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Accessory Minerals in Phosphorites of the Lesser Karatau as an Indicator of Provenance Composition

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Abstract—Issue of determination of the provenance composition based on accessory minerals in the Lesser Karatau phosphate-bearing basin is considered. Detailed lithological studies revealed six types of phosphate-bearing sections with specific composition and genetic affinity of accessory minerals. Vertical and lateral distributions of these minerals are shown for both individual deposits and the entire paleobasin. Data on the composition, genesis, and distribution of accessory minerals in phosphorites of the Lesser Karatau are used to determine the composition of ancient provenance.

Phosphorites of the Lesser Karatau (southern Kazakhstan) have been studied for a long time. Numerous publications consider various aspects of lithology, geochemistry, and mineralogy of the region. Many researchers consider the Lesser Karatau area as a model for phosphorite formation (Eganov and Sovetov, 1979; Paul and Kholodov, 1999), because its geological evolution was also accompanied by complex chemogenic–biogenic processes typical of other Vendian–Cambrian phosphate-bearing basins.

The enrichment of seas with phosphorus at that time is well known. It is thought that phosphorus could by delivered from land, because geological history demonstrates a distinct relationship of changes in the provenance composition with formation and distribution of various types of mineral resources on the Earth’s surface (Bushinskii, 1966; Strakhov, 1963; Kholodov, 1975, 1993, 1996; Yanshin, 1983). Unfortunately, rocks surrounding ancient phosphate-bearing basins are usually overlain by a thick cover of younger sediments. Therefore, geophysical data give only a general idea of composition and occurrence patterns of old rocks.

Study of the distribution of accessory minerals in paleobasins may provide an important information on the composition and location of ancient provenances. Nevertheless, such works have never been carried out in any phosphate-bearing paleobasins. This paper is aimed to fill this gap with the Lesser Karatau as an example, i.e., to determine the composition and location of probable provenances using genesis and spatial distribution of accessory minerals from the phosphate-bearing formation as an indicator.

In order to accomplish this task, one should fulfill the following conditions: (1) clearly understand the meaning of provenances and the role of accessory minerals in the determination of the composition of provenances; (2) calculate the necessary and reasonable number of samples and their volume (weight) for obtaining the representative information; (3) elaborate method for the extraction of accessory minerals from rocks (phosphorites, dolomites, and cherts) with minimal loss and select the most optimal method of their determination; (4) discriminate between two indicative (authigenic and allothigenic) groups of minerals and define their genesis; and (5) study trends in the lateral and vertical distribution of accessory minerals.

PROVENANCES

The term “provenance” was introduced into the geological literature in 1922 by G.B. Mil’ner who elaborated main principles and method for the determination of its composition using accessory minerals (Mil’ner, 1968). The main method for determining the provenance composition, is based on the study of minerals of the heavy fraction, because the light fraction contains an insufficient number of components to adequately reflect individual features of provenances (Baturin, 1947).

Baturin described all geological factors responsible for the formation of various sedimentary rocks (petrographic provenances). He showed that various rock combinations could produce sedimentary material of similar composition and *vice versa*; i.e., similar rocks could provide various sedimentary materials under different sedimentation conditions.

One can identify several associations of accessory minerals for a correct interpretation of the probable type of provenance rocks. For instance, the occurrence of disthene, staurolite, or sillimanite suggests that metamorphic rocks play a substantial or even decisive role in eroded areas. Pyroxenes, spinel, and chromite indicate the ultramafic composition of source rocks. However, pyroxenes can also prevail in mafic intrusive rocks. Zircon, apatite, sphene, hornblende, and monazite are indicators of acid igneous rocks. A detailed study of diagnostic features is required to define the genesis of apatite and sphene. Apatite in ancient formations is generally authigenic, which is evident from the hexagonal prismatic shape of its crystals and absence of any defects on crystal facets. Detrital sphene can be metamorphic. In this case, the mineral is brownish yellow and easily distinguished from the colorless and transparent variety in acid intrusive rocks.

If the provenance is largely composed of basic and intermediate volcanics, the heavy fraction is usually dominated by pyroxenes and hornblendes, whereas the light fraction always contains fragments of effusive rocks. Pyroxenes with associated ilmenite and magnetite represent a significant component of mafic intrusions. The magnetite and ilmenite contents in volcanics amount to 3.15 and 1.45%, respectively. However, ilmenite always prevails over magnetite in sedimentary rocks. Such a distribution pattern of these minerals is related to the high resistance of ilmenite to chemical and physical weathering. This mineral is widespread in various rocks. Therefore, the find of less common magnetite can play an important role in the determination of the provenance composition.

The study of ancient rocks is a complicated task. Regardless of the origin of rocks, they always contain so-called stable minerals (zircon, garnet, tourmaline, and rutile). This phenomenon is insufficiently studied so far, but it should be taken into consideration when interpreting the provenance composition. Moreover, some minerals can be inherited from older rocks. One should also keep in mind that provenances can be heterogeneous in composition. In other words, we should scrutinize properties of individual minerals and the entire mineral association to interprete the composition of source rocks.

Despite many complexities accompanying the study of heavy fraction and interpretation of obtained data, investigation of accessory minerals is an essential task, because they represent “fragments of ancient provenances, which avoided intense chemical destruction” (Baturin, 1947, p. 125).

GEOLOGICAL STRUCTURE OF THE LESSER KARATAU AND SAMPLING METHOD

The Lesser Karatau Ridge is 120 km long and 20 to 30 km wide. It hosts more than 40 phosphorite deposits and occurrences confined to the Chulaktau Formation of the Lower Cambrian Tommotian Stage (Missarzhevskii and Mambetov, 1981). The productive formation is underlain by the Precambrian volcanogenic–terrigenous sequence many kilometers thick and is overlain by the thick carbonate member of the Cambrian–Ordovician Shabakty Formation.

The geological structure of the Lesser Karatau is described in several works (Ankinovich, 1961; Eganov and Sovetov, 1979; Kholodov, 1973; Krasil’nikova, 1975; Sagunov, 1971; Tabyldiev and Cherbyanova, 1976; and others). The majority of researchers subdivide the Chulaktau Formation into four (lower dolomite, siliceous, phosphate, and ferromanganese) units. The productive formation is composed of one to three phosphate members separated by carbonate–siliceous shales. Based on numerous studies and original observations, productive formation sections of the Lesser Karatau can be subdivided into six (lenticular–brecciated carbonate, conglomeratic siliceous–carbonate, stromatolitic–biomorphic siliceous, massive carbonate, highly productive stratified-schistosed, and layered-schistosed siliceous) types.

Sampling method plays an important role in the study of spatial distribution of accessory minerals. Sufficiently objective information can be obtained by sampling in sections of different types. This provides the most reliable and complete data on the composition and spatial (vertical and lateral) distribution of accessory minerals. The availability of many replicate samples makes it possible to smooth out errors by the statistical analysis. Figure 1 demonstrates generalized section types and sampling levels.

(I) Lenticular–brecciated carbonate type. Phosphate-bearing sections of this type are observed in the Baba-ata, Karaul-tyube, Aladzhar, and Kyrshabakty-I areas. They are characterized by small thickness of all units and wide distribution of clastic material. The lower dolomite unit is composed of massive (locally brecciated) medium-grained dolomites. The siliceous unit contains rare layers and lenses of chalcedony rock. The phosphate unit is characterized by the lenticular structure with lenses up to 3.0–3.5 m thick and 15 m long. It is composed of gray carbonate–phosphate sandstones (phosphate breccia with carbonate cement). Phosphorites host intercalations of cherts and shales with lenses of carbonate breccia-conglomerate. The ferromanganese unit is composed of a thin dolomite layer with brownish pink color owing to ferromanganese hydroxides. Sampling was carried out at the Baba-ata phosphate occurrence, where eight samples were taken from two sections.

II. Conglomeratic siliceous–carbonate type. Phosphate-bearing sections of this type are observed in the Severnye Berkuty, Batyrbai-1, Batyrbai-2, Aktas, Karashat, Kyrshatbakty-II, and Aral-tyube areas. The lower dolomite unit (3–5 m thick) hosts carbonate block-breccia. The siliceous unit is found as fragments in sections of this type. The thin productive unit (carbonate–siliceous phosphorites) contains phosphate–carbonate conglomerate beds in the basal and uppermost parts. The middle part contains interlayers and lenses of carbonate shales. The ferromanganese unit makes up a discrete chain of narrow elongated lenses of pinkish brown dolomite with abundant ferromanganese hydroxides. Sampling (18 samples in total) was carried in three sections of this type exposed at the Severnye Berkuty phosphate occurrence.

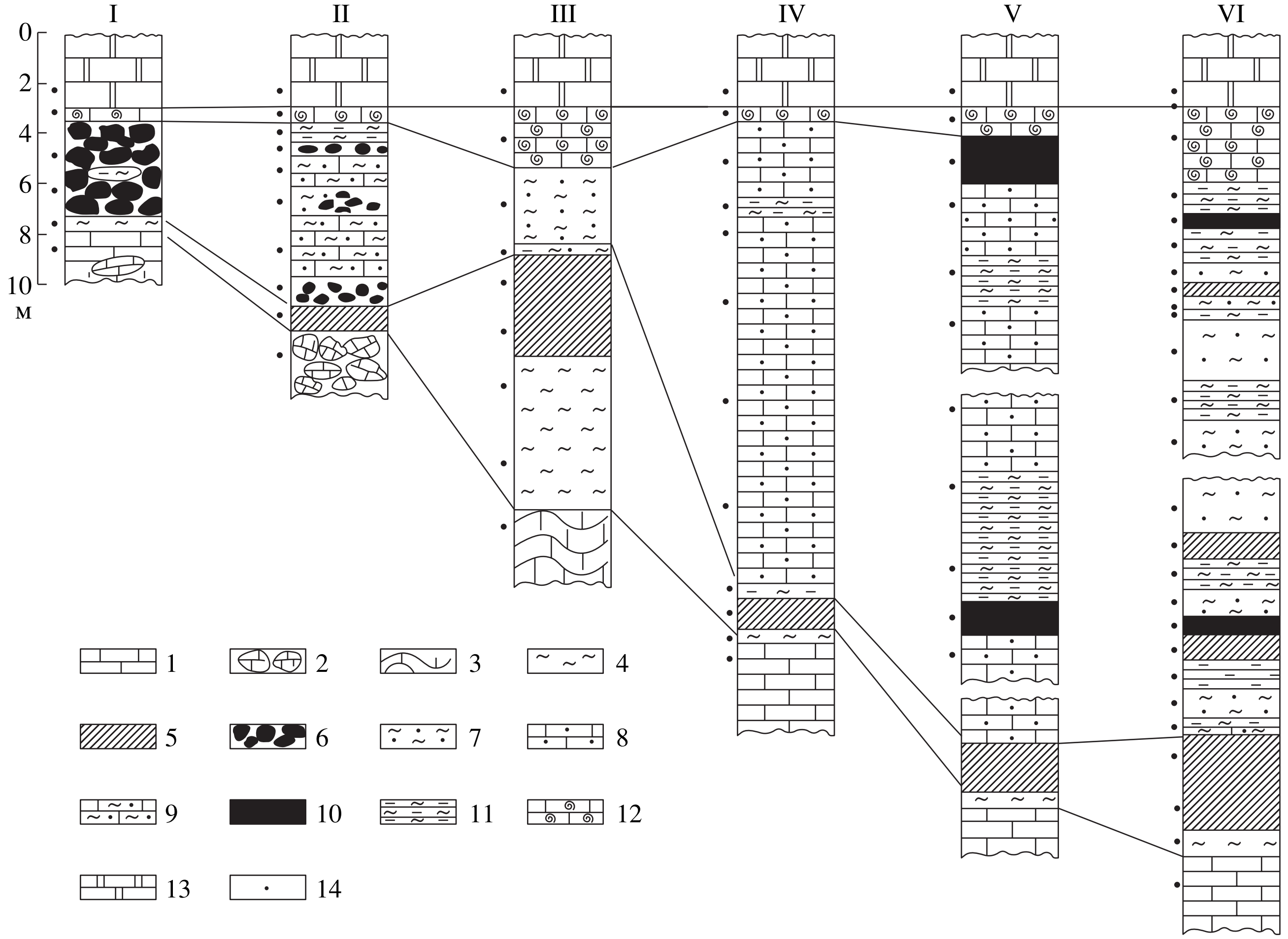

Fig. 1. Types of productive formation sections in the Lesser Karatau. Lower dolomites: (1) massive, (2) brecciated, (3) stromatolitic; siliceous unit: 4) spongolites, (5) phtanites; phosphate unit: (6) breccia-conglomerate, (7) siliceous phosphorites, (8) carbonate phosphorite, (9) carbonate–siliceous phosphorite, (10) monomineral phosphorite, (11) carbonate–siliceous shales, (12) dolomites of the ferromanganese unit; (13) brown dolomites of the Shabakty Formation; (14) sampling sites.

III. Stromatolitic–biomorphic siliceous type. Phosphate-bearing sections of this type are found in the Dzhilan, Berkuty, and Degeres areas. The lower dolomite unit in these sections have the columnar–stromatolitic structure. The base of the thick siliceous unit includes biostrome (Eganov, 1988). The lower part is composed of spongoliths, whereas the upper part consists of phtanites locally transformed by weathering processes into carbonate–siliceous shales (Kholodov, 1973). Nodular, stratiform, and columnar stromatolite buildups are abundant in the entire siliceous unit (Eganov, 1988; Litvinova, 1991). The productive unit has a small thickness and siliceous composition. These sections are characterized by the most complete structure and maximal thickness of the ferromanganese unit (3–4 m). Its algal structure is emphasized by the selective distribution of Fe and Mn in dolomites. It contains abundant oncolites varying in size from < 0.01 to 25 mm. Sampling was carried out in three sections of the most complete and well-exposed Dzhilan phosphorite occurrence (33 samples).

IV. Massive carbonate type. Phosphate-bearing sections of this type are found at the Kotrtas and Arkhalysai phosphorite occurrences and the Geres, Tuatary, and Kis-tas deposits. The lower dolomite unit is composed of dark gray dolomites locally characterized by coarse wavy–layered and less commonly columnar–stromatolitic structures. The siliceous unit is composed of separate chalcedony lenses. The productive unit (carbonate phosphorites) forms a uniform sequence (20–30 m) with rare lenses of carbonate shales. The ferromanganese unit consists of pink or dark brown dolomites with ferromanganese hydroxides and rare phosphate grains. The total thickness of the Chulaktau Formation can be as high as 40 m. Sampling was performed at the Geres deposit, where all units of the productive formation are represented to a variable extent. In total, 24 samples were taken from three sections.

V. Highly productive stratified-schistosed type. Phosphate-bearing sections characterizes of this type are found in the largest Zhanatas, Koksu, and Dzhartas deposits. The lower dolomite unit is composed of mas-

Table 1. Number of samples collected in deposits of different types

Section type	I	II	III	IV	V	VI
Phosphorite deposit	Baba-ata	Severnye Berkuty	Dzhilan	Geres	Koksu	Akdzhar
Number of sections	2	3	3	4	4	4
Number of samples	8	18	33	24	44	54

sive dolomites (crystallized bioherms). The thin siliceous unit usually consists of chalcedony rocks with abundant interlayers and lenses of dolomites.

The productive sequence contains two phosphate members in the Zhanatas and Dzhartas deposits and three phosphate members in the Koksu deposit. They are separated by carbonate shales. Phosphorites include phosphate pellets, which are incorporated into the carbonate–phosphate material, and interbeds of monomineral phosphorites. The uppermost part of productive beds occasionally contains a layer of phosphate conglomerate consisting of carbonate shale fragments. The ferromanganese unit includes separate small lenses of claret dolomite with abundant ferromanganese hydroxides. The total thickness of the Chulaktau Formation is 40 m. Sampling was carried out along four exploration trenches in the Koksu deposit (44 samples).

VI. Layered-schistosed siliceous type. Phosphate-bearing sections of this type occur in the Uchbas, Sarkoba, and Akdzhar deposits. The lower dolomite unit is mainly composed of fine-grained dolomite. Like in the section of type III, the siliceous unit in type VI is characterized by the complete succession: basal biostrome (0.2–0.5 m), spongolites in the lower part, and phtanites in the upper part. Beds and lenses of phosphate–siliceous rocks are abundant in the upper part. The phosphate unit is usually composed of an alternation of phosphorites and intensely phosphatized siliceous shales. Phosphorites can be carbonate, siliceous, and even monomineral. Upsection, the share of phosphate material increases, while the share of siliceous material decreases. The ferromanganese unit (2.5 to 4.0 m thick) is composed of dolomites with an irregular impregnation of Fe and Mn. The rocks are characterized by wavy–bedded structure well developed in the middle part of the section and enclose rare isolated oncolites. Total thickness of the Chulaktau Formation locally amounts to 40 m. Sections of this type are complicated by fractures. Therefore, the least distorted Akdzhar deposit was selected for sampling. In total, 54 samples were taken along four exploration trenches.

Table 1 presents the total number of samples taken from different sections.

The studied rock sections were accumulated in different sedimentation settings of a single basin and controlled by their position within the basin (Fig. 2). For instance, sections of types I–III characterized by a small thickness were deposited in shallow-water settings. Lenticular–brecciated carbonate phosphorites formed in the tidal zone. Conglomerartic siliceous–carbonate phosphorites accumulated along the shoreline of the basin, because conglomerates rolled over the bottom during a longer time (relative to breccia) during the reworking of phosphate material. In the central part of the basin, where stromatolitic–biomorphic siliceous phosphorites accumulated, the intensity of biogenic structure development is comparable with that of younger reefal buildups (banks).

Sections of types IV–VI formed in relatively deep settings of the northwestern part of the basin. They are thick and characterized by good sorting of fine-grained silty–clayey phosphate–carbonate material. Massive carbonate and monomineral stratified-schistosed phosphorites accumulated in calm settings, whereas layered-schistosed siliceous phosphorites formed during permanent currents transporting the silty–clayey material.

Samples weighing 1 kg were carefully taken from every unit of the Chulaktau Formation in order to rule out their contamination with minerals from postore dikes. In deposits with an intricate structure of the phosphate unit, samples were collected from every sequence with a different type of lithology. Sampling was carried out along three or four cross sections in the central part and flanks of each deposit. In total, 181 samples were taken for the analysis (Table 1).

METHOD OF EXTRACTION AND DIAGNOSTICS OF ACCESSORY MINERALS

The main method of diagnostics of accessory minerals is separation of ore concentrate into fractions with a small number of minerals (Chueva, 1950; Mil'ner, 1968).

The rock sample treatment included the following procedures: crushing up to particle size of 1 mm, dissolution in acetic acid, averaging, screening through the sieve, magnetic and electromagnetic separation, and separation by the specific weight in heavy liquids. Magnetic separation was performed after averaging of the sample. Minerals with weak magnetic properties were extracted using the electromagnetic separation method. Based on magnetic properties, all minerals were divided into three (highly, moderately and slightly electromagnetic) fractions. As is known, magnetic properties of minerals are mainly determined by the Fe contents (Mil'ner, 1968). Therefore, the highly magnetic fraction includes black and opaque Fe-bearing ore minerals characterized by a high specific weight (hematite, ilmenite, and chromite). The moderately magnetic fraction mostly consists of colored and transparent rock-

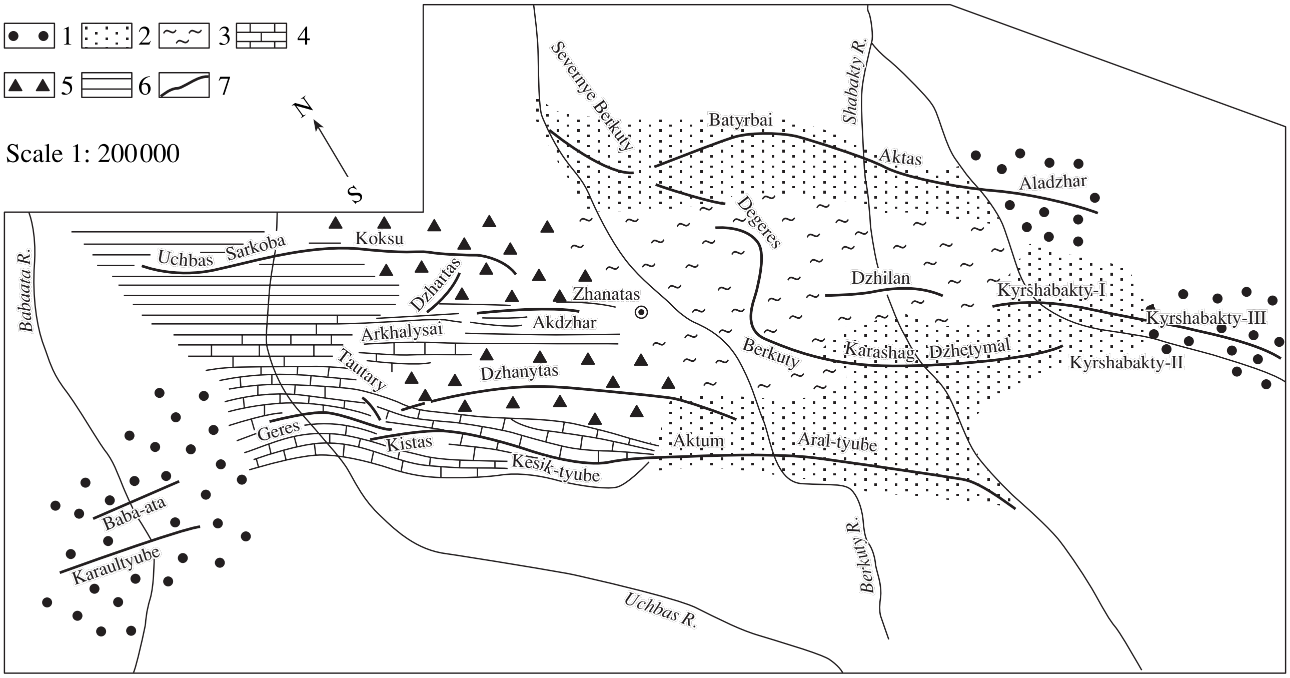

Fig. 2. Distribution of different Chulaktau Formation sections in the Lesser Karatau. Types of phosphate-bearing sections: (1) lenticular–brecciated carbonate, (2) conglomeratic siliceous–carbonate, (3) stromatolitic–biomorphic siliceous, (4) massive carbonate, (5) highly productive stratified-schistosed, (6) layered-schistosed siliceous; (7) exposures of the Chulaktau Formation.

forming silicates with the specific weight <4 g/cm^3 (amphiboles, pyroxenes, garnet, and epidote). The weakly electromagnetic fraction includes Fe-poor minerals or minerals with magnetic property controlled by the content of manganese oxides, rare earth elements and other components.

At the following treatment stage, the nonelectromagnetic fraction was separated in heavy liquid (bromoform, density 2.8–2.9) to remove minerals of the light fraction, because they contaminate samples and hamper the mineralogical analysis. The concentrate separation in bromoform is usually a rapidly and effective process (Chueva, 1950). However, it is time-consuming and complicated in the case of fine-grained samples. Moreover, some heavy minerals occurring in intergrowths with light minerals remain in the suspended state. Therefore, the heavy fraction was additionally examined under binocular microscope after the separation of ore concentrate.

Despite the representativeness of samples, the weight of each fraction was only a few grams, i.e., 0.3–0.8% of the sample weight. Minerals were determined in immersion liquids using the traditional procedure.

Identification of minerals in immersion liquids is based on the determination of the highest and lowest optical values among the series of measurements of several mineral grains. However, our task was complicated by the availability of a limited number of mineral grains. Therefore, one had to search for crushed mineral grains with oriented cross section, which depends on cleavage of minerals. Intermediate parameters Ng and Np were used to determine the major cross sections. As a result, 17 minerals were identified.

ACCESSORY MINERALS

The light fraction mainly includes clay minerals, quartz, amorphous silica (sometimes ferruginate), carbonate and phosphorite intergrowths, and silicified phosphorite. Micas with the specific weight of 2.8–3.2 g/cm^3 were concentrated in the heavy fraction.

The heavy fraction includes ilmenite, pyroxenes, amphiboles, rutile, zircon, garnet, magnetite, apatite, biotite, pyrite, epidote, staurolite, tourmaline, sphene, muscovite, hematite, and chrome-spinels. All of them are subdivided into two (authigenic and detrital or clastogene) groups. Their assumed genesis is indicated in Table 2. The first group includes apatite, pyrite, and partially rutile. All remaining minerals form the second group. Authigenic (*in situ*) minerals are characterized by well-developed crystalline shapes. Detrital accessory minerals are usually rounded due to prolonged transportation.

1. Authigenic Minerals

Apatite is present as tiny (0.01 mm) transparent greenish grains of a regular prismatic shape lacking signs of reworking and inclusions.

Pyrite occurs as brass–yellow, cubic crystals, sometimes with dim iridescence owing to later alterations. Some cubic facets bear striation.

Rutile is characterized by high refraction. It forms prismatic, less commonly acicular, reddish brown to dark brown crystals with pyramids at prism apexes. No signs of reworking are observed.

2. Detrital (clastogene) Minerals

Magnetite, ilmenite, pyroxenes, amphiboles, zircon, and garnet are most abundant.

Magnetite occurs as rounded dim gray opaque cleavage-free grains with serrate fracture.

Ilmenite is observed as angular irregular black opaque grains. The less common well-rounded grains show transitions to iron hydroxides and are typical of the ferromanganese unit.

Pyroxenes are present as well-rounded yellowish green grains with round cross section.

Amphiboles compose subrounded anisotropic, bluish green to dark green, irregular grains elongated along cleavage planes.

Zircon occurs as subrounded transparent colorless (less commonly, pink pale) grains with irregular fracture.

Garnet is observed as well-rounded rhombic violet–red grains wit irregular fracture and inclusions of biotite and less common zircon.

Biotite, rutile, and epidote are less common among detrital minerals in rocks of the phosphate formation.

Biotite occurs as large (0.2–0.4 mm) irregular platy brown flakes, (sometimes with irregular edges) lacking signs of reworking.

Rutile is present as subangular irregular amber-colored grains with irregular fracture and glassy luster.

Epidote forms dim yellowish green irregular grains resembling bottle glass in color, transparency, and shape.

Staurolite, hematite, tourmaline, sphene, muscovite and chrome-spinels are least common among the detrital minerals.

Staurolite occurs as yellowish brown irregular grains with serrate fracture and cleavage planes. In immersion, it demonstrates pleochroism from yellow to reddish color. Some grain facets are overgrown with thin mica (muscovite?) flakes.

Hematite is observed as irregular to rounded, ashy (reddish brown in reflected light), cleavage-free grains with irregular semitransparent to opaque fracture and dim luster. Thin splinters of the mineral display a blood-red color in the transmitted light.

Tourmaline forms irregular, elongate to elongated-prismatic, transparent bluish green grains with irregular fracture. They lack signs of reworking, but contain scarce zircon inclusions.

Table 2. Probable genesis of accessory minerals from the Chulaktau Formation

Authigenic			Rutile, apatite, and pyrite
Detrital	From metamorphic rocks		Tourmaline, biotite, garnet, epidote, amphiboles, hematite, muscovite, staurolite, sphene, and rutile
	From magmatic rocks	From basic and alkaline rocks	Magnetite, pyroxenes, magnetite, and biotite
		From acid rocks	Zircon, muscovite, biotite, and rutile

Sphene occurs as subrounded to rounded, brownish orange, irregular grains with cleavage along /110/.

Muscovite is present in the form of large (0.3 mm) thin transparent rounded flakes with perfect cleavage, low refraction, and wavy extinction.

Chrome-spinels occur as rounded, black to brownish black, angular grains with irregular fracture. In thin splinters, the minerals are yellowish red to brown.

The proportion of minerals of the heavy fraction, i.e., authigenic and detrital (metamorphic and magmatic) minerals, is 1 : 2 : 4 (Table 2).

DISTRIBUTION OF ACCESSORY MINERALS IN ROCKS OF THE LESSER KARATAU

We analyzed the following three aspects of accessory mineral distribution in rocks of the Lesser Karatau: (1) compositional changes of mineral associations in separate deposits; (2) comparison of mineral compositions in sections of different types; and (3) distribution of minerals in different units of the productive formation.

We studied compositional changes in heavy fractions from the following six deposits representing all types of sections: Baba-ata (I), Severnye Berkuty (II), Dzhilan (III), Geres (IV), Koksu (V), and Akdzhar (VI). We also compared the qualitative and quantitative mineral compositions of several sections in each deposit. The results indicate that accessory minerals are rather regularly distributed. Some decrease in their concentrations is registered only at flanks where the thickness of rock units is significantly reduced.

Comparison of data on the distribution of accessory minerals in different deposits revealed that they are universally characterized by virtually similar compositions (Table 3). However, authigenic minerals and minerals from metamorphic and igneous rocks show different patterns of behavior. For instance, minerals of groups I and II (except rutile) usually demonstrate an irregular distribution in sections of different types. Minerals of the magmatic group, including the authigenic rutile, are characterized by a relatively regular distribution. Their concentrations increase simulta-

Table 3. Distribution of accessory minerals in sections of different types in the Chulaktau Formation (Lesser Karatau)

Accessory minerals		Types of Chulaktau Formation sections					
		I	II	III	IV	V	VI
Authigenic	Rutile	$\frac{0.01\text{–}0.5}{0.26/8}$	$\frac{0.01\text{–}0.35}{0.3/24}$	$\frac{0.01\text{–}0.45}{0.32/33}$	$\frac{0.01\text{–}0.61}{0.44/24}$	$\frac{0.01\text{–}0.74}{0.45/44}$	$\frac{0.02\text{–}0.89}{0.51/54}$
	Apatite	0.01/8	tr	tr	0.01	$\frac{0\text{–}1.05}{0.18/44}$	$\frac{0.1\text{–}0.6}{0.19/54}$
	Pyrite	$\frac{0.01\text{–}0.6}{0.3/8}$	0–0.02/24	$\frac{0\text{–}3.05}{0.77/33}$	$\frac{0\text{–}0.5}{1.16/24}$	$\frac{0\text{–}0.84}{0.1/44}$	$\frac{0.01\text{–}0.9}{0.12/54}$
Detrital	Ilmenite	$\frac{0.01\text{–}0.19}{0.06/8}$	$\frac{0.01\text{–}0.21}{0.06/24}$	$\frac{0.02\text{–}0.23}{0.07/24}$	$\frac{0.02\text{–}1.25}{0.10/24}$	$\frac{0.03\text{–}1.52}{0.11/44}$	$\frac{0.03\text{–}1.61}{0.14/54}$
	Magnetite	$\frac{0.01\text{–}1.09}{1.05/8}$	$\frac{0.01\text{–}1.21}{1.16/24}$	$\frac{0.02\text{–}1.23}{1.18/24}$	$\frac{0.03\text{–}21.3}{1.42/24}$	$\frac{0.03\text{–}23.62}{1.98/44}$	$\frac{0.04\text{–}24.1}{2.1/54}$
	Pyroxenes	$\frac{0.01\text{–}1.29}{1.12/8}$	$\frac{0.001\text{–}1.51}{1.13/24}$	$\frac{0.01\text{–}2.54}{1.14/33}$	$\frac{0.02\text{–}2.81}{1.17/24}$	$\frac{0.02\text{–}2.86}{1.18/44}$	$\frac{0.02\text{–}2.92}{1.23/54}$
	Biotite	0.06/8	0.07/24	0.07/33	0.08/24	0.09/44	0.09/54
	Rutile	0.01/8	0.01/24	0.02/33	0.03/24	0.04/44	0.05/54
	Zircon	$\frac{0\text{–}0.09}{0.06/8}$	$\frac{0\text{–}0.1}{0.06/24}$	$\frac{0\text{–}0.81}{0.07/33}$	$\frac{0.01\text{–}1.03}{0.22/24}$	$\frac{0.01\text{–}1.04}{0.26/45}$	$\frac{0.01\text{–}1.06}{0.3/54}$
	Muscovite	ab	tr	tr	tr	0–0.01	0–0.01
	Tourmaline	0.01/8	ab	tr	0.1	0.01	0.01
	Garnet	0.01/8	tr	$\frac{0.1\text{–}5.6}{0.68/33}$	$\frac{0.02\text{–}0.07}{0.04/24}$	$\frac{0.01\text{–}3.59}{0.45/45}$	$\frac{0.01\text{–}3.62}{0.47/54}$
	Epidote	0.01/8	ab	0.01/33	$\frac{0.01\text{–}0.27}{0.02/24}$	$\frac{0\text{–}0.4}{0.05}$	0.05
	Amphiboles	0.01/8	0.01/24	$\frac{0.01\text{–}1.83}{0.35/33}$	$\frac{0.01\text{–}4.38}{1.14/24}$	$\frac{0.01\text{–}7.12}{1.0/45}$	$\frac{0.01\text{–}7.99}{1.04/54}$
	Hematite	tr	ab	$\frac{0\text{–}5.14}{0.5/33}$	$\frac{0.01\text{–}1.44}{0.2/24}$	ab	tr
	Staurolite	tr	tr	tr	0.01	0.01	0.01
	Sphene	tr	ab	ab	0.01	0.01	0.01
	Chrome-spinels	tr	tr	ab	$\frac{0\text{–}0.48}{0.24}$	ab	ab

Notes: Numerator designates minimal and maximal contents of the mineral in samples (in grams); denominator, average mineral content in samples and total number of samples. Abbreviations in Tables 3 and 4: (tr) traces; (ab) absent.

neously with increase in the thickness of phosphate-bearing sections.

A slightly different pattern of mineral distribution is observed in rock units of the phosphate-bearing sequence (Table 4). The content of metamorphic minerals slightly decreases upward the section, suggesting their probable partial derival from older rocks. Magmatic accessory minerals show a relatively regular distribution. Their concentration substantially increases in the phosphate-bearing unit.

DISCUSSION

Magmatic minerals are most informative for defining the provenance composition, because authigenic minerals appeared during the formation of phosphorites

Table 4. Distribution of accessory minerals in different units of the Lesser Karatau phosphate-bearing sequence

		Kyrshabat Formation	Chulaktau Formation				Shabakty Formation
Accessory minerals		lower dolomite	chert	phosphorite	shale	Fe–Mn dolomites	brown dolomites
Authigenic	Rutile	0.02/20	0.02/17	$\frac{0.01–0.89}{0.6/95}$	0.03/15	0.07/14	0.01/20
	Apatite	0.01/20	0.06/17	$\frac{0–0.63}{0.12/95}$	ab	tr	0.01/20
	Pyrite	$\frac{0.01–1.85}{0.54/20}$	$\frac{0.01–1.85}{0.41/17}$	$\frac{0.01–3.06}{0.24/95}$	tr	0.02/14	$\frac{0–0.6}{0.3/20}$
Detrital	Ilmenite	$\frac{0.01–0.19}{0.08/20}$	$\frac{0.01–0.21}{0.09/17}$	$\frac{0.02–1.52}{0.1/95}$	$\frac{0.03–0.23}{0.09/15}$	$\frac{0.01–0.2}{0.09/14}$	$\frac{0.01–0.19}{0.09/20}$
	Magnetite	$\frac{0.01–1.5}{1.08/20}$	$\frac{0.01–1.04}{1.01/17}$	$\frac{0.02–23.62}{1.98/95}$	$\frac{0.01–0.6}{1.08/15}$	$\frac{0.01–0.5}{1.07/14}$	$\frac{0.01–0.5}{1.08/20}$
	Pyroxenes	$\frac{0.01–0.86}{0.44/20}$	$\frac{0.01–0.49}{0.39/17}$	$\frac{0.02–2.4}{1.03/95}$	$\frac{0.01–0.49}{0.39/15}$	$\frac{0.01–0.5}{0.38/14}$	$\frac{0–0.59}{0.39/20}$
	Biotite	0.08/20	0.08/17	0.1/95	0.1/15	0.07/14	0.07/20
	Rutile	0.01/20	0.01/17	$\frac{0.02–0.05}{0.03/95}$	0.03/15	0.02/14	0.01/20
	Zircon	tr	0.01/17	$\frac{0–1.06}{0.07/95}$	0–0.01/15	0.01/14	0.03/20
	Muscovite	tr	ab	0.01	tr	ab	tr
	Tourmaline	0.01/95	tr	tr	tr	tr	tr
	Garnet	$\frac{0.01–3.55}{0.72/20}$	$\frac{0.01–1.13}{0.24/17}$	$\frac{0.01–1.58}{0.16/95}$	$\frac{0.01–0.07}{0.02/20}$	0.01	tr
	Epidote	$\frac{0.02–0.33}{0.14/20}$	$\frac{0.01–0.27}{0.12/17}$	0.03/95	$\frac{0.04–0.32}{0.15/15}$	tr	0–0.01/20
	Amphiboles	$\frac{0.001–4.38}{1.44/20}$	$\frac{0.01–1.34}{0.17/17}$	$\frac{0.01–7.99}{1.87/95}$	0.02/15	0.01/14	tr
	Hematite	0.02/20	$\frac{0–1.44}{0.05/17}$	ab	ab	ab	0.01/20
	Staurolite	$\frac{0–7.7}{0.1/20}$	0.01	tr	ab	ab	ab
	Sphene	tr	0–0.02	ab	tr	ab	ab
	Chrome-spinels	$\frac{0–1.4}{0.23/20}$	ab	ab	ab	0.01	ab

Notes: Numerator designates minimal and maximal contents of the mineral in samples (in grams); denominator, average mineral content in samples and total number of samples.

or at a later stage of sediment redistribution. Metamorphic rocks could not serve as a source of phosphorus, because they are separated from the productive formation by phosphate-free carbonate and volcanogenic–terrigenous sequences several kilometers thick.

The increased proportion of magmatic minerals in phosphorites indicates that magmatic rocks played a major role in the provenance during the formation of the phosphate-bearing unit. Magmatic minerals were derived from acid, basic, and alkaline rocks. Zircon, sphene, apatite, and rutile could be derived from acid magmatic rocks. However, apatite is always authigenic and sphene has a brownish orange color indicating the derival of sphene from alkaline or metamorphic rocks

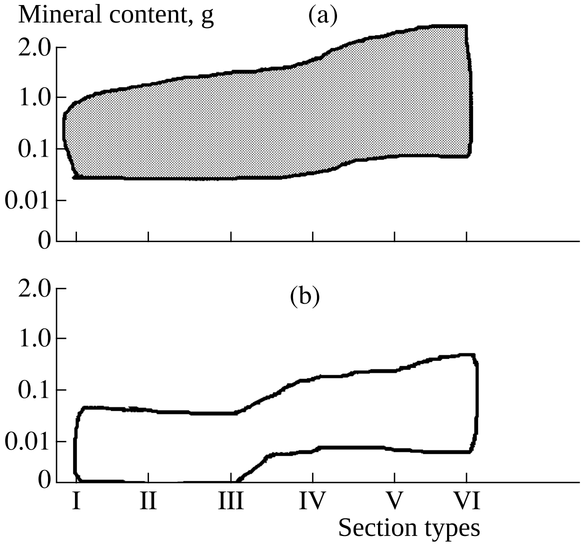

Fig. 3. Distribution of accessory minerals in different deposits. (I–IV) Section types: (I) lenticular–brecciated carbonate, (II) conglomeratic siliceous–carbonate, (III) stromatolitic–biomorphic siliceous, (IV) massive carbonate; (V) highly productive stratified-schistosed; (VI) layered-schistosed siliceous. (a) Distribution of accessory minerals from basic and alkaline magmatic rocks; (b) distribution of accessory minerals from acid magmatic rocks.

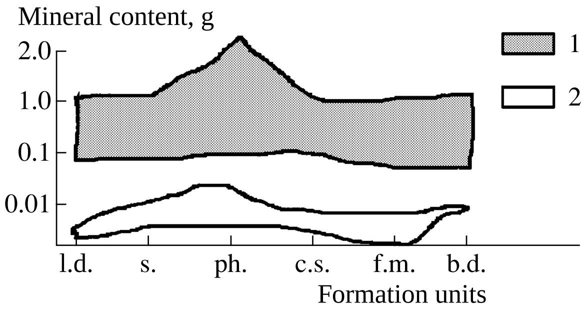

Fig. 4. Distribution of accessory minerals in different lithological units of the phosphate-bearing sequence. Units of the productive formation: (l.d.) lower dolomite, (s.) siliceous, (ph.) phosphate, (c.s.) carbonate–siliceous shales, (f.m.) ferromanganese, (b.d.) brown dolomite. (1) Distribution of accessory minerals from basic and alkaline magmatic rocks; (2) distribution of accessory minerals from acid magmatic rocks.

(Baturin, 1947; Mil’ner, 1968). Detrital rutile is rare and it can at least partly be derived from metamorphic rocks. Micas are widespread among various rocks and are useless for our purpose. Biotite and muscovite are typical constituents of metamorphic rocks. They usually occur in basic and acid intrusions, respectively. In addition, the muscovite content in examined samples is negligible. Judging from the wavy extinction, this mineral is a metamorphic formation. Distribution of accessory minerals from acid and basic igneous rocks in sections of different types (Fig. 3) and units of the phosphate-bearing sequence (Fig. 4) is similar. However, minerals from basic rocks substantially prevail over those from acid varieties. Minerals from magmatic rocks are mainly derived from basic and alkaline intrusions (e.g., magnetite, ilmenite, pyroxenes, and authigenic rutile mostly related to ilmenite and amphiboles) (Tables 3, 4).

The composition of provenances was probably heterogeneous. Basic and alkaline igneous rocks prevailed. Acid intrusions were subordinate as source rocks, because they were less distributed and more resistant to weathering as compared with other rocks (Kholodov, 1973, 1996).

The persistence of mineral composition is probably explained by the transport of sedimentary material from vast homogeneous areas almost entirely composed of basic magmatic rocks. The composition of sediments accumulated after the destruction of these rocks naturally depended on their primary composition. Some decrease in the content of accessory minerals at the flanks of deposits is likely related to specific features of the development of sedimentation basin, which represented a system of small basins periodically united into a single shallow sea (Litvinova, 1991, 2000; Kholodov and Paul, 1999).

According to Kholodov (1975, 1993, 1996), provenances play a substantial role in the supply of material to sedimentation basins and evolve during the geological history. Distribution of various rock-forming components is closely related to rock composition of the provenance. For instance, in addition to basic volcanics, basic intrusions prevailed during the Late Riphean, resulting in the formation of the Earth’s gabbro–anorthosite belts, which promoted the formation of huge accumulations of vanadium-bearing phtanites, stratified and nodular phosphorites, and ferromanganese and iron ores during the Vendian–Cambrian. Changes in the provenance composition in the Phanerozoic were responsible for sharp decreases in these components and their dilution by sedimentary material (Kholodov, 1993).

The composition and distribution of heavy fraction minerals in the Lesser Karatau phosphate-bearing basin suggest that basic intrusions served as source rocks. Most of the available paleogeographic reconstructions demonstrate that sedimentary material was delivered from the areas located southwest and northeast of Karatau Ridge (the Kabankulak and Syr Darya uplifts, respectively) now overlain by young sediments (Fig. 5). According to geophysical data obtained by the Zhanatas geological prospecting expedition, these massifs are largely composed of mafic magmatic rocks. Basic volcanics and acid intrusions play an insignificant role in the Kabankulak Uplift. This is reflected in the low share of accessory minerals from acid igneous rocks. The Syr Darya massif also includes Precambrian metamorphic rocks. The northwestern area of Dzhambul incorporates

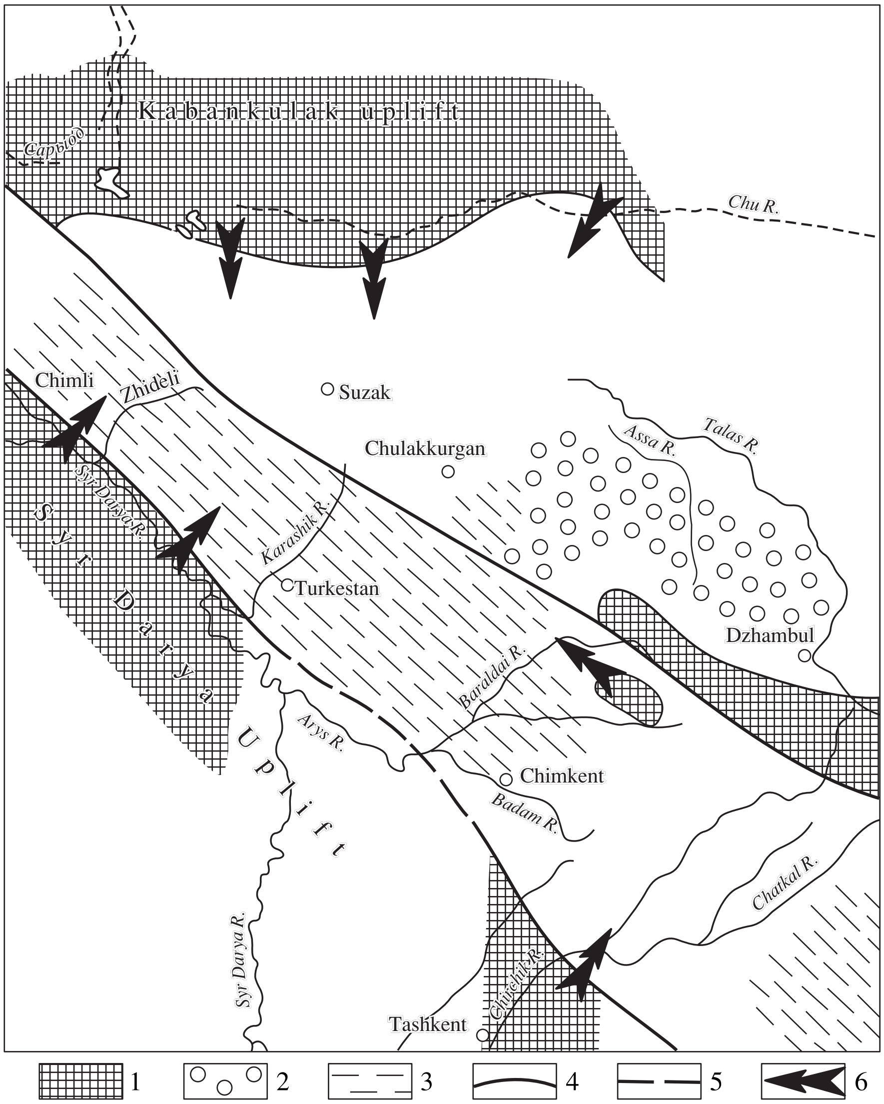

Fig. 5. Schematic paleogeographic map of the Karatau Ridge for the formation period of the Kurumsak–Chulaktau Cambrian sequence (Kholodov, 1973). (1) Precambrian uplifts (land areas); (2) phosphorite-bearing sediments; (3) phtanite-bearing sediments; (4) major faults; (5) assumed faults; (6) direction of sedimentary material transportation.

a zone of local magnetic anomalies corresponding to basic intrusions presumably of the Late Proterozoic age.

Kholodov (1973) reconstructed Eurasian paleogeography of the Vendian–Cambrian transition period and showed that these areas was a land during the formation of phosphorites (Fig. 5). They could serve as provenance that supplied sedimentary material to the Lesser Karatau basin.

CONCLUSIONS

(1) Regardless of the type, phosphorite deposits of the Lesser Karatau show a relatively regular distribution of heavy minerals in both separate lithological units and entire section.

(2) Decrease in the content of minerals at flanks of deposits is consistent with the assumption that a system of shallow-water basins entrapping sediments existed in the Lesser Karatau during the Tommotian (Litvinova, 1991, 2000; Kholodov and Paul, 1999).

(3) Compositions of accessory minerals in six deposits of different types are virtually similar. Their concentrations correlate with the thickness of the productive section, indicating a substantial role of source rocks during their formation.

(4) The mineral composition of heavy fraction from all units of the phosphate-bearing sequence consisting of different rocks is similar, suggesting the prolonged influence of provenances composed of relatively homogeneous rocks.

(5) Pyroxenes, ilmenite, authigenic rutile, amphiboles, magnetite, and biotite are the most widespread accessory minerals in rocks of the Lesser Karatau. The number of these minerals noticeably increases in phosphorites, which is explained by the stronger influence of provenances during their formation.

(6) Distribution of heavy fraction minerals shows that provenances for the Lesser Karatau could be composed of homogenous igneous (mainly basic) rocks that are least resistant to weathering processes (the involvement of alkaline rocks is not ruled out).

(7) Judging from the composition of accessory rocks, acid igneous rocks played a subordinate role in the formation of the Chulaktau Formation in the Lesser Karatau. A slight increase in the proportion of accessory minerals in phosphorites is explained by the general concentration of phosphorus in virtually all Vendian–Cambrian boundary sequences (Ronov and Korzina, 1960; Yanshin, 1983, 1986).

(8) Sedimentary material could be transported into the basin from an ancient massif composed of Precambrian magmatic (mostly basic) rocks and located southwest and northeast of the study region.

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