ISSN 0016-7029, Geochemistry International, 2007, Vol. 45, No. 7, pp. 652–665. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © A.A. Yaroshevskii, A.V. Tevelev, I.A. Kosheleva, 2007, published in Geokhimiya, 2007, No. 7, pp. 718–732.

Geochemical Structure of the Early Carboniferous Volcanic Complexes of the Southern Urals

A. A. Yaroshevskii, A. V. Tevelev, and I. A. Kosheleva

Geological Faculty, Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

Received January 13, 2006

Abstract—In this paper, the concept of a geochemical structure (Yaroshevskii, 2004) was applied to describe chemical variations in the Early Carboniferous volcanic complexes and their distribution over the tectonic zones of the Southern Urals and Transuralian region in order to clarify the geodynamic settings of their formation. The cluster analysis of a geochemical dataset including 325 analyses of volcanic rocks from the Magnitogorsk, Southern Ural, Transuralian, and Valer'yanovskii tectonic zones allowed us to reduce the geochemical diversity of rocks to eight large geochemical groups. Based on average compositions, these geochemical groups (clusters) can be classed with the following rocks: (1) low-K tholeiitic basalts, (2) high-Ti subalkaline basalts, (3) high-Al subalkaline basalts, (4) subalkaline andesites, (5) subalkaline rhyolites, (6) Na subalkaline rhyolites, (7) potassic subalkaline rhyolites, and (8) high-Al potassic trachyandesibasalts. The distribution of these clusters in tectonic zones of the Southern Urals and Transuralian makes it possible to organize these complexes into four groups. The *first group* includes a differentiated series from high-Ti subalkaline basalts to sodic subalkaline rhyolites with the predominance of aluminous subalkaline basalts and subalkaline andesites. This group is most widespread in the Magnitogorsk and Valer'yanovskii zones. The *second group* corresponds to a differentiated series from low-K basalts to Na subalkaline rhyolites with a strong prevalence of high-Ti subalkaline basalts and less abundant aluminous subalkaline basalts. This group is widespread in the Eastern Ural zone. The *third group* includes subalkaline andesites and rhyolites with subordinate ultrapotassic rhyolites and trachyandesibasalts, which compose the Uya–Novoorenburg suture. The *fourth group* comprises high-Ti subalkaline basalts occurring in the Transuralian zone. Such a distinct distribution of the geochemical types of volcanic rocks is well consistent with concepts on the formation of the Southern Ural volcanic belts at the East European paleocontinent margin in a Californian-type setting. The Valer'yanovskii belt was formed at the active margin of the Kazakhstan paleocontinent.

DOI: 10.1134/S0016702907070038

INTRODUCTION

The obvious and well-studied correlations of petrochemical and geochemical characteristics of volcanic rocks with their affiliation to particular associations and geologic (geodynamic) settings (discussed, for example, by Turner and Verhoogen [1], Kuznetsov [2], Magmatic Associations… [3] and, in more recent studies, by Pearce [4–6], Kuz'min [7], Frolova [8], and others) made it possible to use geochemical data for establishing geodynamic settings of geologic objects. A number of criteria, discriminant functions, and discriminant diagrams were proposed for these purposes.

In the past decades, considerable progress has been made in analytical techniques, which led to the accumulation of a large body of geochemical data demonstrating the possibility of a successful solution of these geological problems. At the same time, it has become clear that the complexity of geologic processes, the occurrence of different volcanic rocks in a common geodynamic setting, and their geochemical heterogeneity (compositional dispersion) even within a supposedly single series significantly complicate geochemical linkages with increasing and overlapping indicator ratios and fields in discriminant diagrams, which often prevents an unambiguous interpretation.

Data on the abundance of first of all rock-forming elements are the main source of geochemical information. However, the use of these data in a raw form as tables and correlation diagrams is generally a poor tool for discrimination purposes. This is caused by two reasons. First, the geochemical system is multidimensional (multicomponent) and it is necessary to take into account at least seven major elements (Si, Al, Fe, Mg, Ca, Na, and K) and also many trace elements (Rb, Ba, Ti, Zr, Nb, and other elements, which are widely used in the analysis of geodynamic associations). Second, the quantitative parameters of rocks often show a considerable scatter. This indicates a need for the statistical processing of quantitative geochemical data.

Two approaches can be used for the combined structural, petrographic, and geochemical description of rocks. One approach is that the sampled rocks are grouped according to qualitative geological and petrographic features, with the subsequent distribution of geochemical data among the distinguished groups. Then, the most important statistical parameters are calculated for each group (average content, variance, etc.), comparative investigations are carried out, the significance of difference is calculated, etc. However, this approach has three shortcomings. First, such a grouping is underlain by qualitative data only or, in the best case, by roughly estimated quantitative mineral compositions. Second, the geochemical data appear to be subordinate to geological data, whereas the quantitative characteristics of element distribution are a direct reflection of the geologic process and its laws; therefore, they are more informative and in this sense more fundamental than geological–petrographic information. Third, the geological–petrographic classification is almost always ambiguous and often made by intuition on the basis of a superficial similarity.

The second approach is based on the following logic of data processing [9].

At the first stage, geochemical data proper are processed regardless of geological and petrographic characteristics. They are considered as an array of points representing the object in the multivariate space; each point is characterized by a certain set of quantitative parameters (contents of chemical elements). The first step is aimed at naturally grouping the samples on the basis of similarity in the considered geochemical parameters; neither number nor composition of these groups are given a priori, because geological and petrographic data are deliberately omitted from the set of input parameters.

This problem can be solved by convenient methods of multidimensional cluster analysis. In this study, we used an algorithm and a software for cluster analysis developed at the Geochemical Department, Geological Faculty, Moscow State University [9, 10]. The principle of clustering is based on successive amalgamation of data points, when each step is characterized by the minimum increase in the average geochemical distance in the forming groups. The geochemical distance in Euclidean metrics is the square root of the sum of squares of differences of contents of all the elements normalized to their variance in the whole dataset. The normalization is necessary to adjust the contents of elements, which may differ by an order of magnitude, to a common scale and make the contributions of different elements comparable. The number of elements is arbitrary and is set depending on the character of the study object; the computer program used in this study includes up to ten elements (Si, Al, Fe, Ca, Na, K, Ti, Mn, and P).

Thus, the first stage launches from a construction of a hierarchical system of successive clustering of samples from the dataset in the coordinates of their chemical composition (SiO_2, Al_2O_3, total iron as FeO, MgO, CaO, Na_2O, K_2O, TiO_2) on the basis of their chemical similarity (minimum "geochemical distance"). As a result, n points (samples) of the primary set are successively combined into gradually expanding groups (clusters), and the whole set is convolved into a single cluster after n-1 steps.

The use of this procedure for the solution of the geochemical problem—clustering of the initial dataset into a limited number of geochemically distinctive groups—requires a criterion to choose a certain working level of clustering. Such a criterion is missing in the algorithm, and independent information is required. For this purpose, we used geological data in the form of empirical distributions of significantly different clusters in the magmatic complexes distinguished by traditional geological methods. A comparison of the two groups of independent data is the goal of the second stage of data processing. For this purpose, a matrix was constructed with the distinguished geochemical groups (clusters) along one axis and magmatic complexes along the other. The number of such matrices depends on the number of distinguished clusters, i.e. on the step of sample clustering. The analysis of the obtained matrices starts with the inspection of sample distribution over matrix elements. A key point in the analysis of a series of matrixes is the choice of the clustering step such that the obtained results (number of groups and their average chemical composition) would have a reasonable geological interpretation. Each distinguished geochemical group is named on the basis of the average composition and in accordance with the accepted petrographic systematics; this name is used for all the samples falling into the given cluster.

In this study, the described approach of the convolution of geochemical information was applied to the establishing of geodynamic settings for the Early Carboniferous volcanic belts of the Southern Urals and Transuralian region. The goals of the study were the elimination of the effect of random variations (variance) on the qualification of particular rocks, the distinguishing of statistically different geochemical types, and description of their spatiotemporal distribution. This approach of cluster analysis was previously successfully applied to the solution of similar problems [9, 11–16].

This procedure for the processing of geochemical data has two remarkable features. At the first stage, data on the geological position of samples were excluded from the working dataset, and all the samples were combined into a single general set. However, the geological information was used during the distinguishing of working geochemical groups (clusters), using the interpretability of the selected system of geochemical rock types (clusters) in terms of their geodynamic and geologic setting as the main criterion. Thus, the first stage involved the development of the geochemical systematization of rocks of the given object on the basis of fundamental, geology-independent laws of the behavior of elements in magmatic processes, while geological data were used only at the second stage in order to correlate them with geochemical trends.

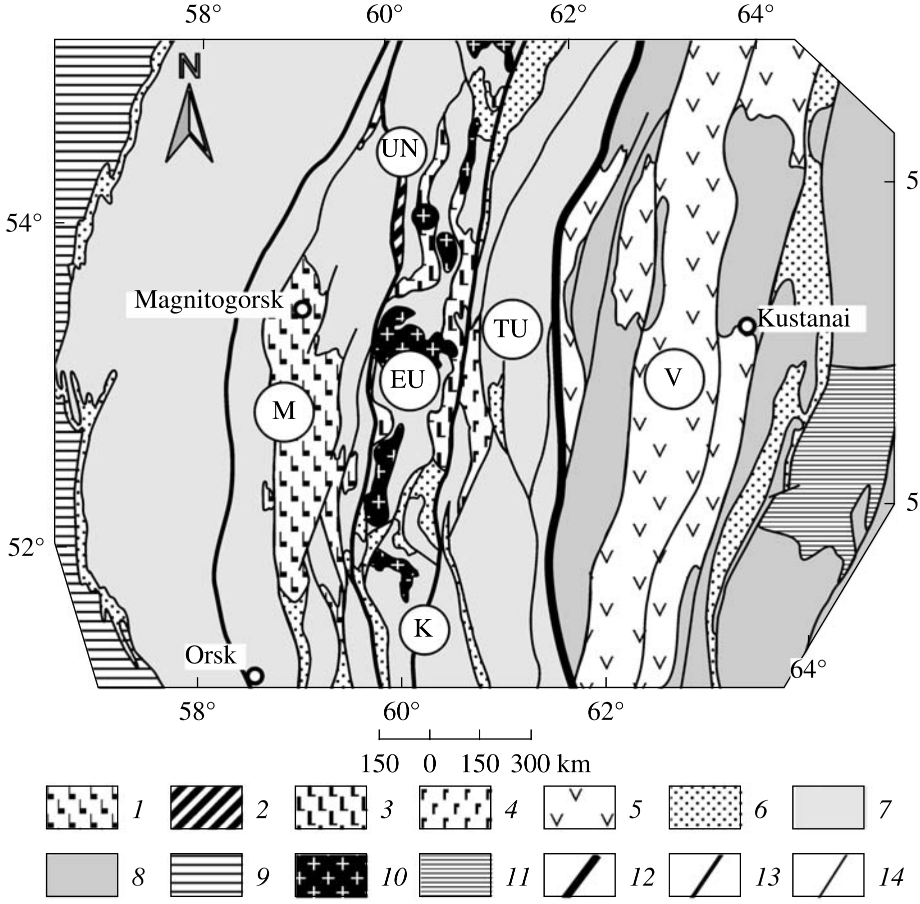

Fig. 1. Sketch map showing the location of Early Carboniferous volcanic complexes in the Paleozoides of the Southern Urals and Transuralian. (*1–5*) Early Carboniferous volcanic complexes of various zones: (*1*) Magnitogorsk, (*2*) Uya–Novoorenburg, (*3*) Eastern Urals, (*4*) Transuralian, and (*5*) Valer'yanovskii; (*6*) Early Carboniferous tuffaceous–terrigenous–carbonate complexes; Pre-Carboniferous complexes (*7–8*): (*7*) margins of the East European paleocontinent; (*8*) margins of the Kazakhstan paleocontinent; (*9–11*) Post-Carboniferous complexes: (*9*) Middle Carboniferous–Permian sediments, (*10*) Late Paleozoic granitoids, and (*11*) Early Triassic basalts; (*12–14*) faults: (*12*) Tobol'sk, (*13*) zone boundary (sutures), and (*14*) others. Letters denote zones: (M) Magnitogorsk, (UN) Uya–Novoorenburg, (EU) Eastern Urals, (K) Kopeisk, (TU) Transuralian, and (V) Valer'yanovskii.

BRIEF CHARACTERISTICS OF THE MATERIAL

This study was based on the data on Early Carboniferous volcanic rocks from the Southern Urals and Transuralian region obtained in the past 10–15 years by both the authors during regional mapping operations [17–19] and other researchers [e.g., 20–22].

The Early Carboniferous volcanic complexes are widespread in the Paleozoides of the meridional segment of the Ural–Mongolian foldbelt (Southern Urals, Transuralian region, and Turgai Trough basement), where they occur in several regional zones (from west to east): Magnitogorsk, Eastern Urals, Transuralian, and Valer'yanovskii (Fig. 1). In the present-day structure, these regional zones are typically bounded by large complex strike-slip zones. The volcanogenic and volcanosedimentary rocks of all zones associate with organogenic limestones, which allows accurate dating of volcanogenic sections.

In the ***Magnitogorsk zone*** [e.g., 20, 23], Early Carboniferous volcanogenic complexes are observed in its eastern part. The Lower Carboniferous rocks overlie thick Middle–Late Devonian island-arc complexes (Magnitogorsk island arc). Volcanic rocks were reported in practically all Early Carboniferous levels, but volcanism occurred very unevenly in time and space. The lower and upper boundaries of volcanogenic formations that are well constrained by organic remains "slide" over biostratigraphic levels within the Late Tournaisian–Late Visean, and both purely sedimentary and volcanogenic sequences may occur in the same stratigraphic level. The volcanogenic sequences form the Magnitogorsk Group consisting of Berezovskii and Grekhovskii formations. The Magnitogorsk Group is pervasively metamorphosed to the prehnite–pumpellyite facies.

The Berezovskii Formation is dominated by moderately alkaline volcanic rocks overlying conformably diverse Late Devonian–Early Carboniferous rocks. The most common rocks are trachybasalt, basalt, rhyodacite, and rhyolite; rarer are trachyrhyodacite, trachyrhyolite, basaltic andesite, basaltic trachyandesite, trachyandesite, and, occasionally, andesite. In addition to these lavas, there are abundant pyroclastic, volcanosedimentary, terrigenous, and carbonate rocks. The thickness of the formation varies from 300–500 to 4200 m.

The Grekhovskii Formation conformably overlies the Berezovskii sequence. It is made up of predominant trachybasalts, trachyandesites, trachyrhyodacites, rarer basaltic trachyandesites, basalts, basaltic andesites, andesites, rhyolites, and corresponding clastolavas, tuffs, tuffites, tuffaceous–sedimentary rocks of variable grain size intercalated with limestones. The predominant rocks are trachybasalts and basaltic trachyandesites, which often have a fresh appearance and aphyric or microporphyric textures. The thickness of the formation is from 1300 to 3300 m.

The ***Uya–Novoorenburg*** suture at the junction of the Magnitogorsk and Eastern Ural zones hosts Carboniferous rocks, which are constituents of a packet of steeply dipping tectonic slices made up of partly tectonized complexes of different age. The *Polotskii volcanosedimentary sequence* distinguished there consists of variably metamorphosed (typically under prehnite–pumpellyite facies) trachybasalts, trachyrhyolites, trachyrhyodacites, as well as their tuffs and tuffites. Less common are basalts, basaltic trachyandesites, rhyolites, rhyodacites, and apovolcanogenic greenschists intercalated with carbonaceous metasiltstones, marmorized limestones, and marbles. The thickness is 1000–1400 m.

Within the ***Eastern Ural zone*** [18], Early Carboniferous volcanic rocks are confined to the western and eastern flanks. Volcanogenic sequences were found in a series of bent synform packets of tectonic slices composed of diverse Early Carboniferous and Late Devonian complexes. The packets of slices are overthrust onto the Early Paleozoic metamorphic complexes of the core zone. In the western part, Early Carboniferous rocks compose the Berezinovskii sequence, which rests on Tournaisian–Early Visean rocks without an apparent unconformity. In the east, the Early Carboniferous rocks compose the Tayanda Formation, which lies on the coaliferous Bredin Formation of the Tournaisian–Early Visean. The volcanic rocks of both the sequences are pervasively metamorphosed to low-grade prehnite–pumpellyite facies.

The Berezinovskii sequence composes several near-meridional tectonic slices, more than 40 km long and 2–16 km wide. They consist of volcanogenic, volcanosedimentary, and sedimentary rocks ranging in thickness from a few meters to hundreds of meters at a total thickness of the sequences of 1500 m. Basaltoids, their tuffs, and volcanic breccias are confined to the lower parts of the sections, where they associate with tuffaceous–terrigenous and siliceous rocks. The upper part is built up of intermediate and silicic volcanic rocks, which are overlain by lithic basaltic tuffs with rhyolite and rhyodacite clasts. The most abundant rocks are highly porphyritic massive and pillowed trachybasalts and basalts. Porphyritic and fluidal spherulitic rhyolites are common among the silicic volcanics.

The Tayanda sequence is an analogue of the Berezinovskii sequences in the eastern part of the Eastern Ural zone. It occurs in several submeridional tectonic slices, up to 30 km long and 4–9 km wide. It consists of tuffaceous schists, tuffstones, and tuffconglomerates, which are overlain by dolerites, rhyolites, andesites, basaltic andesites, and andesidacites, as well as their tuffs. The predominant volcanic rocks are dolerites, spilites, and amygdaloidal basalts. The sequence is 800 m thick.

The Transuralian zone is separated from the Eastern Ural zone by the Kopeisk suture of a strike-slip nature. The Lower Carboniferous volcanogenic *Akkarginskii sequence* extends as a meridional band over 80–90 km, and its width ranges from 2 km in the north to 6 km in the south. It composes a narrow synform disturbed by a great number of reverse faults and thrusts. No reliable normal stratigraphic contacts were documented between the Akkarginskii sequence and the underlying Upper Devonian–Lower Carboniferous terrigenous–carbonate rocks.

The volcanogenic sequence is mainly composed of pillow basalts, basaltic andesites, diverse hyaloclastites, and volcanic breccias, intercalated with minor mafic tuffs, tuffites, cherts, and limestones. The volcanic breccias sometimes contain numerous xenoliths of organogenic limestones. The sequence is metamorphosed at places under greenschist-facies conditions.

The Valer'yanovskii zone is separated from the Transuralian zone in the west by the large meridional Late Paleozoic Tobol'sk strike slip. The complexes of the Valer'yanovskii zone are mostly overlain by the Mesozoic–Cenozoic cover of the Turgai Trough and were studied mainly in drill cores and during mining operations in the largest iron deposits, which occur in the Carboniferous volcanogenic sequence [21, 24–26, etc.].

The sequence is made up of low-grade Visean and Serpukhovian volcanic and volcanosedimentary complexes, mainly of andesite, basaltic andesite, and basalt composition. The total thickness of Lower Carboniferous volcanogenic rocks in the Valer'yanovskii zone is up to 6–7 km. The proportions of sedimentary and volcanic rocks vary widely in all the complexes. The amounts of lavas and pyroclastic rocks are equal in the northern part of the belt, whereas the southern part is dominated by pyroclastic rocks. The percentage of silicic volcanic rocks increases slightly from north to south, while the amounts of basalts, basaltic andesites, and andesites are almost invariant. A detailed differentiation of the Early Carboniferous volcanosedimentary rocks is hampered by the strong facies variability and the absence of marker horizons [26].

The basal level usually consists of terrigenous–carbonate rocks, which are overlain by basaltic andesite lavas and tuffs with thin intercalations of calcareous tuffites and limestones (2000 m). They are followed by basalts, basaltic andesites, andesites, and their tuffs, tuffites, and tuffstones (2000–3000 m). The volcanic rocks are dominated by porphyritic plagioclase and pyroxene–plagioclase leucobasalts and basaltic andesites. Intermediate and mafic tuffs are also abundant.

The Carboniferous volcanic complexes have been studied for many years [18–22, 26–30, and others]; however, many problems of their origin and setting remain controversial. The most widely accepted model suggests that the Carboniferous volcanic rocks of the north–south-trending segment of the Ural–Mongolia belt were formed in an active continental margin setting. The volcanoplutonic series of the Magnitogorsk and Eastern Ural zones are interpreted as island arc complexes of the East European margin, and the volcanic rocks of the Valer'yanovskii zone are considered as complexes of the Andean-type margin of the Kazakhstan continent [31, 32].

However, subsequent detailed studies of the composition and structure of the volcanic rocks of the Magnitogorsk and Eastern Ural zones revealed their significant difference from typical island arc complexes. It was concluded that they were formed during a collision between the Magnitogorsk island arc and the Eastern European continent, which was accompanied by significant local extension (rifting) [18, 20, 33]. The suprasubduction setting of the volcanogenic complexes of the Valer'yanovskii zone was recently questioned and their rift origin was proposed [34]. Tevelev et al. [19] suggested that the Southern Ural volcanic belts were related to the evolution of the East European active margin of the Californian type [19].

Another unanswered question is the existence of Early Carboniferous basins with the oceanic crust, which are alleged between the Eastern European and Kazakhstan continents in many paleogeodynamic reconstructions [31, 35, etc.]. However, complexes formed within such basins were never found.

Thus, there are many problems concerning the interpretation of geodynamic settings for the formation of the Early Carboniferous volcanogenic complexes of the Southern Urals and Transuralian. Attempts to use geochemical indicators of geodynamic settings were hampered by the extremely wide diversity of volcanic rocks in all the zones, which resulted in a blurred picture. In addition, the application of different geochemical criteria to the same rocks often leads to controversial results [19]. The situation is further complicated by the fact that the analytical data used in this study were obtained from the 1970s to 2003 and in different laboratories. It was therefore necessary to generalize geochemical information, distinguish major characteristics, and eliminate variance.

In our studies, we analyzed the geochemical features of Early Carboniferous volcanic rocks in a complete lateral series of tectonic zones from the eastern boundary of the East European platform to the western framing of the Kazakhstan Precambrian inliers. In the following considerations, all Early Carboniferous volcanic rocks were arranged into seven general volcanic complexes:

—Magnitogorsk zone: *the Berezovskii* complex and its analogs (Late Tournaisian–Early Visean), *the Grekhovskii* complex and its analogs (Middle Visean);

—Uya–Novoorenburg suture: *the Polotskii* complex and its analogs (Middle Visean);

—Eastern Ural zone: *the Berezinovskii* complex and its analogs, *the Tayanda complex* and its analogues (both complexes are Middle Visean);

—Transuralian zone: *The Akkarginskii* complex and its analogs (Late Visean–Serpukhovskian age);

—Valer'yanovskii zone: *Valer'yanovskii complex* (including all volcanic rocks with an age from the Middle Visean to the initial Bashkirian).

This study is based on 325 analyses, 175 of which were obtained by us.

RESULTS OF GEOCHEMICAL DATA PROCESSING

The Early Carboniferous volcanic complexes of the Southern Urals vary considerably in composition from basalts of varying alkalinity, basaltic andesites and andesites to rhyolites. They show systematic correlations typical of volcanic rocks (Fig. 2); however, a significant scatter made many correlations statistically poor or insignificant. This scatter could reflect the geochemical heterogeneity of volcanic rocks within individual complexes, as well as the effect of low-grade metamorphism, which leads to local redistribution of the most mobile components (primarily, alkali metals and calcium). The compositional variations of rocks from various volcanic complexes result in a considerable overlap of their fields in almost all diagrams (Fig. 2), which strongly complicates the identification of characteristics suitable for the geochemical discrimination of the complexes with the aim of clarifying their geodynamic setting. Only some general features can be given.

First, the distribution of intermediate and silicic volcanic rocks is typomorphic. They are widespread

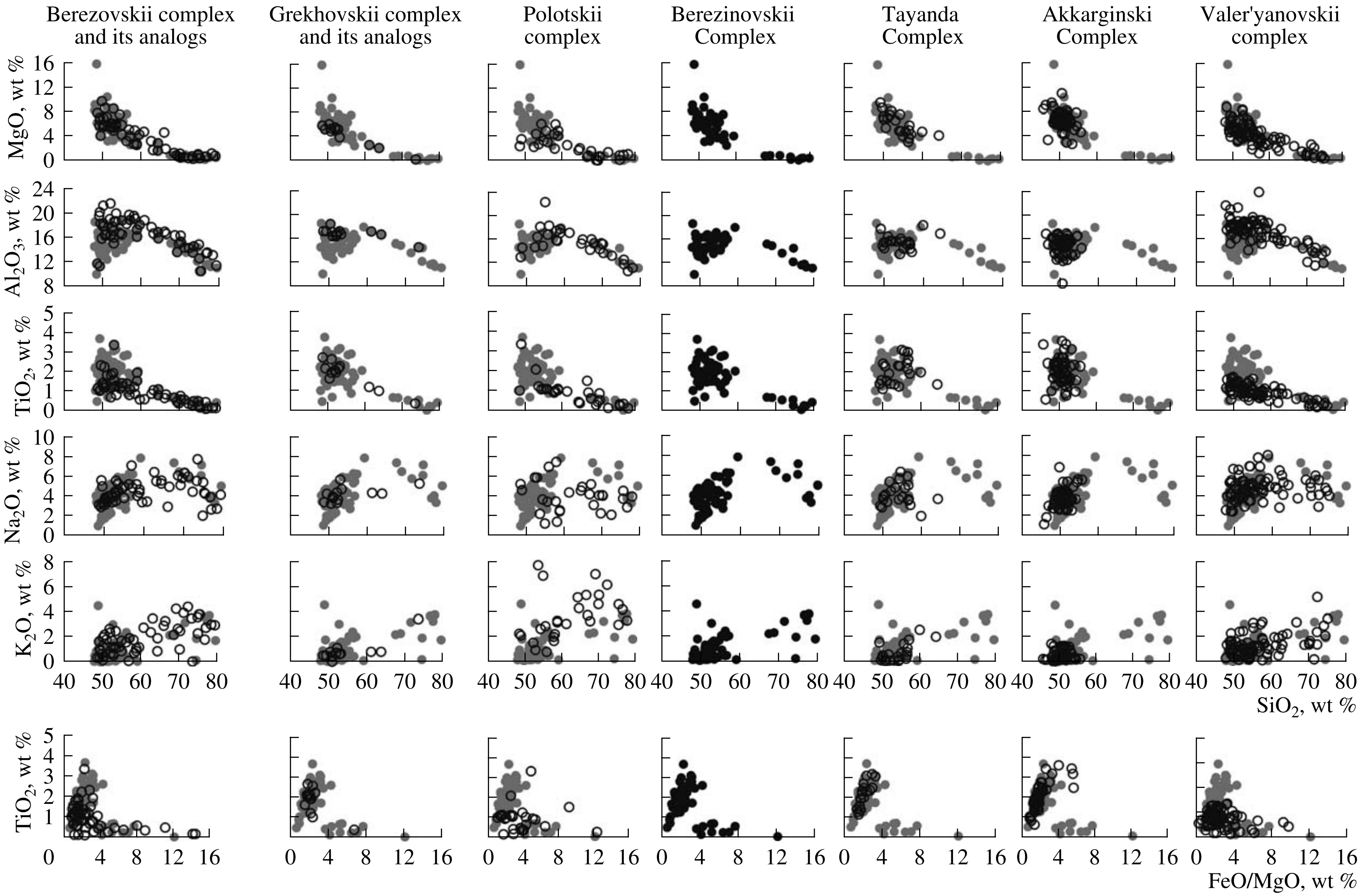

Fig. 2. Variations in MgO, Al_2O_3, TiO_2, Na_2O, and K_2O versus SiO_2 and TiO_2 versus FeO*/MgO in the rocks of the Early Carboniferous volcanic complexes of the Southern Urals and Transuralian. In all diagrams, the points show the compositions of rocks from the Berezinovskii complex, which are compared with the compositions of all other complexes shown by circles.

among the rocks of the Berezovskii, Polotskii, and Berezinovskii complexes and Valer'yanovskii group but are very scarce in the Grekhovskii, Tayanda, and Akkarginskii complexes. Second, the rocks of the Polotskii Complex have relatively high potassium contents. Third, the volcanic rocks of the Berezovskii Complex show elevated Al_2O_3 contents over the whole range of SiO_2 content. In addition, the rocks of all the volcanic complexes of the Southern Urals have elevated Na_2O (typically 4–6 wt %) and K_2O contents (1–4 wt %). However, these features are obscured by the aforementioned significant scatter in all components; this significantly complicates the assignment of complexes to geochemical types, which could be considered typomorphic of particular geodynamic settings [19].

The cluster analysis of the entire dataset yielded a complex and obscure dendrogram structure for the subsequent combination of samples into geochemically similar groups. This was caused by the wide compositional variations of particular samples and the almost complete absence of significant correlations between element contents within small clusters. The distribution of clusters among volcanic complexes was analyzed for different clustering levels (28, 13, and 8). The distribution of 28 and 13 geochemical types (clusters) appeared to be complex, without any distinct systematic patterns. Eventually, we favored the discrimination into eight large geochemical groups, which showed some systematic variations over volcanic complexes (Table 1).

Based on the average chemical compositions of the eight geochemical types (clusters), the Early Carboniferous volcanic rocks of the Southern Urals (Table 2) can be qualified in the following way:

cluster 1—low-potassium tholeiitic basalts;

cluster 2—high-titanium subalkaline basalts;

cluster 3—aluminous subalkaline basalts;

cluster 4—subalkaline andesites;

cluster 5—subalkaline rhyolites;

cluster 6—sodic subalkaline rhyolites;

cluster 7—potassic subalkaline rhyolites; and

cluster 8—high-aluminum potassic basaltic trachyandesites.

The distribution of the geochemical types (clusters) among the volcanic complexes showed systematic features (Table 1).

Type 1. Low-potassium basalts occur only in the Eastern Ural zone, being a typomorphic geochemical type in the Berezinovskii volcanic complex only.

Type 2. Rocks assigned to the geochemical type of *high-Ti subalkaline basalts* occur in almost all complexes. An exception is the Grekhovskii complex, which can be explained by the limited number of samples. At the same time, this geochemical type is of major importance (more than 25% analyses) only for the Eastern Ural and Transuralian zones.

Type 3. Rocks assigned to the geochemical type of *aluminous subalkaline basalts* account for a significant fraction of volcanic rocks in all the complexes. They can be considered typomorphic for the entire Carboniferous volcanism of the Southern Urals and Transuralian.

Type 4. Subalkaline andesites are typomorphic (more than 25% analyses) of the Berezovskii, Polotskii, and Valer'yanovskii complexes, less common in other complexes, and lacking in the Akkarginskii complex.

Type 5. Subalkaline rhyolites are typomorphic of the Berezovskii and Polotskii complexes, i.e., of western tectonic zones, less common in other complexes, and lacking in the Tayanda and Akkarginskii complexes.

Type 6. The geochemical type of *sodic rhyolites* occurs in small amounts in the Berezovskii, Berezinovskii, and Valer'yanovskii volcanic complexes, i.e., in almost all major tectonic zones, with the exception of the Transuralian zone and the Uya–Novoorenburg suture. Sodic rhyolites are typomorphic rocks of the Early Carboniferous volcanic complexes of the Southern Urals.

Types 7 and 8. High-potassium rocks are subdivided into two geochemical types: *potassic rhyolites* and *potassic basaltic trachyandesites.* Both of these types were identified only in the Polotskii complex, being typomorphic of the Uya–Novoorenburg suture.

All the Early Carboniferous volcanic complexes are characterized by the wide occurrence of subalkaline rocks: basalts in the Eastern Ural and Transuralian zones and basaltic andesites in the Magnitogorsk, Eastern Ural, and Valer'yanovskii zones. All the volcanic rocks of the Uya–Novoorenburg zone, from andesites to rhyolites, are subalkaline. In general, the Early Carboniferous volcanism of the Southern Urals obviously showed a subalkaline affinity.

Based on the regular distribution of geochemical types (clusters), we proposed the following geochemical systematics and zoning of the Early Carboniferous volcanic complexes of the Southern Urals and Transuralian.

1. *The Berezovskii volcanic complex* (lower part of the Magnitogorsk Group) has "an extended" geochemical structure, encompassing five geochemical clusters from high-Ti subalkaline basalts to sodic subalkaline rhyolites (clusters 2–6). The most abundant (20–30%) are aluminous subalkaline basalts (cluster 3), subalkaline andesites (cluster 4), and subalkaline rhyolites (cluster 5). Thus, the Berezovskii Complex can be described as a continuous differentiated series of high-sodium subalkaline volcanic rocks.

Table 1. Distribution of the geochemical types of rocks (clusters) among the Early Carboniferous volcanic complexes of the Southern Urals and Transuralian region and percentage of samples of complexes in each cluster

Tectonic zones	Volcanic complexes	Geochemcial rock types (clusters)								Total number of samples in complexes
		1	2	3	4	5	6	7	8	
		LKB	TiSAB	AlSAB	SAA	SAR	NaSAR	KSAR	KTBA	
Magnitogorskii	Berezovskii	–	12.3	*26.3*	*28.1*	*21.0*	12.3	–	–	57
	Grekhovskii	–	–	*76.9*	15.4	7.7	–	–	–	13
Uya–Novoorenburg	Polotskii	–	10.3	3.4	*34.5*	*34.5*	–	*10.3*	*7.0*	29
Eastern Ural	Berezinovskii	*25.8*	*27.4*	*24.2*	6.5	6.5	9.6	–	–	62
	Tayanda	4.7	*52.4*	*28.6*	14.3	–	–	–	–	21
Transuralian	Akkarginskii	–	*93.7*	6.3	–	–	–	–	–	63
Valer'yanovskii	Valer'yanovskii	–	5.0	*41.2*	*40.0*	3.8	10.0	–	–	80

Note: Hereafter, LPB—low-potassium basalts, TiSA—Bhigh-Ti subalkaline basalts; AlSAB—aluminous subalkaline basalts; SAA—subalkaline andesites; SAR—subalkaline rhyolites; NaSAR—sodic subalkaline rhyolites; KSAR—potassic subalkaline rhyolites; and KTBA—potassic basaltic trachyandesites. The clusters shown in italics are typomorphic for particular complexes.

Table 2. Average chemical composition of geochemical rock types (clusters) from the Early Carboniferous volcanic complexes of the Southern Urals, wt %

Cluster No.	Number of samples	SiO_2	Al_2O_3	FeO*	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Total
1	17	49.81	14.05	14.15	6.48	10.47	2.65	0.14	1.80	0.25	0.20	100.00
2	101	50.73	14.85	11.56	6.57	9.27	3.69	0.72	2.09	0.18	0.34	100.00
3	84	52.25	17.27	9.94	5.51	7.47	4.52	0.96	1.60	0.18	0.30	100.00
4	67	58.07	17.69	7.98	3.93	4.28	4.90	1.66	1.08	0.15	0.26	100.00
5	30	72.51	13.46	3.39	0.83	1.07	4.26	3.84	0.45	0.06	0.13	100.00
6	21	72.22	14.01	3.44	0.86	1.38	5.71	1.66	0.49	0.10	0.13	100.00
7	3	70.32	14.30	3.97	0.55	0.41	2.84	7.08	0.34	0.04	0.15	100.00
8	2	54.13	20.24	9.42	3.07	2.67	1.75	7.26	1.20	0.05	0.21	100.00

Note: FeO* is total Fe expressed as FeO.

2. *The Grekhovskii volcanic complex* (upper part of the Magnitogorsk Group) inherited the geochemical structure of the Berezovskii complex (clusters 3–5) with a sharp predominance of aluminous subalkaline basalts (cluster 3). The absence of the extreme members of the geochemical spectrum (clusters 2 and 6) is most likely explained by the limited number of available analyses.

3. *The Polotskii volcanic complex* has a more complex structure strongly different from that of the above complexes. It consists mainly of subalkaline andesites and rhyolites (clusters 4 and 5), whereas subalkaline basalts (clusters 2 and 3) occur in subordinate amounts. At the same time, only the Polotskii complex contains ultra-K (up to 7% K_2O) rocks, both silicic and mafic (clusters 7 and 8).

4. A very complex geochemical structure including six clusters is typical of the *Berezinovskii volcanic complex.* Unlike the above complexes, the rocks of this complex are shifted toward basaltic compositions: clusters 1, 2, and 3 are most abundant (approximately 25% each), whereas subalkaline andesites and rhyolites (clusters 4, 5, 6) occur in subordinate amounts. The main distinctive feature of the Berezinovskii complex is the wide occurrence of low-potassium basalts (cluster 1).

5. The geochemical structure of the *Tayanda volcanic complex* is, in general, similar to that of the Berezinovskii complex, except for the subordinate role of low-potassium basalts and the complete absence of rhyolites. The latter is presumably related to sampling gaps, because silicic volcanic rocks were described in the Tayanda Formation.

6. *The Akkarginskii volcanic complex* has a surprisingly simple structure, consisting of predominant (>90%) high-Ti subalkaline basalts (cluster 2) and subordinate aluminous subalkaline basalts (cluster 3).

7. The geochemical structure of the *Valer'yanovskii volcanic complex* is similar to that of the Berezovskii complex, except for the low content of subalkaline rhyolites (cluster 5) and, correspondingly, the increasing role of aluminous subalkaline basalts and subalkaline andesites (clusters 3 and 4).

The geochemical structure of the Early Carboniferous volcanic complexes allows us to subdivide them into four groups:

—*the first group* includes the Berezovskii, Grekhovskii, and Valer'yanovskii complexes and corresponds to a differentiated series from high-Ti subalkaline basalts to sodic subalkaline rhyolites with the predominance of aluminous subalkaline basalts and subalkaline andesites;

—*the second group* includes the Berezinovskii and Tayanda complexes and ranges in composition from low-potassium basalts to potassic subalkaline rhyolites with a strong predominance of high-Ti subalkaline basalts and a minor occurrence of aluminous subalkaline basalts; the rocks of this group are shifted toward mafic compositions relative to the first group.

—*the third group* is represented by the chemically (and, perhaps, genetically) heterogeneous Polotskii volcanic complex, which is dominated by subalkaline andesites and rhyolites and also contains ultrapotassic rhyolites and basaltic trachyandesites;

—*the fourth group* is, by contrast, extremely homogenous and consists of high-Ti subalkaline basalts of the Akkarginskii volcanic complex.

The distribution of samples among the four groups of clusters is shown in Table 3.

The analysis of the geochemical systematics of volcanic rocks and their distribution in the tectonic structures of the Southern Urals must take into account the specific character of our grouping method based on the geochemical similarity of rocks. As was mentioned above, the applied method of cluster analysis is multidimensional and based on a geochemical distance between points (rock samples), which is calculated from the contents of eight components (SiO_2, Al_2O_3, FeO*, MgO, CaO, Na_2O, K_2O, and TiO_2). This approach is sharply different from the common procedure of hierarchical grouping that is used for the successive amalgamation of rocks into groups: first, into mafic, intermediate, and silicic rocks by SiO_2 content; then, normal, subalkaline, and alkaline varieties by Na_2O and K_2O contents; normal and aluminous rocks by Al_2O_3 content; and, finally, low- and high-TiO_2 rock varieties. In our approach, the goal is not the classification of rocks, but their grouping into geochemical types (clusters), the compositional differences (in all eight components) within which are smaller than between the clusters. In such a case, we do not know beforehand which element will appear to be the main discriminant criterion. It is important in this approach that the study object is characterized by a wide compositional scatter and the absence of tight correlations between the contents of various components. As a result, each of the distinguished groups (geochemical types) included a wide range of compositions, extending beyond the standard classification boundaries. This situation is illustrated by histograms of the distribution of component contents in the clusters (Fig. 3). In such a case, the distinguished clusters cannot be correlated with particular petrographic and petrochemical rock types. Therefore, the groups were termed "geochemical types," and their average chemical compositions were compared with the standard compositions of corresponding rocks in the accepted systematization of volcanic rocks. The rocks involved into such a geochemical type show variations both in subordinate components and in the major classification component, silica. This is logical,

Table 3. Distribution of the geochemical rock types (clusters) of Early Carboniferous volcanic complexes among the tectonic zones of the Southern Urals and Transuralian

Tectonic zone	Geochemical rock type (cluster)								Total number of rock samples in zone
	1	2	3	4	5	6	7	8	
	LKB	TiSAB	AlSAB	SAA	SAR	NaSAR	KSAR	KTBA	
Magnitogorsk	–	6.1	51.6	21.8	14.4	6.1	–	–	70
Uya–Novoorenburg	–	10.3	3.4	34.5	34.5		10.3	7.0	29
Eastern Ural	15.3	39.9	26.4	10.4	3.2	4.8	–	–	83
Transuralian	–	93.7	6.3	–	–	–	–	–	63
Valer'yanovskii	–	5.0	41.2	40.0	3.8	10.0	–	–	80

because, unlike a classification based on arbitrarily chosen criteria, the natural grouping of real compositions is based on equal weights of all major chemical components. Within this approach, minor and trace elements could be used, when necessary, in grouping as criteria for geochemical differences, provided the relevant data are available.

GEODYNAMIC INTERPRETATION

It can be seen (Table 3) that the distinguished groups of geochemical structures reflect the distribution of volcanic complexes among tectonic zones. The first group characterizes the Magnitogorsk and Valer'yanovskii zones; the second group, the Eastern Ural zone; the third group, the Uya–Novoorenburg zone; and the fourth group, the Transuralian zone. This indicates that the obtained geochemical structures can be used with confidence to establish the geodynamic settings of formation of the Early Carboniferous volcanic complexes.

The apparent similarity between the geochemical structures of volcanic rocks from the Magnitogorsk and Valer'yanovskii zones attests to their formation in similar geodynamic environments. The distinct predominance of aluminous subalkaline (medium-Ti) basalts, the abundance of subalkaline andesites, and the minor occurrence of high-Ti basalts are typical of continental margin assemblages. At the same time, the absence of low-Ti basalts precludes the assignment of these volcanic associations to island-arc complexes. It should be emphasized that the resemblance of the geochemical structures of these volcanic rocks is related to similar geodynamic settings rather than to their occurrence in a common structure or their simultaneous formation. For instance, the Valer'yanovskii and Magnitogorsk complexes were formed at the margins of different continents, Kazakhstan and the East European, respectively; moreover, the Early Carboniferous volcanism of the Valer'yanosvkii complex postdated that of the Magnitogorsk zone by 20 Ma.

The geochemical structure of volcanic rocks from the Eastern Ural zone (second group) resembles, in the set of clusters, the geochemical structure of the Magnitogorsk zone but differs in the abundance of low-potassium basalts (15%), which are absent in the Magnitogorsk zone, and the predominance of subalkaline basalts (40%). Such geochemical characteristics are typical of riftogenic volcanic belts that were initiated on a fairly thick continental or transitional crust. This conclusion is consistent with available reconstructions, which often interpret the Eastern Ural zone with its thick crust as an Early Carboniferous microcontinent.

The boundary position of the Uya–Novoorenburg zone is reflected in the geochemical structure of the Polotskii volcanic complex, which contains diverse rocks with an elevated K content. An important fact is the almost complete absence of aluminous basalts, which occur in significant amounts in other zones. Such associations of volcanic rock were described in conti-

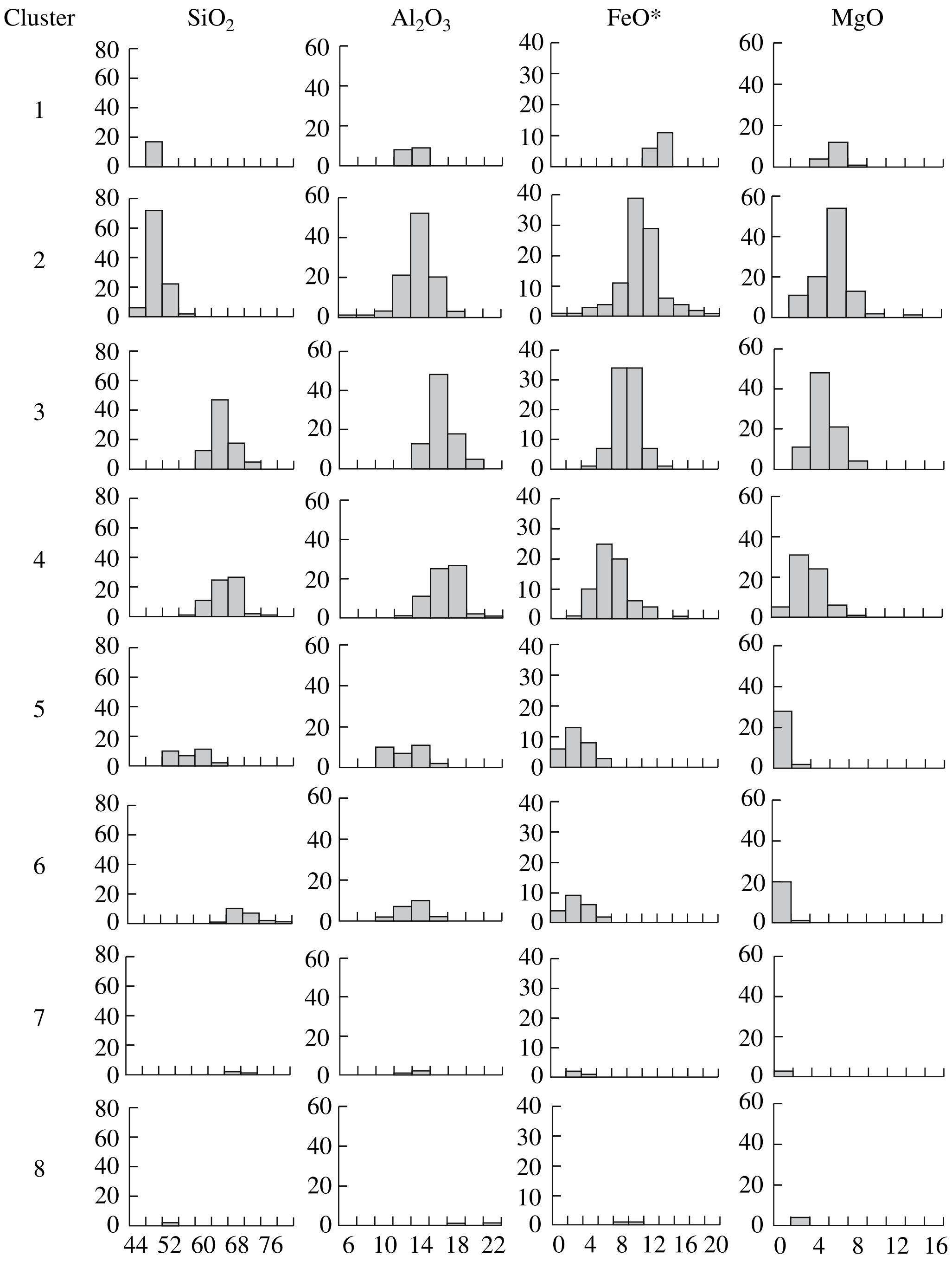

Fig. 3. Histograms of component contents in the geochemical rock types (clusters) of the Early Carboniferous volcanic complexes of the Southern Urals and Transuralian.

nental rifts connected with magmatic sources of different depths.

Of special interest is the geochemical structure of volcanic rocks from the Transuralian zone. The remarkable homogeneity of the structure (the presence of only high-Ti subalkaline basalts at an extremely low content of aluminous basalts) suggests a within-plate rather than continental-margin setting. At the same time, such complexes could be formed in back-arc basins initiated on a thick crust.

The presented data and conclusions are well consistent with concepts suggesting the formation of the volcanic belts of the Southern Urals at the Californian-type margin of the East European paleocontinent [19]. The

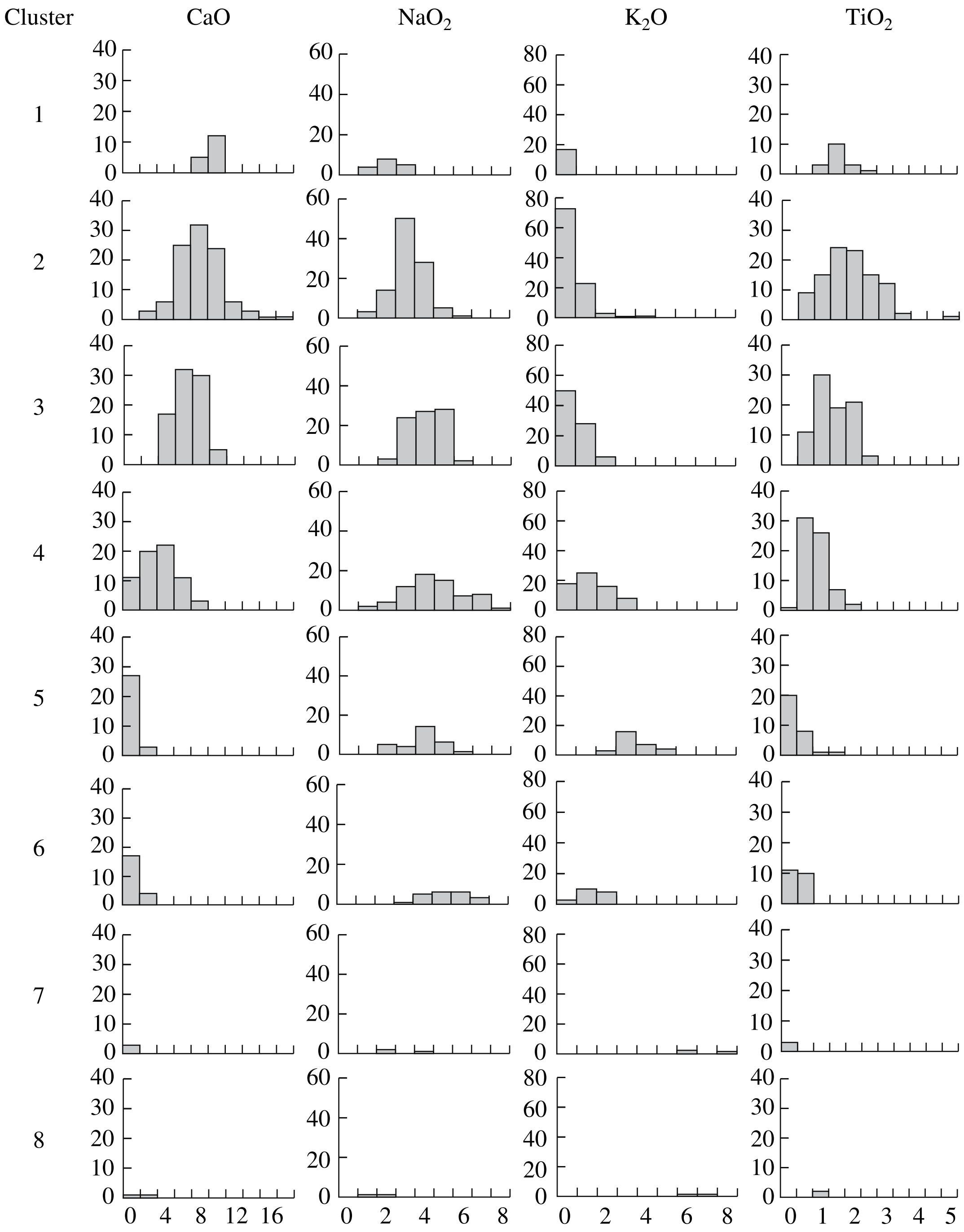

Fig. 3. Contd.

Valer'yanovskii belt was formed at the active margin of the Kazakhstan paleocontinent.

CONCLUSIONS

The observed distribution of the geochemical types of volcanic rocks in the tectonic zones of the Southern Urals is in adequate agreement with previous conclusions and reveals some interesting and geologically important features. First, the volcanic complexes of different tectonic zones are heterogeneous and contain geochemically (and genetically?) different rocks and series. Second, the appearance of specific geochemical rock types in particular zones shifts their general geochemical signature, but it is "diluted" by nonspecific rock types, which, coupled with significant compositional variations, complicates the geodynamic interpretation of the volcanic complexes.

The discrete character of geochemical variations in the volcanic complexes is much more poorly expressed than, for example, in layered intrusions [9]. However, the "soft" discrimination method—hierarchical cluster analysis discriminating the compositions of points at any degree of difference, except for complete identity—allowed us to distribute the rocks among geologically interpretable groups. The distinguished discrete groups can be used in geological mapping, which traditionally includes the outlining of distribution areas of different (by certain parameters, in our case, geochemical) rocks and boundaries between them. As was shown in this study, they may also be helpful in geodynamic reconstructions.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 03-05-64569) and the Federal Program for the Support of Leading Scientific Schools (project no. 326.2003.5)

REFERENCES

1. F. J. Turner and J. Verhoogen, *Igneous and Metamorphic Petrology* (McGraw-Hill, New York, 1960; Inostrannaya Literatura, Moscow, 1961).
2. Yu. A. Kuznetsov, *Major Types of Magmatic Associations* (Nedra, Moscow, 1964) [in Russian].
3. *Magmatic Associations of the USSR* (Nedra, Leningrad, 1979) [in Russian].
4. J. A. Pearce and J. R. Cann, "Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses," Earth Planet. Sci. Lett. **19**, 290–300 (1973).
5. J. A. Pearce, B. F. Gorman, and T. C. Birkett, "The Relationship between Major Element Chemistry and Tectonic Environment of Basic and Intermediate Volcanic Rocks," Earth Planet. Sci. Lett. **36**, 121–132 (1977).
6. J. A. Pearce and M. J. Norry, "Petrogenetic Implications of Ti, Zr, Y, and Nb Variations in Volcanic Rocks," Contrib. Mineral. Petrol. **69**, 33–47 (1979).
7. M. I. Kuz'min, *Geochemistry of Magmatic Rocks from Phanerozoic Mobile Belts* (Nauka, Novosibirsk, 1985) [in Russian].
8. T. I. Frolova and I. A. Burikova, *Magmatic Associations of Modern Geotectonic Settings* (Mosk. Gos. Univ., Moscow, 1997) [in Russian].
9. A. A. Yaroshevskii, "Geochemical Structure of Magmatic Complexes: An Example of the Kivakka Layered Olivinite–Norite–Gabbronorite Intrusion, Northern Karelia," Geokhimiya, No. 12, 1251–1270 (2004) [Geochem. Int. **42**, 1107–1125 (2004)].
10. J. H. Ward, Jr., "Hierarchical Grouping to Optimize an Objective Function," J. Am. Stat. Assoc. **58**, 236–244 (1963).
11. A. A. Yaroshevskii, A. V. Abramov, and E. E. Kameneva, "Geochemical Systematics, Possible Genetic Relations of Lunar Magmatic rocks, and Rock Types from Mare Crisium," in *Regolith from Mare Crisium* (Nauka, Moscow, 1980), pp. 196–218 [in Russian].
12. A. A. Yaroshevskii, D. A. Ionov, Yu. V. Mironov, et al., "Petrography and Geochemistry of the Ioko-Dovyren Dunite–Troctolite–Gabbro–Norite Layered Massif (Northern Baikal Area)," in *Petrology and Ore Potential of Natural Rock Associations* (Nauka, Moscow, 1982), pp. 86–117 [in Russian].
13. A. A. Yaroshevskii and T. I. Tsekhonya, "Petrochemical Types of Sea Floor Magmatic Rocks, Their Associations and Distribution among Structural–Morphological Zones," in *Oceanic Magmatism. Evolution and Geological Correlation* (Nauka, Moscow, 1986), pp. 95–103 [in Russian].
14. B. S. Kireev, E. V. Koptev-Dvornikov, and A. A. Yaroshevskii, "Geochemical Structure of the Kuz'movskii Dolerite Sill of the Trap Association (Lower Reaches of the Podkamennaya Tunguska River)," Geokhimiya, No. 6, 796–809 (1986).
15. A. A. Yaroshevskii, A. V. Tevelev, and I. A. Kosheleva, "Experience in the Application of Cluster Analysis for the Investigation of Petrochemical Trends in the Volcanism of the Southern Tokrau Depression," in *Proceedings of 4th Kazakhstan Petrographic Conference on Petrology and Metallogeny of Kazakhstan* (Nauka, Alma-Ata, 1988), Part 1, pp. 97–99 [in Russian].
16. A. A. Yaroshevskii, T. I. Tsekhonya, and G. A. Burba, "Principle of the Geochemical Mapping of Volcanic Rocks on the Ocean Floor," Dokl. Akad. Nauk SSSR **306**, 461–465 (1989).
17. Al. V. Tevelev, M. Ya. Kats, I. A. Kosheleva, and Ark. V. Tevelev, "Tectonic Zoning of the Eastern Slope of the Southern Urals," in *Geological Problems of the Ural–Mongolian Belt* (Mosk. Gos. Univ., Moscow, 1998), pp. 84–94 [in Russian].
18. Al. V. Tevelev and I. A. Kosheleva, "Geologic Structure and Evolution of the Southern Urals (Eastern Ural Rise and Transuralian Region)," in *Proceedings of the Laboratory of Fold Belts, Geological Faculty, Moscow State University* (Mosk. Gos. Univ., Moscow, 2002) [in Russian].
19. A. V. Tevelev, K. E. Degtyarev, P. L. Tikhomirov, et al., "Geodynamic Setting of the Formation of Carboniferous Volcanic Complexes in the Southern Urals and Transuralian Region," in *Essays on Regional Tectonics. Vol. 1. Southern Urals* (Nauka, Moscow, 2005), pp. 213–247 [in Russian].
20. D. N. Salikhov and A. V. Yarkova, *Lower Carboniferous Volcanism of the Magnitogorsk Megasynclinorium* (IG UrO RAN, Ufa, 1992) [in Russian].
21. A. M. Pumpyanskii, "Carboniferous Deposits of the Kurgan Transuralian Region," in *Proceedings of 4th Toporkov Readings, Russia, 1999* (Rudnyi, 1999), pp. 55–62 [in Russian].
22. G. I. Samarkin and E. Ya. Samarkina, "Comparative Geological and Petrochemical Characteristics of the Early Carboniferous Iron-Bearing Volcanic Series of the Northern and Southern Segments of the Valer'yanovskii Belt, Urals," Ural. Geol. Zh., No. 3, 3–36 (2002).
23. I. B. Seravkin, A. M. Kosarev, D. N. Salikhov, et al., *Volcanism of the Southern Urals* (Nauka, Moscow, 1992) [in Russian].

24. *Geology and Mineral Resources of the Southeastern Turgai Trough and Northern Ulutau* (Nauka, Alma-Ata, 1984), Vol. 1 [in Russian].
25. *Iron Formations of the Transuralian Region* (IgiG UrO AN SSSR, Sverdlovsk, 1987) [in Russian].
26. A. M. Pumpyanskii, "Carboniferous Deposits of the Tyumen–Kustanai Trough," in *Biostratigraphy and Lithology of the Upper Paleozoic of the Urals* (IGiG UrO AN SSSR, Sverdlovsk, 1988), pp. 27–42 [in Russian].
27. T. V. Dianova, "Preliminary Results on Volcanogenic Rocks from the Southern Part of the Eastern Zone, Eastern Ural Trough," in *Volcanism of the Southern Urals* (UNTs AN SSSR, Sverdlovsk, 1974), Issue 12, pp. 130–140 [in Russian].
28. E. P. Smirnov, "Middle Carboniferous Subalkaline Volcanic Rocks of the Middle Urals," in *Petrological Problems of the Volcanic Rocks of the Urals* (UNTs AN SSSR, Sverdlovsk, 1975), pp. 71–76 [in Russian].
29. T. I. Frolova and I. A. Burikova, *Geosyncline Magmatism* (Mosk. Gos. Univ., Moscow, 1977) [in Russian].
30. V. A. Koroteev, T. V. Dianova, and L. A. Kabanova, *Middle Paleozoic Magmatism of the Eastern Urals* (Nauka, Moscow, 1979) [in Russian].
31. L. P. Zonenshain, V. G. Korinevskii, V. G. Kaz'min, et al., "Structure and Evolution of the Southern Urals in the Light of Plate Tectonics," in *Evolution of the Ural Paleocean* (Nauka, Moscow, 1984), pp. 6–56 [in Russian].
32. L. P. Zonenshain, M. I. Kuz'min, and L. D. Natapov, *Tectonics of Lithospheric Plates of the USSR Territory* (Nedra, Moscow, 1990), Vol. 1 [in Russian].
33. V. N. Puchkov, *Paleogeodynamics of the Southern and Middle Urals* (Dauriya, Ufa, 2000) [in Russian].
34. G. I. Samarkin, E. Ya. Samarkina, and A. M. Pumpyanskii, Geodynamics of the Lower Carboniferous Belts of the Southern Urals: Subduction, Collision, and Rifting," in *Proceedings of 4th Toporkov Readings, Russia, 1999* (Rudnyi, 1999), Issue IV, pp. 101–104 [in Russian].
35. A. M. C. Sengör, B. A. Natal'in, and V. S. Burtman, "Tectonic Evolution of Altaids," Geol. Geofiz. **35** (7–8), 41–58 (1994).