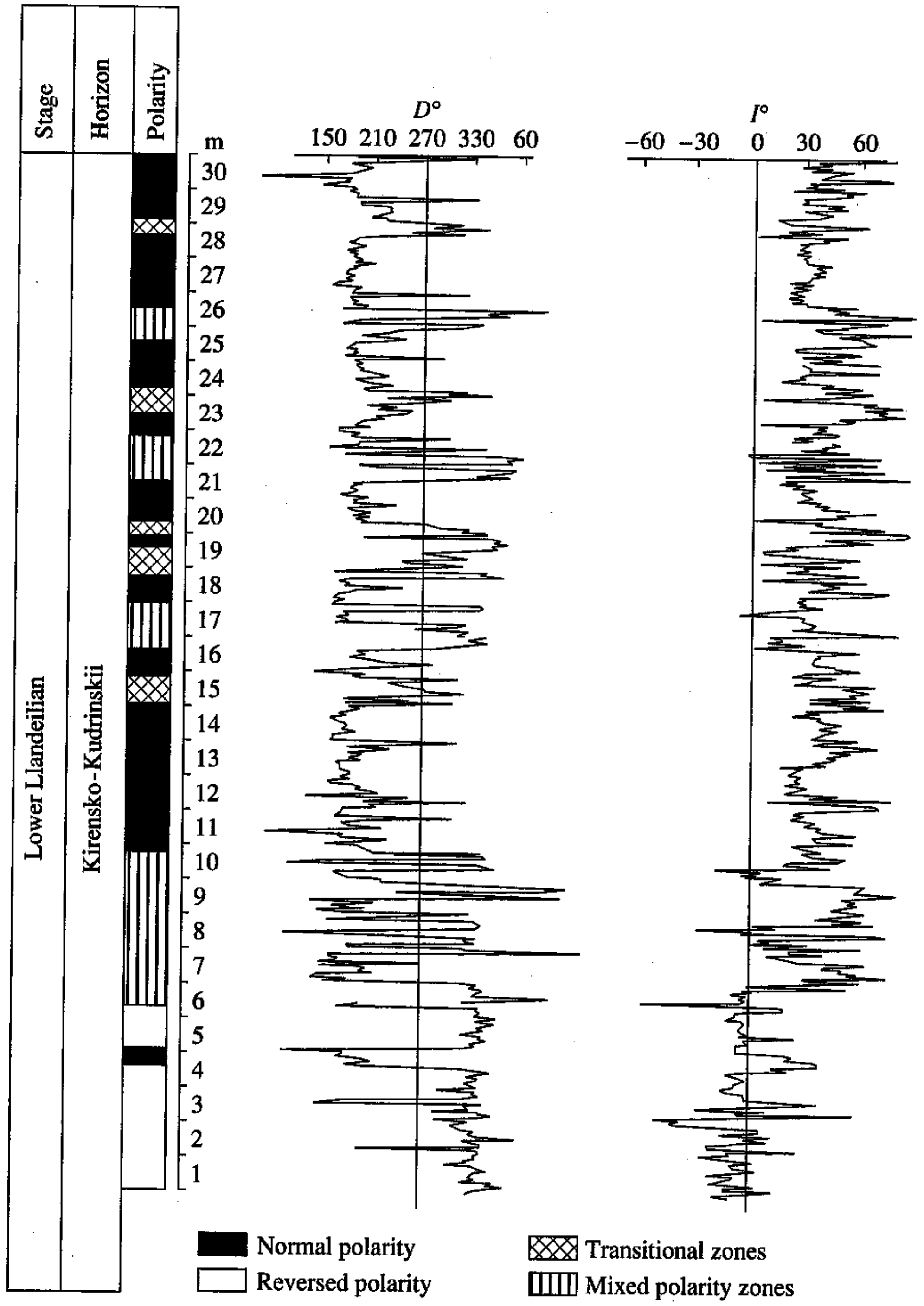

Fig. 2. NRM direction variation in the upper part (transitional beds) of the Polovinka section, mid-Ordovician Kirensko-Kudrinskii horizon, from data of V.P. Rodionov.

member of greenish–gray friable argillite with sandstone interbeds.

This member underlies deposits of the Volginskii and Kirensko-Kudrinskii horizons attributed to the lower Llandeilian. Volginskii rocks are alternating limestone and argillite, colored with gray, greenish, and sometimes reddish tints. The Kirensko-Kudrinskii horizon begins as greenish-gray limestones overlain by a 23-m member of thin-bedded and platy greenish-gray argillites. A portion of this member of about 13 m in thickness is poorly exposed and virtually inaccessible

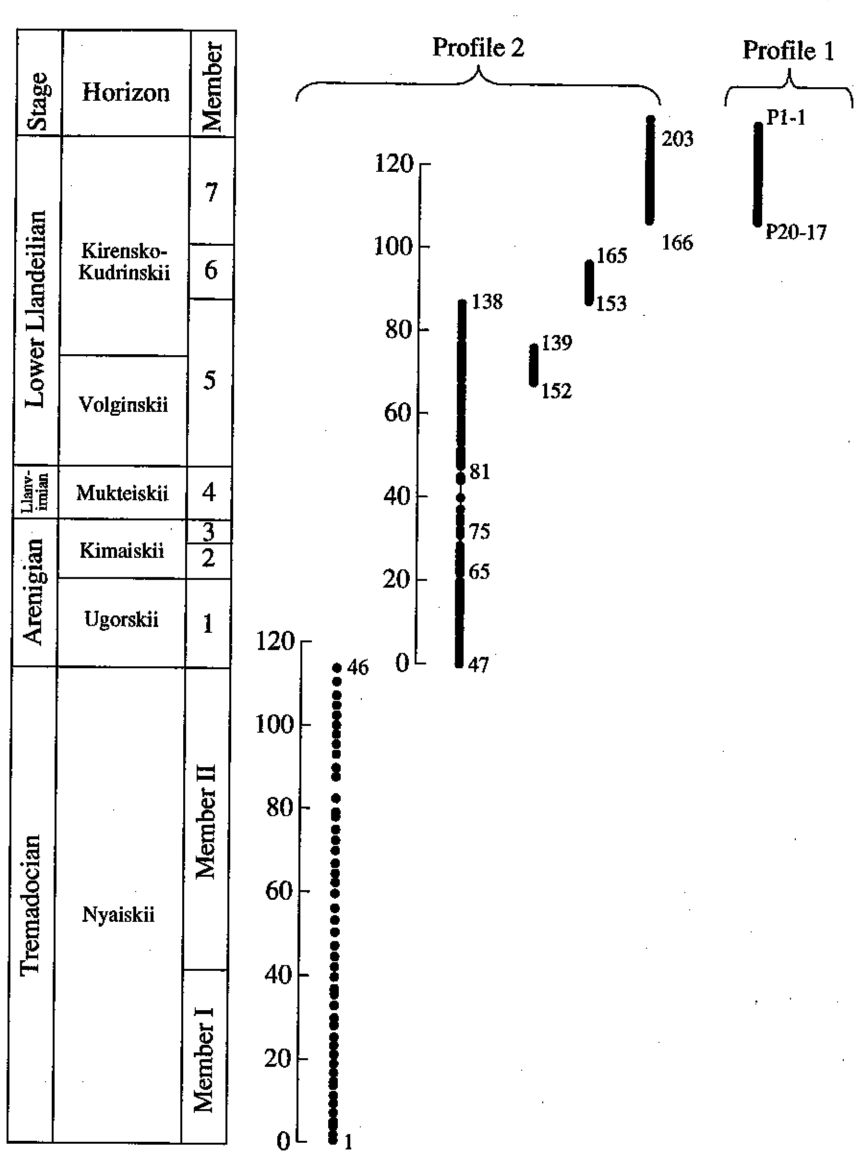

Fig. 3. Position of the study samples in the Polovinka section. Profile 1 (samples p1-1 to p20-17) was sampled by V.P. Rodionov in 1970. Profile 2 (samples 1 to 203) was sampled by V.E. Pavlov in 1996. Thicknesses of members I and II and their stratigraphic correlation are given after Tesakov *et al.* [1975]. Thicknesses of members 1 to 7 and their stratigraphic correlation are given after Kanygin *et al.* [1989].

for sampling. The upper part of the Kirensko-Kudrinskii horizon, corresponding to the Kudrinskii subhorizon, is represented by red, cherry-colored, and occasionally gray sandstones. Interbeds of red-colored aleurolite and argillite, previously ascribed to the base of the Chertovskii horizon [Tesakov *et al.*, 1975] occur in the uppermost part of the section. The rocks under study appear as a monocline dipping to the south at angles of 5°–15°.

We should note that the problem concerning the relationship between the Siberian and General stratigraphic scales of the Ordovician is rather complicated and was not solved until recently. In view of objective reasons (high endemism of fauna, variety of facies settings, etc.), some regional stages of the Siberia Ordovician are correlated, more or less formally, with stages of the English stratotype. Specifically, the Volginskii and Chertovskii stratigraphic intervals are the most reliable correlation datums, and their correlation with the Llandeilian is supported by significant biostratigraphic evidence. In our study, we used the correlation scheme, in particular, described by Kanygin *et al.*, [1989]. Presently, it is widely used and most probable.

Two collections were studied in our work. The first of these (profile 1) consists of samples collected by Rodionov in the early 1970s from the red-colored upper

Table 1. Mean directions of the characteristic magnetization vectors

	N	Geographic coordinates				Stratigraphic coordinates			
		D	I	K	α_{95}	D	I	K	α_{95}
Profile 1									
Reversed polarity	35	341.6	–1.6	15.5	6.4	341.3	2.3	16.5	6.4
Normal polarity	7	178.0	36.3	40.9	9.6	174.2	27.2	56.2	8.1
Profile 2									
Reversed polarity	33	345.7	–0.3	14.2	6.9	345.7	8.6	14.1	6.9
Normal polarity	5	194.1	45.9	13.0	22.1	194.0	33.5	10.4	24.9
Total									
Reversed polarity (component $K1$)	68	343.6	–1.0	14.9	4.6	343.4	5.4	14.9	4.6
Normal polarity	12	183.9	40.5	19.8	10.0	181.8	30.1	17.5	10.7

Note: N, the number of samples involved in the calculation of paleomagnetic directions; D and I, declination and inclination; α_{95} and K, parameters of the Fisher distribution.

member of the section, correlating with the upper subformation of the Krivolukskaya Formation (Fig. 3) and thereby with the Kudrinskii subhorizon. The samples were taken with an interval of 10–20 cm; in total, over 150 samples were collected from the sequence about 20 m thick. The second collection (profile 2) representing the entire Polovinka section was gathered by V.E. Pavlov in 1996. Samples of this collection (in total, 203) were taken with a sampling interval of 1–3 m.

PALEOMAGNETIC ANALYSIS AND INTERPRETATION OF RESULTS

According to the quality of paleomagnetic record, the study section may be subdivided into three intervals.

1. An interval from the section base to member 4. Because of either a chaotic or very complicated variation pattern of the natural remanent magnetization (NRM) vector, no magnetization component could be identified from demagnetization of samples taken from this interval. In some samples (mostly from the lowermost part of the section), the variation pattern of the NRM vector during demagnetization supposedly provides constraints on the polarity of the characteristic component.

2. Member 7. Two stable magnetization components are reliably identified from most samples of this member (Fig. 4). The first of these (K1) has, on average, a NNW declination and an inclination close to zero, and the second (K2) is characterized by comparatively higher inclinations and mostly southern declination. The K1 component typically has lower intensity than K2. Some samples yield only one of these components (Figs. 4a–4d), but both components are fairly often present (Figs. 4e–4h).

In samples with both components present, the K1 component is typically a characteristic one (Figs. 4e–4g). This component is recognized from either a well-defined linear segment passing through the origin of coordinates on the Zijderveld diagram (Figs. 4e and 4f) or the behavior of the NRM vector during demagnetization process (Figs. 4g and 4h). Maximum values of unblocking temperatures point to hematite as a carrier of both magnetization components.

3. Members 4, 5, and 6. The NRM in samples from this interval shows very "noisy" behavior during the demagnetization process, but either both or one of the components K1 and K2 are rather often and reliably revealed against the noise background. The direction determination accuracy of both components from this section interval is considerably lower than from samples of member 7.

The vector set derived from the component analysis may be subdivided into two groups according to their temperature stability. The first includes vectors of the characteristic magnetization component, and the vectors of a less stable component form the second group. Interestingly, the K1 component is mostly characteristic, and K2 is typically less stable.

The vector distribution of the characteristic and less stable components is shown in Fig. 5. Monoclinal occurrence of the study rocks complicates the use of the fold test for determining the formation age of the inferred magnetization components. However, the Enkin modification of the fold test [Enkin, 1990] applied to the vectors associated with the K2 compo-

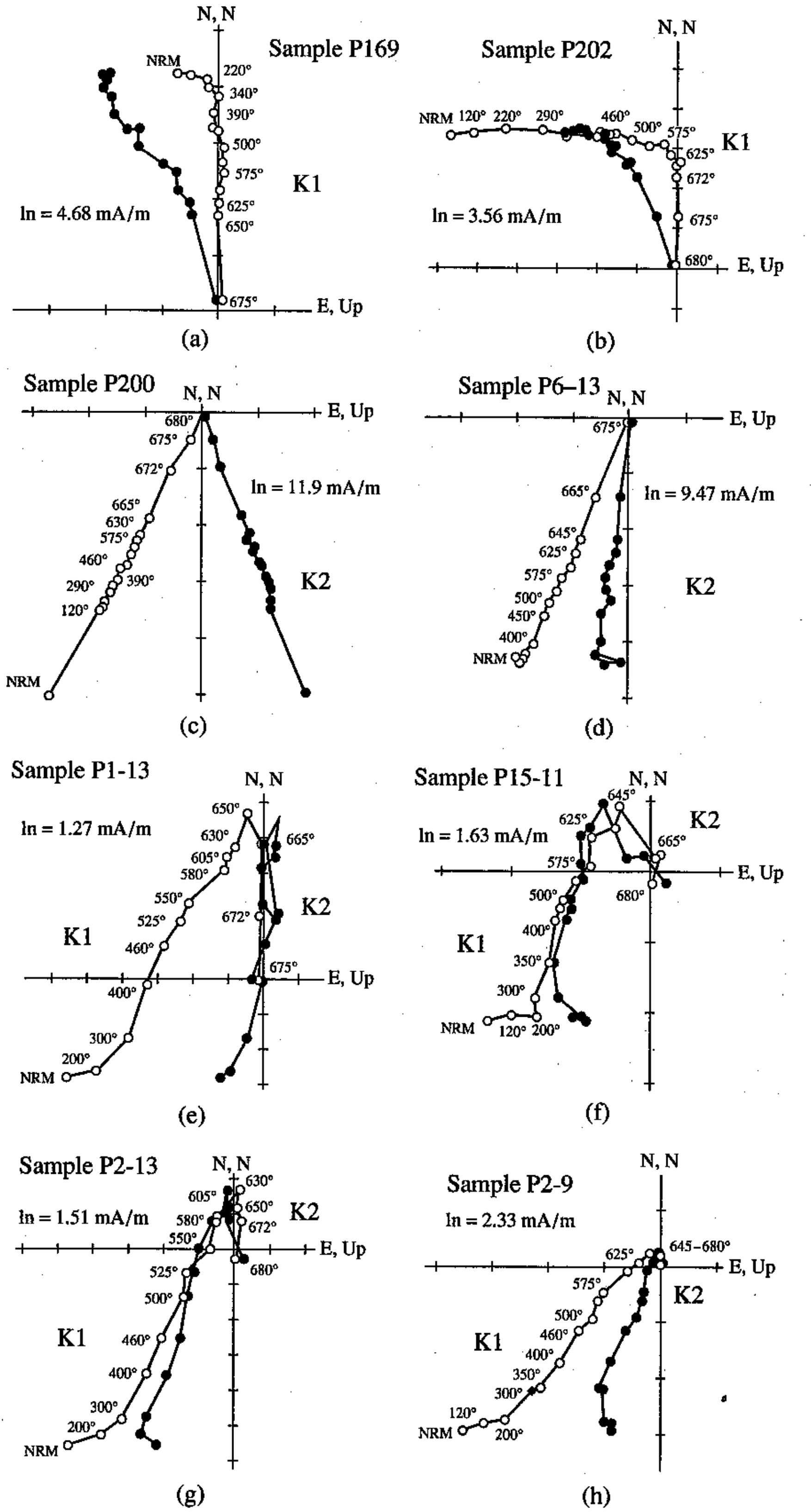

Fig. 4. Zijderveld diagrams of typical samples in stratigraphic coordinates. Solid and open circles are projections of vectors onto horizontal and vertical planes, respectively.

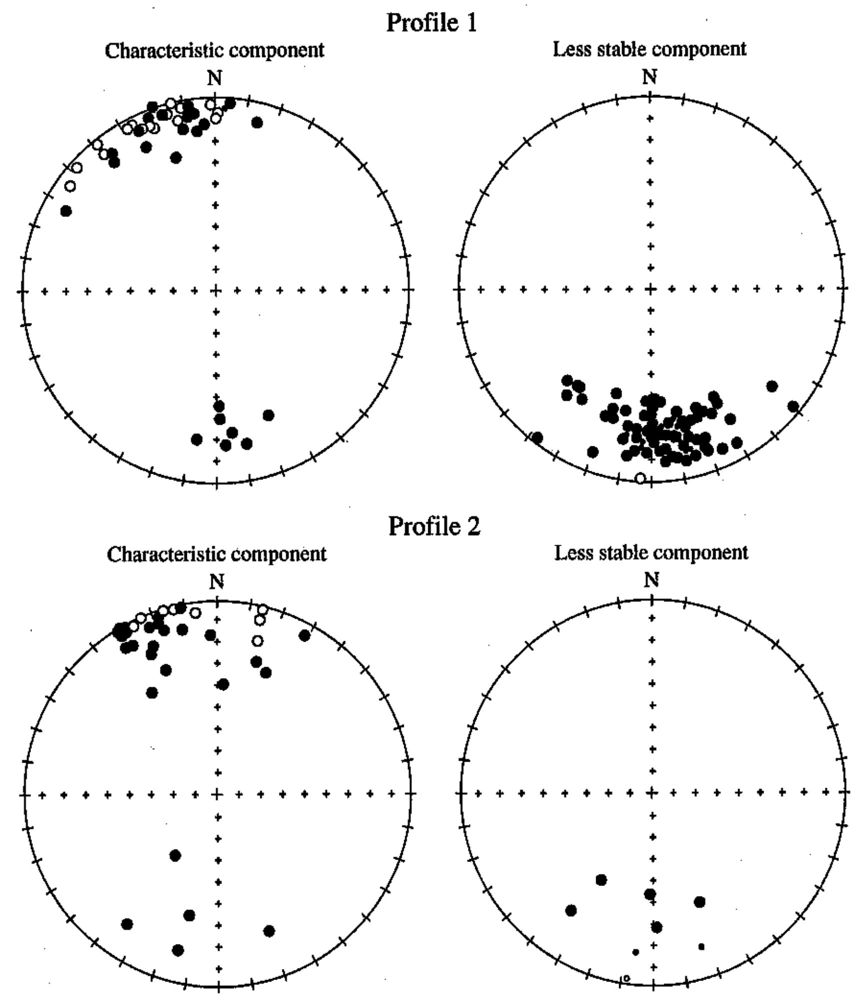

Fig. 5. Direction distributions of the characteristic and less stable components from the Polovinka section.

nent gives a definite result (probably, due to a large number of the vectors analyzed), indicating a prefolding age of this component. The result of the same test is indefinite for the vectors associated with the K1 component. However, even if the attitude elements of the study rocks were significantly different and the fold test yielded an assuredly prefolding age of magnetization, this would be practically useless for dating acquisition of the inferred components because the age of movements that changed the rock attitude is unknown.

In our case, much better constraints on the age of the components under consideration are derived from the comparison of their mean directions (Tables 1 and 2) with previously estimated paleomagnetic directions from the region studied. In the 1960s–1970s, V.P. Rodionov and A.N. Khramov [Khramov *et al.*, 1974] studied rocks of the Krovolutskaya (Llandeilian) and overlying Makarovskaya (supposedly Caradocian–Ashgillian) Formations, outcropping in numerous exposures in the Lena River valley. Their inferred paleomagnetic directions were confirmed by Torsvik *et al.* [1995a], who used up-to-date instrumentation and techniques. As seen from Fig. 6a, the paleomagnetic pole from the K1 component ($\Phi = -31.2°$, $\Lambda = 133.2°$, $dp/dm = 2.3°/4.6°$) agrees well with the pole obtained by these authors, whereas the paleomagnetic pole from the K2 component ($\Phi = -16.5°$, $\Lambda = 116.7°$, $dp/dm = 2.1°/3.9°$) lies close to Late Ordovician–Early Silurian poles.

Thus, we may state with confidence that the K1 component formed during or soon after formation of the rocks studied, and the K2 component is metachronous and as old as the Late Ordovician or younger. The territory under study is known to have emerged from water in the Late Ordovician and Early Silurian [Tesakov *et al.*, 1975], and at that time, the Polovinka rocks could have been involved in a zone of free water exchange, which might result in oxidation of ferrous iron minerals accompanied by formation of metachronous magnetization. In this case, unblocking temperatures of the K2 component are typically lower than those of the K1 component (Figs. 4e–4f).

Because the fact that K1 and K2 are two diachronous components, rather than two coeval components of opposite polarities, is crucial to our further interpretation, we give once more the arguments in favor of this statement.

1. These components have different directions; moreover, whereas the K1 pole lies near Llandeilian poles from the region considered, the K2 pole lies in the zone of Late Ordovician–Early Silurian poles.

2. The components have different physical properties for the following reasons: (a) in the majority of cases, their blocking temperatures are different; (b) the initial magnetization value for the K2 component is always greater than that for K1, and this relationship persists regardless of whether these components are single stable components in samples or both of them are present.

Declination and inclination along-profile distributions of the characteristic component are shown in Fig. 7. Reversed polarity being generally predominant, isolated vectors of normal polarity are observed on profile 1 and even form a group covering a 4-m interval on profile 2. May the presence of these vectors be considered as evidence of a normal polarity field that existed during the early Llandeilian? The answer to this question is most probably negative because, on the one hand, the reversal test [McFadden and McElhinny, 1990] applied to characteristic magnetization vectors of normal and reversed polarities gives a reliable negative result (profile 1: $\gamma = 32.0°$, $\gamma_{cr} = 14.0°$; profile 2: $\gamma = 51.5°$, $\gamma_{cr} = 18.8°$) and, on the other hand, the normal polarity vector set of characteristic magnetization is statistically indistinguishable from the less stable component K2.

The inferred vector distribution (Figs. 5a–5c) may be essentially interpreted as a result of superposition of a later (for example present) abrupt magnetization on an initially bipolar distribution of synchronous magnetization. However, first, detailed thermomagnetic cleaning reveals no presence of such a component, and second, if the actual paleomagnetic direction is estimated, in line with this hypothesis, by using the reversal test, one obtains a result diverging with the Llandeilian directions previously obtained from the Siberian platform (see the summary presented by Torsvik *et al.* [1995a]). An alternative hypothetical explanation of the inferred distribution is the assumption that a nondipole geomagnetic field existed in the mid-Ordovician, but this is not supported by magnetostratigraphic data from mid-Ordovician rocks in Sweden, indicating that the mean vector directions of normal and reversed polarities differ by an angle close to 180° [Torsvik *et al.*, 1995b]. Therefore, the characteristic magnetization vector distribution inferred from the Polovinka section may be most plausibly interpreted as a superposition of distributions of a synchronous reversed polarity component (K1) and a metachronous normal polarity component (K2).

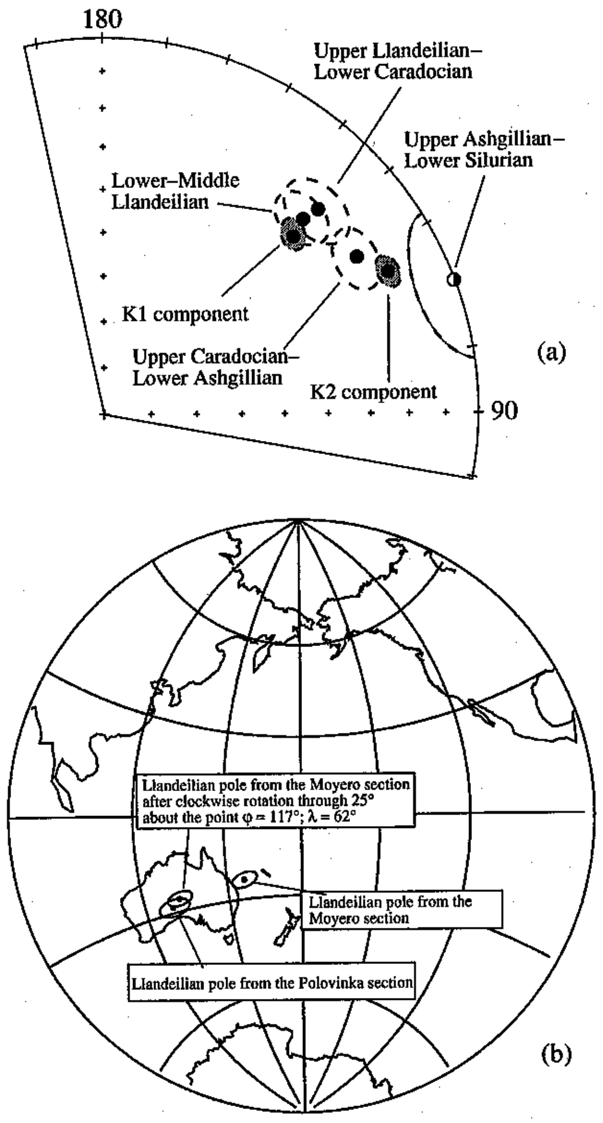

Fig. 6. (a) Comparison of Middle Ordovician–Early Silurian paleomagnetic poles from the K1 and K2 components and from the Aldan block, Siberian platform. (b) Comparison of Llandeilian paleomagnetic poles from the Aldan (Polovinka section) and Anabar (Moyero section) blocks, Siberian platform.

Should we understand this in the sense that a synchronous normal polarity magnetization is completely absent in the Llandeilian section studied? The answer is negative, but even if normal polarity zones are present in the section, their number and thickness are very small. Previously, we obtained a similar result from the study of Moyero River deposits of the lower Llandeilian. Moreover, in their study of coeval deposits of other Lena River sections, Torsvik *et al.* [1995a] derived directions that also had solely reversed polarity. Thus, these results give no evidence of a high frequency of geomagnetic polarity reversals during the early Lland-

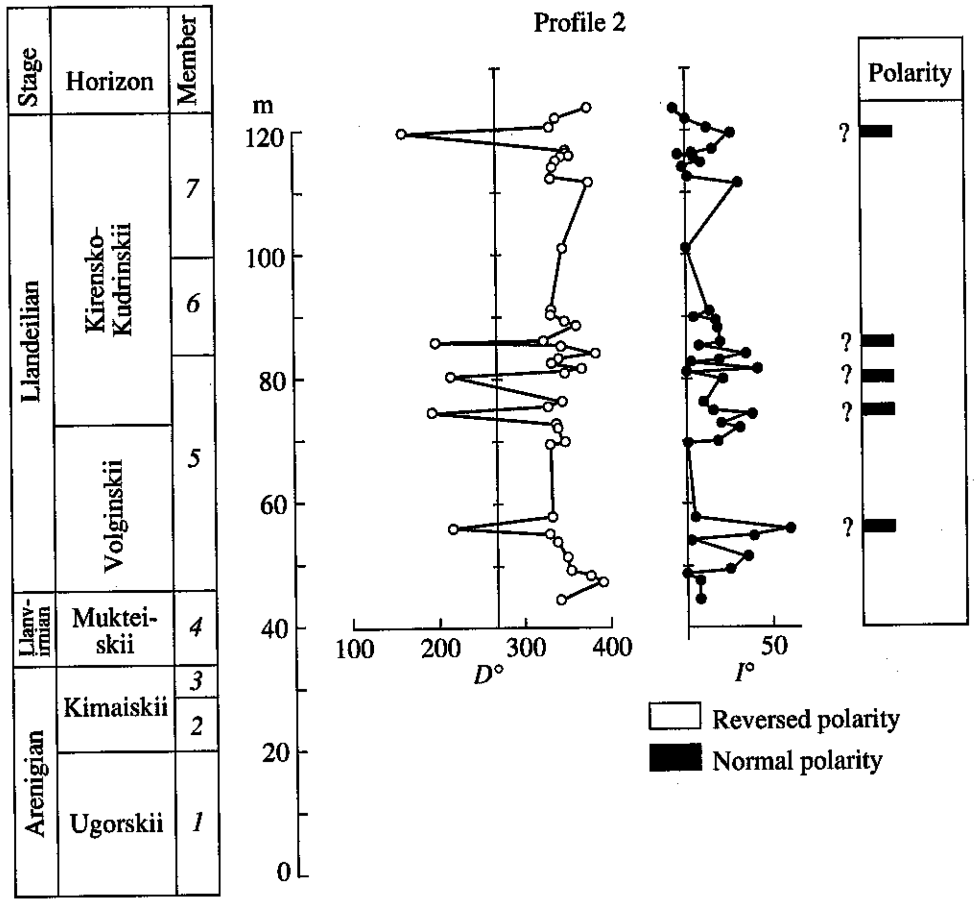

Fig. 7. Variations in declination and inclination of the characteristic component along the profiles studied.

eilian and indicate that this time period was dominated by a reversed polarity field.

The inferred paleomagnetic directions may be used for verifying the hypothesis on relative rotation of the Aldan and Anabar blocks of the Siberian platform at the post-Early Silurian time. This hypothesis was first proposed by Gurevich [1984], who compared paleomagnetic directions of mid-Ordovician deposits in the Lena and Moyero river valleys. Based on a considerably longer series of paleomagnetic determinations, Gallet and Pavlov [1996] and Pavlov and Petrov [1997] confirmed and refined this hypothesis. New results, obtained with the use of the same up-to-date paleomagnetic instrumental and processing procedures, enable comparison of paleomagnetic directions.

Figure 6b shows the Llandeilian position of paleomagnetic poles from the northern (Moyero River valley, Anabar block) and southeastern (Polovinka section, Lena River valley, Aldan block) Siberian platform before and after a clockwise rotation of the Anabar block through 25° around the Euler pole with coordinates ($\lambda = 117°$; $\varphi = 62°$), which lies at the base of the Vilyui aulacogen (for details see [Pavlov and Petrov, 1997]). As seen from the figure, such rotation virtually brings these poles into coincidence, which additionally confirms the relative rotation of the Anabar and Aldan blocks at the post-Ordovician time.

Table 2. Mean directions of the less stable component

	N	Geographic coordinates				Stratigraphic coordinates			
		D	I	K	α_{95}	D	I	K	α_{95}
Profile 1	82	178.0	29.1	17.6	3.8	176.3	25.2	19.2	3.7
Profile 2	8	184.3	38.6	10.6	17.9	184.3	28.3	11.4	17.1
Total (component K2)	90	178.4	30.0	16.5	3.8	177.0	25.4	18.2	3.6

Note: See Note to Table 1.

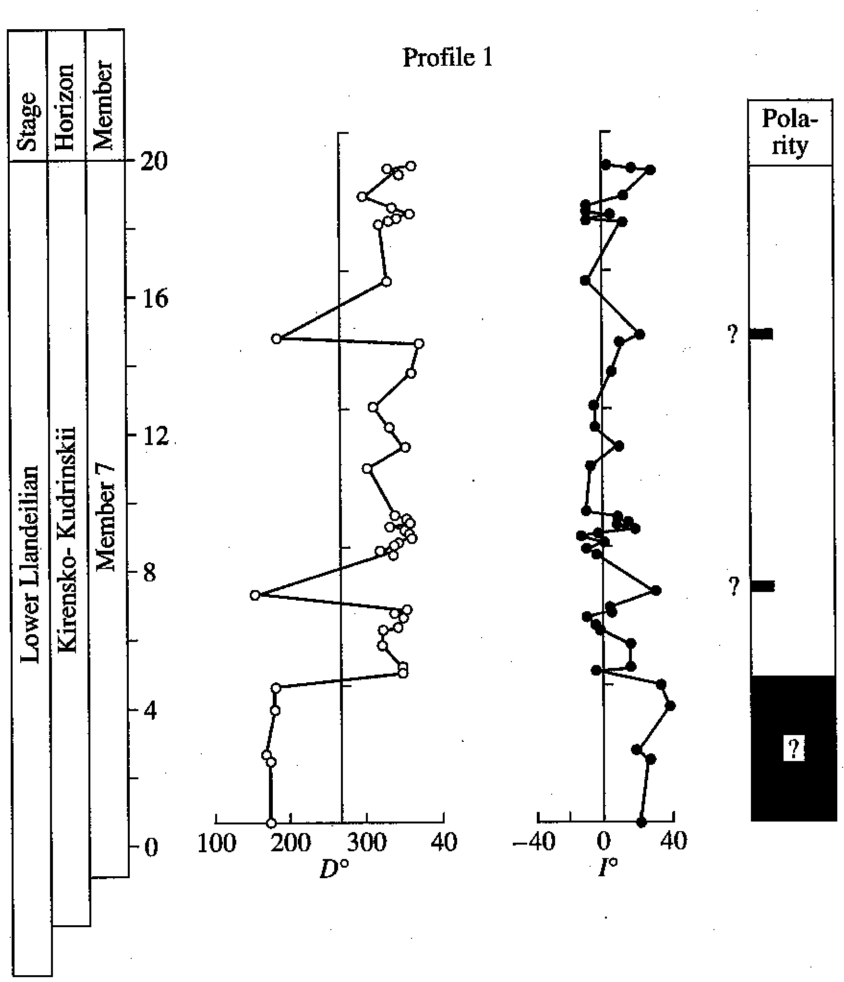

Fig. 7. (Contd.)

CONCLUSIONS

1. The geomagnetic field in the early Llandeilian was dominated by reversed polarity with very rare or completely absent episodes of normal polarity.

2. Our data indicate that Ordovician deposits of the Lena River typically carry a Late Ordovician–Early Silurian overprint, which should be taken into account in order to correctly interpret the magnetostratigraphic record.

3. Comparison between the Llandeilian paleomagnetic poles from the northern and southeastern Siberian platform, derived with the use of the same up-to-date paleomagnetic instrumentation and processing procedures, confirms the previously inferred conclusion [Gurevich, 1984; Pavlov and Petrov, 1997] about a relative rotation of the Aldan and Anabar blocks at the post-Ordovician time.

ACKNOWLEDGMENTS

We are grateful to Vincent Courtillot, the director of the Paris Institute of Earth Physics, who provided us with the possibility to perform thermal demagnetization of samples using the instrumentation of the Institute's paleomagnetic laboratory and R. Enkin, Geological Survey of Canada, who afforded us his paleomagnetic software free of charge. This work was supported by the Russian Foundation for Basic Research, project nos. 95- 05-14519 and 97-05-64798.

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Variations in Groundwater Levels of the Garm Test Area, Tajikistan, and Possibilities of Earthquake Prediction

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Received August 25, 1997; in final form April 14, 1998

Abstract—Groundwater level variations in six wells within the test area are considered in a series time range of a few hours to a few years. It is shown that both long-term and short-term hydrogeodynamic earthquake precursors with $K \leq 13$, as well as groundwater level variations caused by lunisolar tidal waves, are clearly observed in the wells mostly confined to high mountain plateaus. Wells drilled on flood plain terraces commonly reveal small-amplitude variations associated with tidal waves and yield no evidence of hydrogeodynamic precursors. An exception is flood plain wells, in which groundwater level variations caused by low-frequency wave trains from remote strong earthquakes are observed.

INTRODUCTION

According to the present concepts, variations in the stress–strain state of the medium occur in large volumes of the crust at various stages of the preparation of an earthquake. They are manifested as changes in geophysical, hydrogeodynamic, and other parameters. The problem of earthquake prediction can only be solved on the basis of the analysis of the whole data set by various methods. However, one should first clearly realize the prediction possibilities of every individual method. This paper presents a retrospective review of the prediction possibilities provided by observations of groundwater level variations in wells of the Garm test area [Nersesov *et al.*, 1990a]. From the standpoint of instrumentation, such observations are simplest.

Hydrogeodynamic earthquake precursors have been discussed in a number of publications [Sadovsky *et al.*, 1977; Monakhov *et al.*, 1979; Kissin, 1982; Sobolev, 1993; Kissin, 1984; Kissin and Savin, 1986]. Previously, we presented the results derived from the studies of groundwater level variations at the Garm test area in a series of papers [Bokanenko *et al.*, 1990; Bokanenko *et al.*, 1992]. However, they addressed individual periods or problems of the studies. Here, the data concerning various aspects of the groundwater level observations are generalized for the longer-term interval of a decade from 1979 to 1988. In so doing, we focus on three issues: (1) groundwater level variations in various time ranges, (2) hydrogeodynamic earthquake precursors in the same time ranges, and (3) selection criteria for hydrogeodynamic observation areas most promising for the purposes of earthquake prediction.

The data presented below were obtained from well monitoring observations conducted by the Joint Seismological Expedition (JSE) of the Institute of Physics of the Earth, Academy of Sciences of the USSR. The studies were initiated by the Head of JSE I.L. Nersesov and proceeded under his permanent supervision. Very helpful was the collaboration of V.N. Krat from the South Hydrogeologic Expedition of the Geological Administration of the Tajik SSR.

CHARACTERISTICS OF THE WELLS

By the end of 1988, observations of groundwater level variations were conducted at six sites of the Garm test area (Fig. 1) in wells with depths of 80 to 400 m (Table 1). Levels of interstitial and formation water within Quaternary deposits widely developed in the Surkhob and Obikhingou river valleys. Geological parameters of the rocks penetrated by the wells are presented in Table 1. Hydrographically, five wells are drilled in the basin of the Surkhob River (Fig. 1), and the sixth one (Tavil’-Dara), in the Obikhingou River valley. Orographically, mouths of three wells (JSE, Zavod, and Tavil’-Dara) are located on the first-level floodplain terraces. Mouths of the Navdy and Khait wells are located on high mountain plateaus. The Glubokaya well is intermediate: it was drilled from a slope surface in the transition zone between a high mountain plateau and a floodplain terrace of the Surkhob River.

INSTRUMENTATION

In order to perform the level observations, the well top was cased with a reinforced concrete conduit-pipe ring 1 m in both height and diameter. From the top, the ring was closed with a steel lid with a minor rim.

On a support in the tube, an analog float water-level gage [Bokanenko and Perederin, 1990] was installed. The gage had the following characteristics: internal well diameter, not less than 110 mm; range of water-