The paleoreconstruction of sedimentation conditions at Beshpagirske deposit of the Stavropol Krai based on the results of pebble morphology investigation

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Abstract. The morphology of pebbles provides important information for lithological-facial and paleogeographic constructions. The shape of the pebbles carries quite a variety of information about the geological processes of the distant past. Today, there is a large number of foreign and domestic studies devoted to the material and granulometric composition of psephites, while much less attention is paid to the morphological characteristics. Although very often it is the shape of the pebbles that can unambiguously resolve the issues of determining their genesis. Debris shape analysis includes the degree of contour rounding or roundness and the ratio of the three axial dimensions of the pebble: length, width and thickness. Based on the ratio of linear dimensions, judgments were made about the genesis of deposits, the direction of flow, the possibility of redeposition. The most popular are two factors: the shape factor of the fragment and the isometric factor. Conclusions: the end result of the genesis of the pebble material of the Beshpagirskiy quarry is the river alluvium of the ancient river network, subsequently rounded and polished in the coastal delta zone of the Sarmatian Sea. The flat-topped uplift of the Stavropol arch in the middle–upper Sarmatian can be considered the source of the supply of coarse-grained material. The research is of great interest for the search for mineral deposits.

1. Introduction
In 25 km to the east of Stavropol, there are the Beshpagir heights, quite well-known outside the Stavropol Krai, which name is associated with a complex Turkic combination "besh-pa-gir", in literal translation meaning "five beginnings of streams". These water sources to this day feed the small Beshpagirka river, flowing near the village of the same name, located on the slopes of heights and being part of the Grachevsky district.

At a distance of 2.3 km from the western outskirts of the village there is a rather interesting geological phenomenon: relict sea pebble beaches of the Sarmatian Sea, traces of which were found in the Beshpagirskiy quarry at the deposit of sand and gravel mixture (SGM) of the closed joint stock company "Stavropol quarry management". To date, the work of the quarry has been suspended due to the depleted industrial reserves of raw materials, and the organization itself has ceased to exist. However, there are plenty of on-site exploration targets, including pebble deposits and numerous open bedrock outcrops within the quarry walls. There are also interlayers of a conglomerate consisting of pebbles, quartz sand and carbonate cement. These coarse-grained sedimentary rocks (pebbles and conglomerate), due to certain features of their lithogenesis, make it possible to reconstruct the paleogeographic and paleotectonic conditions of sedimentation with sufficient accuracy [1]. At a short distance from the mined one there is another deposit, which is in the status of the state reserve, so in
the future it will be possible to conduct research in order to clarify all the aspects related to the formation of sea pebble beaches of the ancient sea in the southern steppes. Actually, this work is devoted to this topic.

Depending on the agent responsible for the transportation of clastic material, the deposits of gravel-sandy raw materials are associated with deposits of alluvial, eluvial, fluvioglacial, marine, lacustrine, proluvial and deluvial genesis.

Deposits of sand and gravel mixtures in the Stavropol Krai are usually associated with two genetic types of deposits: modern and ancient alluvial, less often with fluvioglacial. The former are the products of the activity of rivers, the latter are related to the results of the glaciation process. The Beshpagirskoe deposit, according to many obvious features, which will be discussed below, is of marine origin.

2. Morphology of pebble material

The paleoreconstruction issues are inextricably linked with understanding the processes and methods of sedimentation, the range of transport and the conditions of burial of sedimentary rocks. The morphology of pebbles from ancient terrigenous deposits can provide important information and become a decisive tool for lithological-facial and paleogeographic constructions. In fact, the form of clastogenic rocks (pebbles) carries a fairly diverse information about the geological processes of the distant past of our planet. Today, there is a large number of national and international studies devoted to various issues of the material and granulometric composition of psephites, while much less attention is paid to their morphological characteristics. Although very often it is the shape of the pebbles that can unambiguously resolve the issues of determining their genesis.

For example, in coastal-marine sediments, pebbles are usually better rounded, have a greater flattening and a symmetrical shape [2]. In glacial (fluvioglacial) deposits, flat-iron pebbles are often found, which is directly related to the conditions of their transportation. Wind activity forms specific aeolian polyhedra (drakantors) from the debris. However, with all the variety of external outlines, there are only four basic concepts of a general form. The division is based on the ratio of the three main axes: a (length), b (width), c (thickness). The quantitative ratio of the axe sizes can be completely different, but the condition $a > b > c$ is always satisfied. And then, depending on the degree of symmetry, the convexity of the faces and the dimensions of the axes, the following types are distinguished: 1) elliptical pebbles (flattened elongated samples); 2) disc-shaped pebbles (flattened rounded specimens); 3) cylindrical pebbles (rounded elongated samples); 4) spherical pebbles (spherical, ovoid specimens).

It should be said that the process of actually measuring the sample in any case fixes the degree to which a pebble approaches one of these four “perfect” types. The "perfect" type is the degree of roundness and the ratio of the pebble axes, at which further grinding does not lead to an arbitrary decrease in the axes and the degree of convexity of the edges, but only to a simple decrease in volume while maintaining proportions, i.e. having reached a certain shape, the pebbles, upon further rolling, change only the volume, but not the shape [3].

In addition to the shape of the pebbles, an equally important indicator is its size or particle size distribution. As part of a facial analysis, this is a strictly necessary procedure. To separate the material into fractions, you can use either a set of sieve screens, which are a column of frames with holes in the mesh that double from 160 to 1.2 mm, or special wire frames with sides: 25-50; 50-75; 75-100; 100-150 mm. In the field, frames are usually used. Also, in order to obtain reliable data reflecting the main characteristics of the studied material, it is necessary to solve the problem of the volume and randomness of the sample.

In the Beshpagirskky quarry, several dozens of samples were taken in succession from the bedrock along the level of the pebble layer. The recalculation showed 182 of them. With the help of frames, a batch of samples was divided into 4 fractions: small (10–25 mm), medium (25–55 mm), large (55–75 mm), coarse (>75 mm). Of the selected pebbles, the largest sample turned out to be with a length (a) of 106 mm, which is 6 mm larger than the size range and can be attributed to fine-grained boulders. Below is a diagram of the distribution of the sample material by fractions (Fig. 1). The mode of the number series in this set is the variant of 49.5% associated with an average fraction of 25–
55 mm. Further, in descending order, a fine fraction of 10–25 mm with an indicator of 35.7% is distributed. The lowest occurrence was noted for the large and coarse-grained group of pebbles: \(10.4\% + 4.4\% = 14.8\%\).

![Sample Material Distribution Diagram](image)

**Figure 1** – Diagram of the distribution of the sample material by fractions

Judging by the prevailing average fraction of 25–55 mm and the presence of small and large pebbles, the rock can be tentatively classified as medium pebble, poorly sorted. The content of the middle fraction in this sample is very close to 50%—the boundary between "weakly sorted" and "medium sorted" ore-quality grades.

### 3. Interpretation of granulometric data.

Interpretation cannot be made separately from other lithological indicators and the entire sediment in the complex, however, with a separate assessment of each lithological feature—the degree of sorting or size—some assumptions can already be made. For example, poor sorting combined with good overall roundness of sea pebbles may indicate storm sediments. One of the main signs of the storm impact is a sharp and uneven wavy bottom contact of layers (Fig. 2), a chaotic orientation of the long axes of the pebble material. All this can be observed in the walls of the quarry, oriented to the west, i.e., to the Stavropol Upland.

The shape of the wavy bedding reflects the nature of the movement of the aquatic environment in which the sediment accumulates. Wavy-curved layering surfaces are formed during low tides, high tides and powerful storm surges in shallow coastal zones of the sea. It is similar to the facies of rip currents.

![Sharp Wavy Bottom Contact](image)

**Figure 2** – An example of a sharp and uneven wavy bottom contact of layers

The rip currents are formed in behind-bank lagoons. A necessary condition for their occurrence is the creation of an excess volume of seawater during the surge of storm waves into the behind-bank space, or the overflow of the same space with fresh water from a river carrying alluvium to the sea. In any case, the excess pressure of the aquatic environment tears apart the sandy body along the coastal bar, and along such furrows, gullies, the underwater stream rushes towards the open sea. As a rule, grooves and gullies, which look like shallow gutters, are located across the bar lagoon. Detrital material carried by rip currents fills the gullies, forming pebble bodies, a similar picture is shown in Figure 2.
River alluvium is also often poorly sorted, and it is possible that the relict river network of the Stavropol arch supplied various sizes of local sedimentary rocks to the coastal zone [4], and only then the waves, together with sea sand, rounded pebbles well. The question of the future is the study of traces of ancient paleo-channels of the eastern slope of the Stavropol Peninsula in the upper Sarmatian. In the Miocene, the peninsula was adjacent to the expanding Caucasian mountainous land [5], but it was not a mountainous country itself, and the river network, most likely, was closer to the plain. In the selected sample, the maximum size along the long axis of the sample was 106 mm, and the maximum weight was 277 g. According to the calculations, if this pebble was originally an alluvium of the paleorivers of the Stavropol arch, then the river flow velocity should had been at least 2.0 m/s. For the main fraction of gravel in a quarry of 25–55 mm, the rate of material flow by the river could not be lower than 1.75 m/s.

The obtained velocities of paleorivers flowing down from the eastern arch of the Stavropol Upland are not exorbitant. Even the modern lowland rivers of Russia in floods develop an average flow rate of up to 2.0 m/s. Thus, the ancient flows of the local network could well develop a current speed close to that necessary for rolling and dragging large debris along the bottom [6].

Based on the foregoing, the lack of sorted pebble material at the preliminary stage can be explained either by the fact that initially, before sea processing, it was a river alluvium of various sizes, or an active hydrodynamic situation near the coast and storm waves disturbed the natural sorting of beach material by grain size composition.

Further analysis of the shape of the debris includes the degree of rounding or roundness and the ratio of the three axial dimensions of the pebbles.

Roundness can be defined in different ways. The first group of methods is considered the most accurate, but at the same time, more laborious. It is based on special measurements and calculations, which are often quite laborious and require measuring one or more roundings of each pebble and axial dimensions, calculating spheres, etc.

The second group of methods is the scoring characteristics of the degree of roundness, which are determined visually in comparison with the test tables of the contours. The descriptive part of each degree is used to help the tables. In this work, a five-point scale by A.V. Khabakov was implemented for separation of detrital particles according to the degree of roundness: 0 – acute-angled fragments (crushed stone); 1 – angular pebbles with frayed edges; 2 – angular-rounded (subingular) pebbles with frayed edges, but still retaining their original faceting; 3 – well-rounded pebbles that retain only traces of their original form; 4 – perfectly rounded pebbles.

The coefficient of circularity according to A.V. Khabakov is presented as the following equation:

$$K_{round} = \frac{n_0 + n_1 + 2n_2 + 3n_3 + 4n_4}{\sum n_i},$$

where $n_0$, $n_1$, $n_2$, $n_3$, $n_4$, $n_5$ are the numbers of pebbles in each roundness class.

To represent the result as a percentage, it must be multiplied by 25. Non-rounded sharp-angled debris will have a roundness class of 0, and a fully rounded grade 4 pebble will have a 100% index.

The pebbles of the Beshpagiskiy quarry showed a fairly high degree of roundness (Fig. 3). The largest fraction with a size of 75–100 mm had a roundness degree of 96.88%, the smallest fraction of 10–25 mm had a roundness degree of 87.31%. The dynamics of the rolling process consists in the rotational movement of a rock fragment under the action of the forces of transfer of terrigenous material. In particular, if water is the agent of motion, then the rolling occurs either under the action of sea (lake) waves of the surf, or under the action of the flow of water in the river.
The four main factors affecting the roundness of the pebbles are: the initial size of the fragment (large, small), the exposure time of the transfer agent, the dynamics of motion (saltation, laminar flow, etc.) and the type of anisotropy of the petrostructure (the ability of the rock to abrade in different directions). It should be noted that the term "roundness" is not identical with "sphericity". The first is responsible for the degree of smoothing and rounding of the boundaries of the edges of the fragment (or smoothing of the edges), the second means the convexity of the edges [7].

The data on the roundness of the Beshpagir material (see Fig. 3) fully confirm the prevailing ideas about the indicator used in combination with the granulometric composition. It is generally accepted that there is a direct relationship between the size of the fragment and the highest roundness degree. Fractions of material 55–75 mm and 75–100 mm mainly have the 4th degree of roundness, and only a few have the 3rd degree. Particles of fraction 10–25 mm more often have the 3rd degree and occasionally 2nd degree of roundness. But in any case, the total percentage is quite high (92.74%), which is the evidence of either a long distance of material transfer to the place of deposition or prolonged exposure to the aquatic environment.

There are certain techniques that, based on the average degree of roundness of the material, can assume the distance of material transfer from the place of destruction of the rock to the place of sedimentation. However, this has to do with river alluvium. In the case of the marine genesis of the pebble material, so far it is possible to speak only about the duration of the rounding of the debris by waves.

In the Beshpagirskiy quarry, the material is characterized by a rather high roundness indicator (92.74%), which indicates a long distance of material transfer to the place of deposition or long-term exposure to the wave-breaking marine environment. In this case, an extended transfer by the river is impossible, because the distance from the watershed of the Stavropol arch (the presumable source of the Sarmatian paleorivers) and to the place of pebble deposition could be no more than 30 km. This distance, according to the data from literary sources (A.P. Sigov, 1946), would clearly not be enough even for relatively soft rocks, especially for rocks with high roundness rates, to which the material of the Beshpagirskiy quarry belongs. At the same time, with an exclusively marine genesis, i.e. when the cliffs are destroyed, the coarse material also could not have such a high roundness index. In this case, undoubtedly, along with the rounded material, there should be traces of a fresh collapse of the sea coast indicated by angular fragments of rubble and unrolled boulders. Looking ahead, one must also say about the non-coincidence in most cases of the petrographic composition of the pebble material and bedrocks of the Beshpagirskiy quarry.

Further study of the pebbles was carried out using three main axes: a (length), b (width) and c (thickness). By the ratio of the linear dimensions, one can judge the genesis of the deposits, the direction of flow, the possibility of redeposition, etc. The most popular at the present time are two coefficients: the shape coefficient of the fragment F and the isometric coefficient S with subsequent processing in the software package "Graham and Midgley’s spreadsheet method" [8, 9].

Fragment shape factor F is calculated as \((a-b)/(a-c)\) and allows the samples to be divided into flat \((F < 0.33)\), elliptical \((0.33 < F < 0.67)\) and prolate \((F > 0.67)\) ones.
There is a database that includes fluvial, glaciofluvial, moraine, cryogenic (colluvium and eluvium), marine coastal sediments, etc. As a result of numerous studies of pebble shapes, several empirical fields have been obtained that allow associating the shape of fragments with a specific genesis [10]. Reference SF diagrams with plotted data are provided in the specialized literature. Comparing the results obtained with the reference ones, one can draw certain analogies and make educated guesses.

Undoubtedly, the final result of the genesis of the coarse-clastic part of the terrigenous material in the quarry is of a marine nature and the exposed layers can be unambiguously attributed to marine coastal shallow-water sediments, however, the previous “pre-marine” genetic history of pebbles can be traced by examining the shape and isometric parameters on the SF diagram (Fig. 4).

Large fractions (55–75 mm and 75–100 mm) fit well enough into the corresponding fields and fully correspond to the marine genesis (blue zone II in Fig. 4). Small and medium fractions (10–25 mm and 25–55 mm) are clearly out of the boundaries and tend to be more to isometric fields, and this is already more like a truncated field of river alluvium (pink zone I in Fig. 4). Alluvium pebbles most often have isometric, isometric-prolate or isometric-ellipsoid shapes. Most of the figurative points of the shape coefficients of such pebbles are concentrated in the upper part of the SF diagram. The same summary diagram clearly shows that for the marine genesis the pebble material of the Beshpagirskiy quarry leaves the lowest part of the empirical field empty and, conversely, for the alluvial genesis there are no representatives of the upper part of the field or isometric forms. Quite possibly, there is the following explanation: the pebble deposits under study represent the former river alluvium of an ancient river network. Once in the coastal delta zone, the material began to undergo wave action, which affected the pebbles, which had an isometric shape, and they were flattened in the first place. This unloaded the upper part of the empirical alluvium field in the SF diagram.

Summing up the results of the studies (particle size distribution, roundness, isometric shape coefficients), it should be noted that when reconstructing the sedimentation environment, it is very important to use several criteria or indicators of morphology, since each of them can be responsible only for individual features of sediment formation and carries its own specific genetic meaning. Granulometry, for example, is directly related to the dynamics of sedimentation conditions and the structure of sedimentary layers. The roundness is undoubtedly an indicator of the transfer distance or the duration of exposure to agents of the sedimentation environment. The isometricity is often responsible for the maturity of sediments, and the shape factor is responsible for the basic conditions of the formation environment.

4. Conclusions

1. Reconstruction of paleoconditions and the process of changing the geometrical dimensions of pebbles are very often associated with morphology inherited from previous sedimentation settings. It is often very difficult to trace this process, but in the case under consideration, we can say with a high
degree of confidence that the end result of the genesis of the pebble material of the Beshpagirsky quarry is river alluvium of an ancient river network, subsequently rounded and polished in the coastal delta zone of the Sarmatian Sea.

2. The flat-topped uplift of the Stavropol arch in the middle–upper Sarmatian can be considered the source of the local coarse-grained material. The terrigenous material entered the coastal-delta part in a different-sized and coarse-rounded form, because the small length of paleorivers (less than 30 km) did not allow achieving such high indicators of the roundness ratio, which is possessed by today’s pebbles of the Beshpagirskiy deposit. The “single-top” structure of the material’s granulometric composition diagram and the overall roundness score can indirectly indicate one main source of drift; however, there is a possibility that a certain additional part of debris will be supplied as a result of the washing of more ancient bottom sediments during the regression of the Sarmatian Sea and land advancing towards the seabed. The active phase of these processes took place 7.6–8.0 million years ago.

3. The next important task in the direction of studying the coarse-grained material of the Beshpagir plateau may be a set of works on the petrography of pebbles and the exploration of paleoriver channels on the eastern slope of the Stavropol Upland. This will confirm the conclusions about the primary alluvial genesis of the pebble material. In addition, according to the conclusion of many researchers, the channels of ancient rivers and the bodies of alluvial genesis associated with them may be of great interest in the search for mineral deposits.

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