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The composition, genesis, and mantle xenoliths of the Late Miocene fergusite-carbonatite-syenite series of the Pamir: The problem of superthick crust formation in mobile belts

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Abstract. The aim of this paper is to offer the geostructural and petrochemical characteristics of the diatremes and dykes of the Late Miocene fergusite-carbonatite-syenite series and of the mantle xenoliths. The evidence obtained in this study for the petrogeochemistry of the subvolcanic bodies and for the composition and thermobarometry of their mantle and crustal inclusions allowed us to clarify the conditions of magma intrusion and differentiation, as well as the depths and types of the potential sources of the ultrapotassic alkali-basic magmas. Models are offered for the formation of a superthick crust and a newly formed pyroxenite-eclogite upper mantle under the Pamir region. The tectonic positions of the Late Miocene rock bodies and their formation analysis proved their association with the post-collision conditions. A view is advanced that the horizontal displacement of the Pamir (at least of its eastern block), as well as the formation of its modern structural style, associated with the India-Asia collision, was completed in the Late Miocene.

1. Introduction

The main problem of crustal geodynamics and petrology is the contributions of the plume and plate tectonic processes [*Grachev,* 2000; *Khain,* 2000; *Yarmolyuk et al.,* 2000]. The recent tectonics and evolution of the Cenozoic lithosphere under the eastern segment of the Alpine-Himalayan mobile belt had been associated in many respects with the processes induced by the India-Asia collision which began 45–50 million years ago and is believed by many investigators [*England and Molnar,* 1997; *Pevnev et al.,* 1978], to name but a few, to continue at the present time. The Pamir Mts., sitting at the cusp of the Hindustan peak, experienced the greatest effect of the India-Asia collision. The Cenozoic geodynamics and the modern structural style of the region seem to have been caused by tangential compression and horizontal displacement, this having been responsible for the formation of the so-called Pamir "arcs" (Pamir-Himalayan syntaxis). At the same time, the territory of the Pamir, Tibet, and other regions overlies the huge region of the "hot" low-density mantle [*Grachev,* 2000], qualified as the Tibet Plume [*Pogrebnoi and Sabitova,* 2001]. The excellent exposure, deep vertical incisions, and good knowledge of the Pamir region allow one to consider it as a natural site for studying the processes of the evolution and origin of the intracontinental structural features in the eastern segment of the Alpine-Himalayan Belt.

A specific place in this region is occupied by the Late Miocene fergusite-carbonatite-syenite series of the Kimmeridgian Alpides of the South Pamir (Dunkeldyk Complex). The ultrapotassic alkaline leucitic basic rocks restricted, in association with carbonatite and syenite, to the collision-related orogenic belts (post-collision structural features) are fairly scarce [*Kovalenko,* 1987] and poorly known. The data available for the age, lithology, and stratigraphy of these rocks allow us to used them for reconstructing the specific geodynamic conditions in the Cenozoic history of the Pamir region. Another important fact is that the fergusite dyatremes contain mantle and crust xenoliths which provide information for the depth levels of the formation of the enclosing basic rocks, for the compositions of their sources, for the evolution of the lithosphere, and for the potential mechanisms of the superthick crust formation in

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the Pamir-Himalayan region [*Dmitriev,* 1976; *Ducea et al.,* 2003; *Lutkov,* 2003; *Lutkov and Lutkova,* 1998].

2. The Crustal Structure of the Southern Pamir Area

As follows from the seismic data available, the eastern block of the South Pamir and some of the neighboring regions are underlain by the abnormally thick crust (up to 70–75 km), this being in good agreement with the data available for the lower crustal layers ($V_{\rm P}$=7.2–7.7 km sec^{-1}) [*Belousov et al.,* 1984].

In terms of the lithology, the upper crustal layers (granite and metamorphic rocks) in the South Pamir area are composed of $\rm Ar_2$–$\rm Pr_1$ granite and metamorphic rocks, the average composition of which corresponds to dacite [*Lutkov and Mogarovskii,* 1999]. The lower crust includes Precambrian granulite-charnockite complexes, its average composition correlating with potassic andesite [*Lutkov et al.,* 2002].

The rocks of the South Pamir and Karakorum areas also showed high seismic wave velocities ($V_{\rm p}$ = 8.2–8.4 km s^{-1}) in the mantle top and (8.3–8.6 km s^{-1}) in the subasthenospheric rocks. Yet, generally the Pamir-Himalayan region is characterized by the low-density lithosphere, the high ratio of the "granite" and "basalt" layer thicknesses, the low background and poor differentiation of the magnetic field, and the high heat flow (90–120 mW m^{-2} in the Pamir and Himalayan region) [*Duchkov et al.,* 2002]. The other characteristics of this region are the shallow depth (100–120 km) and large thickness of the asthenospheric layer (150–200 km) with $V_{\rm p}$ values of 7.1–7.5 km s^{-1} [*Belousov et al.,* 1984].

The crustal structure of the region was controlled in many respects by the existence of a large body of low-density, "hot" mantle material residing under the territory of the present-day Tibet, Pamir, Karakorum, and Tien Shan territory, and coinciding with a negative gravity anomaly, which is believed to be the largest on the Earth in terms of its intensity (up to 550 mGal) and size (2500–1000 km) [*Grachev,* 1999, 2000; *Pogrebnoi and Sabitova,* 2001]. The upper surface of this anomalous body coincides with the top of the asthenosphere, the lower has been traced using tomography to a depth of not less than 300–600 km [*Grachev,* 1999; *Pogrebnoi and Sabitova,* 2001]. This mantle anomaly, named after the Tibet Plume (obviously, superplume), records an independent body, unassociated with the India-Asia collision [*Pogrebnoi and Sabitova,* 2001].

3. South Pamir Magmatism Evolution

Our brief discussion of the pre-Cenozoic tectonic and magmatic history allows us to specify the place of the Cenozoic igneous rocks of the region in the evolution series and classify them in terms of their belonging to the Cenozoic igneous rocks of the region (Figure 1A). It should be noted that some of the specific features of the endogenic processes that had operated over the larger territory of the Pamir-Himalayan region are comparable, this allowing us to classify this region, as a first approximation, as one petrographic (geochemical) province. The main feature of the igneous activity in the South Pamir and the adjacent regions is the predominance of K(K-Na) granitoids (including S-granite), and generally the products of melting of the old continental crust. Also widely developed are latite-monzonitic, less basic (usually subalkalic) rock associations.

At the same time the tectonic structures of the South Pamir, where the transzonal bodies of Late Miocene fergusite-carbonatite-syenite are developed, show apparent differences in their geologic evolution and crustal structure.

The Central Pamir is a constituent of the Afghanistan-Central Pamir-Tashkurgan Alpine fold system (1500×50–80 km). Its dominant rocks are often bimodal subalkalic basic rocks and alkalic-salic rocks, varying in age from Pr to $\rm N_1$, owing to which the region evolved during some periods of time as a paleorift [*Lutkov et al.,* 2003]. Its orogenic period was marked by trachybasalt lava flows and by the emplacement of subalkalic, gabbro-granitoid, monzonite-syenite, and other rock complexes (34–61 Ma) [*Pavlov,* 1988].

During the Ꝑ$_3$-$\rm N_1$ time the India-Asia collision initiated the horizontal displacement of the Pamir block in the NNW direction, which involved changes in the morphology and the shortening of the tectonic structures. In contrast to the typical collision-associated S-granites of the SW Pamir, Karakorum, and the High Himalayans (Ꝑ$_3$-$\rm N_1$) [*France-Lanord and Le Fort,* 1988; *Hodges et al.,* 1988; *Vladimirov et al.,* 1992], the Central Pamir granites of the same age (15–20 Ma) show low Al contents and are rich in alkalis up to the transition to alkaline granites. Thereafter Ti-rich alkali gabbroid bodies were intruded. This activity was followed by the intrusion of the ultrapotassic syenite porphyry of the Northern dike belt (Figure 1B).

The Rushan-Pshart zone is represented by Far-Spaced blocks produced by the Alpine collision. Their volcanic rocks are dominated by high-Ti K-Na metabasic rocks and picritoids of Permian-Triassic age, which have been classified as continental rift products [*Pavlov,* 1988; *Vladimirov et al.,* 1992] or as plum-associated (prerift) formations [*Grachev,* 2000]. This volcanic rock sequence is terminated by the Ꝑ$_3$ trachybasalt, trachyandesite and rhyolite and, finally, by the diatremes and a subvolcanic multiphase body of the alkaline basic rocks of the Dunkeldyk Complex (Figure 1B). The potassic granitoids, including the S-granites, were emplaced in the $\rm T_3$–Ꝑ$_3$ interval to time. On the whole, this zone is distinguished by its rift-related mantle and crustal orogenic magmatism. This structural feature developed, at least since Riphean? on the sialic continental crust, different from the crystalline basement of the Central Pamir.

The Southeastern Pamir is considered here, along with the Rushan-Pshart zone, as the indocinides reactivated in the Alpine time [*Vladimirov et al.,* 1992]. It is represented by a system of carbonate-terrigenous troughs which developed in the Precambrian crystalline basement. Its volcanic rocks are represented by subalkalic basalts and

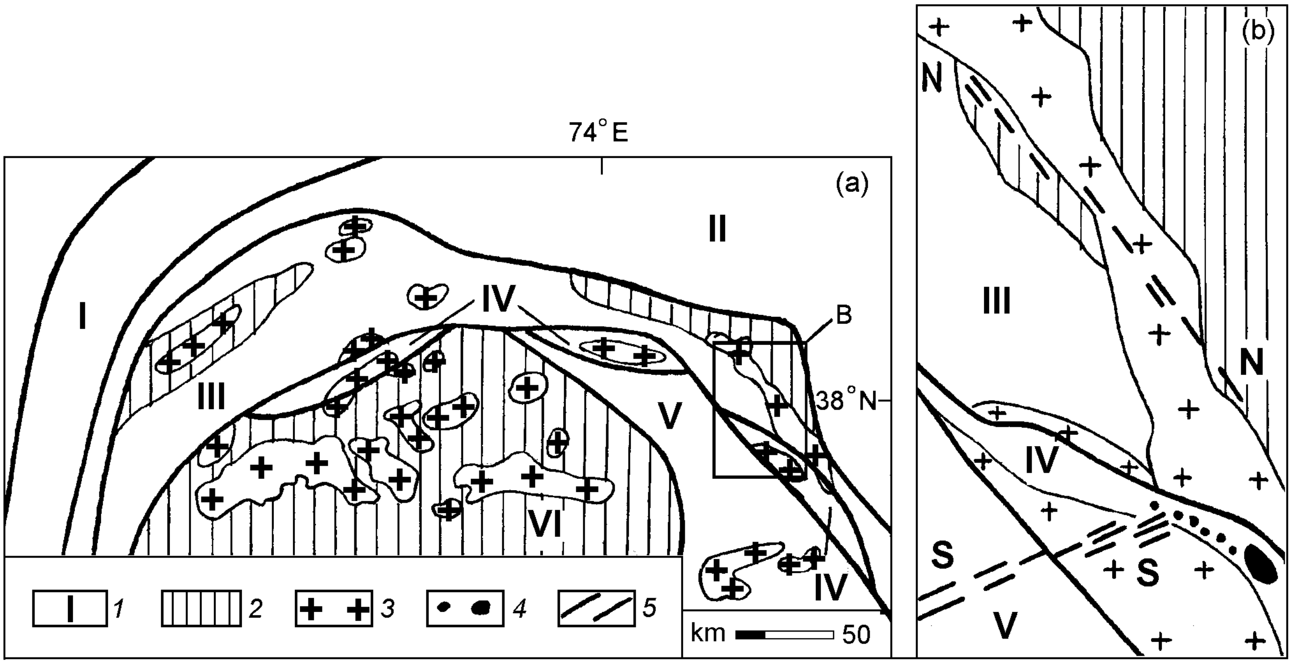

Figure 1. Schematic tectonic map of the Pamir area (A) and the geological positions of the Late Miocene fergusite-carbonatite-syenite bodies (B): (1) tectonic zones and fold systems; (2) blocks of Precambrian rocks; (3) intrusive rock massifs, dominated by potassic granitoids (Ar_2-N_1); (4–5) fergusite-carbonatite-syenite bodies: (4) diatremes; (5) Northern (N) and Southern (S) dike belts; (I–II) Hercynides (I) and Indocinides (II) of the Northern Pamir; (III–VI) South Pamir zones of Kimmerides and Alpides in the South Pamir region (III – Central Pamir, IV – Rushan-Pshart zone, V – Southeast Pamir, VI – Southwest Pamir).

Ti-bearing K-Na (K) picritic basic rocks of Permian-Triassic age. Restricted to these rocks are small (20–30 m) bodies of ophiolite-type ultrabasic rocks. These bodies might have been squeezed out of from the mantle along crustal fault zones which controlled the intraplate picrite-basic rock volcanism. This activity had not been associated with any substantial spreading with the general preservation of the continental crust [*Lutkov and Lutkova,* 1998]. The K-granitoids had been emplaced during the T_3–P_3 time. Various granite-granodiorite, rare-metal granite, monzonite-latite, and other rock complexes have been identified there [*Baratov et al.,* 1978; *Vladimirov et al.,* 1992]. The petrology of these rocks and the metamorphic rock xenoliths found in the granitoids suggest that the Southeastern Pamir had developed on the old sialic crust [*Vladimirov et al.,* 1992]. The syenite-porphyry and fergusite bodies of the Southern dike belt, intersecting the boundary between the Southeastern Pamir and the Rushan-Pshart zone, were intruded during the Late Miocene (Figure 1B).

The Southwestern Pamir is the protrusion of the Precambrian basement representing the crystalline basement of the Southeast Pamir and of the Rushan-Pshart zone. It is mainly composed of the Ar_2-Pr_1 gneiss, crystalline schist, migmatite, quartzite, marble, and granitoids of the amphibolite (disthene-gneiss) and granulite facies. The results of the thermobarometry and formation analysis of these metamorphic rocks [*Budanova,* 1991] suggest that the mature crust, up to 40–45 km thick, had been formed in the South Pamir region as far back as Ar_2-Pr_1.

Widely developed in this region are plutonic rocks (T-₽$_3$) which vary from subalkalic, titanous K-picritic basic rocks to monzonitoids and granitoids. The igneous activity of this region was terminated by the intrusion of Miocene Himalayan-type S-granites containing pegmatite-type rare-metal mineralization (Li, Cs). The typical patterns are their conjugation with the Alpine zones of blastocataclasis and restriction to thermal metamorphic domes [*Vladimirov et al.,* 1992].

One of the important characteristics of the pre-Cenozoic magmatism evolution in the South Pamir region is **the recurrence (inheritance)** of the chemical compositions of the igneous rocks of various ages, as well as, a geochemical correlation between the mantle basic rocks and the crustal granitoids [*Baratov et al.,* 1978]. The inheritance of the chemical compositions of the mantle and crust igneous rocks, associated with the evolution of some structural features, suggests the existence of long-lived deep "roots", namely, some mantle fluid-magma systems which controlled, directly or indirectly, the development of polychronous rock associations at different depths [*Lutkov and Mogarovskii,* 1993]. The above evidence suggests the absence of any significant horizontal displacements in the pre-Cenozoic history of the Pamir region.

The Cenozoic volcanic rocks, mainly the subalkalic (alkalic) basic rocks had been emplaced over the significant territory of High Asia at the background of the Tibet superplume existence. The evolution of the latter seems to have been responsible for the emplacement of the Paleogene subalkalic Fe-Ti basaltic rocks of the pre-rifting type in the northern Tien Shan area [*Grachev,* 1999]. In the South Pamir region the Neogene period witnessed the intrusion of subalkalic (alkalic) Ti-bearing Na basic rocks with high Mg contents, and later the intrusion of the diatremes and dikes of the ultrapotassic fergusite-carbonatite-syenite series [*Ducea et al.,* 2003; *Pavlov,* 1988]. The Tibet area is known for its wide development of polychronous volcanic rocks (N-Q), which vary from typical plume-related alkalic Ti-basalts to shoshonite [*Ducea et al.,* 2003; *Grachev,* 2000; *Hacker et al.,* 2000; *Puzankov et al.,* 2000]. These wide compositional variations of the subalkalic and alkalic basic rocks suggest the overlapping of magmatic activity in different geodynamic environments and/or confirm the view of a great variety of the igneous rock types (Fe-Ti plateau basalts, kimberlites, bimodal series, alkalic granites), associated with the evolution of continental mantle plumes [*Dobretsov et al.,* 2001].

4. Late Miocene Fergusite-Carbonatite-Syenite Series

The potassic alkaline rocks of this series are the youngest igneous rocks of the Pamir region. They are developed in various geological structures of the region (Figure 1B) over and area of more than 1500 km^2. Their analogs are known also far east of this region, e.g., in the Tashkurgan Zone of China [*Geological...,* 1996]. The geological, petrographic, and some of the mineral and geochemical features of these rocks were reported in many papers and in the book of *Dmitriev* [1976]. Later, these data were supplemented by the evidence for the parageneses and compositions of the minerals, for the PT conditions of the formation and chemistry of melt inclusions, rare-element geochemistry, isotope geochronology, and the genesis of the rocks [*Ducea et al.,* 2003; *Lutkov and Lutkova,* 1998; *Mogarovskii et al.,* 1996; *Puzankov et al.,* 2000; *Sharygin and Pospelova,* 1994; *Solovova et al.,* 1996].

Specific geological characteristics of the rock bodies. This series includes three groups of rocks: (a) ultrapotassic alkaline gabbro and basalts (fergusite and fergusite porphyry), (b) various syenitoids (leucitic and sanidine-pyroxene syenite porphyry, alkalic syenite, leucitic tinguaite, quartz syenite, trachyrhyolite, etc.), and (c) carbonatite bodies. In facies terms this rock series combines shallow-depth, mostly subvolcanic rocks, such as diatremes, necks, dikes, and multiphase volcanic bodies. The rocks composing them may have both intrusive or volcanic appearance (explosive breccias, tuff dikes, and the like).

The northern dike belt (30×3 km) is located in the contact zone between the Proterozoic (?) rock block and the Central Pamir Phanerozoic rocks surrounding it (Figure 1B), intruding the stratified and intrusive rocks varying from Proterozoic to Neogene in age. The dikes of this belts intrude the Miocene subalkalic granites of the Shatput Complex (15–20 Ma), this dating the lower age boundary of this rock series. Most of the dikes of this belt range between 0.5 m and 8 m in thickness and are composed of syenite porphyry, alkalic syenite, and lamprophyre (minette and grorudite). The southern dike belts (30×4 km) is developed in the Southeast Pamir and in the Rushan-Pshart zone. The dykes, as wide as 25–30 m, often have blunt ends bordering the brecciated host rocks. In the places of these contacts the dikes contain numerous xenoliths of the surrounding rocks. The rocks of this belt are dominated by pseudoleucite tinguaite and pyroxene-sanidine syenite porphyry, there are also occasional fergusite porphyry. The dikes of multiphase structure show the following sequence of the rock formation (listed from old to young): pyroxene-sanidine syenite porphyry – pseudo leucite tinguaite – bostonite – fergusite porphyry.

The largest subvolcanic body (2.5×1 km in size), known as the Upper Dunkeldyk massif of the Rushan-Pshart zone, has a poorly expressed concentric structure with the leucite basite developed in the middle of the body, and syenitoids occurring along the periphery. The massif apotheses intrude the vertical and gently north-dipping zones of cataclasis and mylonitization, ranging between 100 m and 200 m in thickness [*Dmitriev,* 1976]. The early phases of the massif are represented by fergusite, leucitic syenite, syenite porphyry, and borolanite. The later rocks are alkaline aegirine-diopside syenite and syenite porphyry, the latest rocks being granosyenite porphyry and explosive trachyrhyolite dikes. The carbonatite veins, up to 3–4 m wide, cut across the granosyenite porphyry dikes, with fergusite porphyry occasionally intruding them. The processes, characteristic of the post-magmatic activity, are fenitization, fluoritization, and carbonitization. A rare earth fluorite ore deposit is known to be associated with the carbonatite [*Faiziev,* 2002; *Faiziev and Iskanderov,* 1992].

The Rushan-Pshart zone includes, near its contact with the Central Pamir, a sublatitudinal chain, 15–20 km long, composed of nine diatremes (Eclogite, Podkova, Dvukhfaznaya, and other bodies). The largest of them are as wide as 250–300 m across and have a multiphase structure, ranging the following early to later rocks: (a) pyroxene-sanidine syenite porphyry, (b) predominant fergusite (fergusite porphyry), (c) pseudoleucite syenite porphyry, and (d) eruptive and explosive fergusite breccias. The diatremes contain xenoliths varying from (a) those of the enclosing rocks, (b) early crystallization inclusions (cumulates and early-phase rocks), and (c) mantle and crust rock nodules [*Dmitriev,* 1976].

Geologic and isotope age. The bodies composed of the Dunkeldyk rocks cut the stratified and intrusive rocks, up to the Paleogene ones in the Central Pamir Zone, the Miocene granites, and the Alpine zones of cataclasis and mylonitization. Some of these bodies occur inside of these zones, but do not show any traces of any superposed deformation [*Dmitriev,* 1976].

Earlier, the bulk samples, as well as the sanidine and leucite samples, collected from the fergusite and syenitoids of the dike belts, diatrems, and the subvolcanic body, were dated using a K-Ar method at the laboratories of the Moscow State University, Moscow Institute of Geochemistry, and the

Table 1. ^{40}Ar/^{39}Ar ages of the Dunkeldyk Complex rocks

Sample no.	Geologic object	Rock type	Mineral	Age, Ma
A-2000	Diatreme	Fergusite	Amphibole	11.1±0.14
A-2000	Diatreme	Fergusite	Sanidine	11.1±0.14
A-2000	Diatreme	Fergusite	Sanidine	10.9±0.14
B-2000	Diatreme	Fergusite	Sanidine	11.0±0.14
D-5	South belt	Syenite porphyry	Sanidine	10.8±0.15
D-5	South belt	Syenite porphyry	Biotite	10.9±0.2
D-4	South belt	Syenite porphyry	Sanidine	10.9±0.4
D-4	South belt	Syenite porphyry	Rock type	10.9±0.14

Institute of Geology, Tajik Academy of Science. The results of these determinations showed the ages of 14 Ma to 77 Ma. Most of the resulting ages (8 analyses) showed the age interval of 14–23 Ma. These data were taken to be doubtful because of their proximity to the time when the South Pamir alkalic rocks and Neogene granites had been formed. Later, various minerals from the fergusite diatremes and syenite porphyry of the Southern dike belt were analyzed at the Stanford University by a Ar-Ar method using various minerals from the fergusite of the diatremes and sienite porphyry of the South Dike Belt (Table 1). These analysis proved the late Miocene age (10.8–11.1±0.15 Ma) of the rocks and confirmed the fact that they had the same age in different zones of the South Pamir [*Ducea et al.,* 2003].

Petrography and mineralogy. The phenocrysts found in the fergusites are represented by clinopyroxene and leucite (the latter being more common) and, less commonly, by biotite, sanidine, and apatite. The groundmass (30–40%) is fine-grained, glassy (biotite, leucite, sanidine, aegirine, carbonate, magnetite, and glass), and highly carbonatized. The fergusite was ranked as a leucocratic variety, devoid of olivine and containing less than 30–40% of pyroxene. The fergusite of the subvolcanic body was found to contain up to 5–12% of Ti-Ca garnet (andradite, melanite) with 1.6–3% TiO_2 [*Solovova et al.,* 1996]. The pyroxene is represented by zoned salite (F = 21–40%) with low Al and Na contents (3–7% aegirine) [*Sharygin and Pospelova,* 1994; *Solovova et al.,* 1996]. Its groundmass is enriched in aegirine. The biotite phenocrysts (TiO_2 = 4.3–5.1%) are poor in Si and Al and are enriched in Ba. They show a reverse zoning: the contents of Mg and Ba grow and those of Ti and Fe decline from the cores of the phenocrysts to their margins and to the ground mass grains. Sanidine is developed mainly in the groundmass and is distinguished by its extremely low contents of Ca and Na, by the absence of Sr, and by the high concentrations of Ba (3.4–6.8%) and Fe. The F apatite is characterized by the notable Sr and light lanthanoid admixture and by the nearly complete absence of Ba and Cl [*Solovova et al.,* 1996]. The titanomagnetite contains up to 7.3–11% TiO_2. In addition to the minerals mentioned above, the fergusite contains perovskite, nepheline, sphene (titanite), fluorite, orthite (allanite), epidiolite, pyrite, galena, and some xenocrysts of rutile, kyanite, and Mg-garnet [*Dmitriev,* 1976], as well as, Sr-F apatite, Ca rinkite (mosandrite), Ba scapolite, Ba and Sr zeolites, gerfisherite (K-Ca sulfide), Sr calcite, and others [*Solovova et al.,* 1996].

The syenitoids contain the phenocrysts of clinopyroxene, potash feldspar (± leucite, biotite, amphibole, and apatite); the ground mass contains potassium feldspar, pyroxene, glass, and biotite (± quartz). The near-contact varieties of pseudoleucite tinguaite in the dikes of the Southern Belt are similar to leucite. The potassium feldspar composition varies from that of K (Ba-K) sanidine ($-2V = 20$–$37°$) with the low content of albite (10–15%) and anorthite and the high content of Ba and Fe up to high and intermediate orthoclase ($-2V = 50$–$65°$). The pyroxene from the tinguaite shows a high Na content (6–9% in aegirine). The pyroxenes of the syenitoids and carbonatites (the latter being somewhat higher in TiO_2 and Na_2O) belong to the same series as, as the fergusite pyroxenes, confirming the petrologic association of all rock types. The apatite of the tinguaite (F=2.9%) is poor in Cl (0.05%) and Ba, and enriched in SrO (2.2–3.5%) and in light lanthanoids, that is, is close to the fergusite apatite [*Solovova et al.,* 1996].

Petrochemistry. The fergusite and syenoids show some common (serial) properties, although the latter experienced some changes during the evolution of the alkali-basic melts (Table 2; Figures 2 and 3). The features common for all study rocks are their high Na and K contents at the background of the low Na concentrations Na(K/Na = 3–6). Generally the melt evolution was of the miaskite character, which was reflected in the growth of the Si, Al, and alkalis contents and in the decline of the rock femicity during the differentiation (Figures 2 and 3) [*Sharygin and Pospelova,* 1994].

The fergusites are characterized by their low Ti and Mg contents, their low ferruginosity (38–43%) being caused by their low Fe content (Table 2). The Fe content grows slightly in the syenitic rocks (45–49%), being as high as 60% only in the tinguaite and quartz syenite. The silica content grows slowly in the similar manner from the basic rocks to the syenite, this process being faster in the quartz syenite and trachyrhyolite. The common characteristic feature of the rocks is the high role of the Ca oxide, whose concentration continues to decline in the late differentiates, yet being not lower than 3–6%. The maximum contents of CaO (15%)

Table 2. Average chemical compositions of the Dunkeldyk Complex rocks, wt %

	1	2	3	4	5	6	7	8	9	10	11
	III	III	IV	I	IV	II	III	II	I	IV	IV
SiO_2	45.3	43.6	46.0	55.8	54.3	52.8	53.6	52.3	63.2	65.3	16.1
TiO_2	1.12	1.21	1.22	1.49	0.78	0.86	0.81	0.94	1.0	0.33	0.61
Al_2O_3	12.0	13.2	13.5	13.3	14.9	14.9	14.1	15.9	14.2	14.6	3.4
Fe_2O_3	4.7	7.1	5.1	2.7	3.2	4.8	4.0	4.9	1.7	1.6	
FeO	3.1	2.9	2.0	2.3	1.2	1.2	1.5	1.6	2.8	1.1	5.5
MnO	0.14	0.17	0.13	0.09	0.10	0.11	0.09	0.19	0.07	0.05	
MgO	4.8	7.4	3.1	3.5	1.8	2.1	2.0	1.4	1.9	0.9	0.2
CaO	12.0	10.0	15.0	6.6	8.3	6.6	7.2	5.7	3.9	3.2	37.2
Na_2O	1.6	2.7	1.3	1.5	2.0	1.5	1.7	2.8	2.2	2.9	2.8
K_2O	7.4	7.1	6.2	9.5	9.3	9.5	8.9	8.3	7.3	7.0	2.0
P_2O_5	1.24	1.09	0.93	1.33	0.53	0.48	0.64	0.18	0.39	0.10	
LOI	5.7	3.1	4.7	1.6	3.0	4.6	5.0	5.4	1.0	2.5	
Total	99.1	99.6	99.2	99.7	99.4	99.5	99.6	99.6	99.7	99.6	99.1
CO_2	4.2		3.1	1.3			1.0	1.5	0.1		29.3
n	9	1	8	7	7	8	5	14	5	7	1

Note: (1-3) fergusite, (2) highest Mg variety; (4–10) syenitoids: (4–7) syenite porphyry and syenite, (8) pseudoleucite tinguaite, (9–10) quartz syenite, (11) calculated composition of carbonatite melt inclusions in fergusite pyroxene (1.5% H_2O, 0.9% BaO, 0.34% SrO) [*Solovova et al.,* 1996]. (I–II) Northern (I) and Southern (II) Dike Belts; (III) diatremes and necks; (IV) subvolcanic rock massif; (n) is the number of samples. The oxide contents were rounded to mas. %.

were found in the fergusite and borolanite of the subvolcanic body, yet, remaining relatively high in the syenite porphyry of the body.

Melt inclusions. Melt and gas-liquid inclusions were studied in pyroxene, mica, sanidine, apatite, leucite, sphene, garnet, and fluorite [*Faiziev,* 2002; *Faiziev and Iskanderov,* 1992; *Sharygin and Pospelova,* 1994; *Solovova et al.,* 1996].

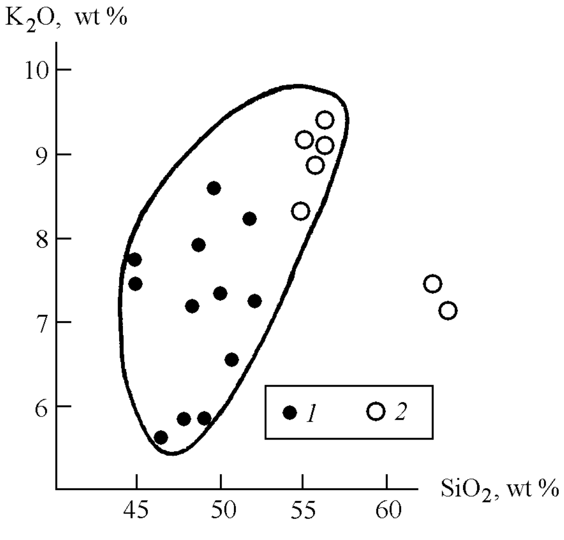

Figure 2. K_2O-SiO_2 ratio in the fergusites (1) and syenitoids (2). Plotted in this figure and also in Figures 2–3, 5, and 6 are the results of individual fergusite analyses and the average values of the syenitoids. All silicate analyses were recalculated for the dry residue.

The microprobe analyses of glass inclusions in different minerals allowed the comparison of the results with the chemical compositions of the enclosing rocks. Generally, the melt inclusions preserved the main chemical features of the alkaline basic rocks (syenites), namely, their high K, Ca, and Ba concentrations and their low Ti content (Table 3). The chemistry of the glasses in melt inclusions varies from that of high-K alkalic leucobasic rocks to the predominant syenitoids. No complete analogs of the host fergusite have been found among the glasses, the dominant materials being the products of the differentiation of the alkaline basic magmas poor in femic components.

The homogenization of melt inclusions in pyroxene, leucite, and apatite phenocrysts occurred at the temperature of 1100–1300°C [*Sharygin and Pospelova,* 1994] or at 1000–1200°C [*Solovova et al.,* 1996]. The authors of the lat-

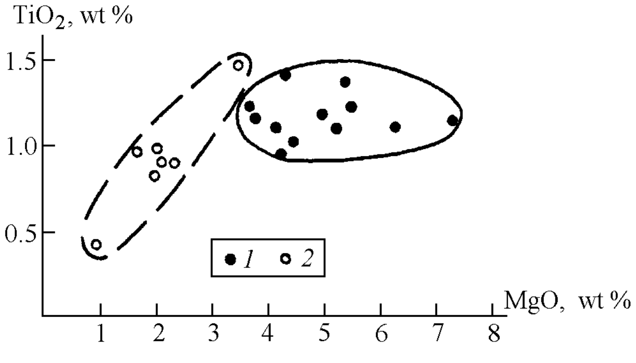

Figure 3. The TiO_2-MgO ratios in the fergusites (1) and syenitoids (2). See Figure 2 for the explanation of the other symbols.

Table 3. Representative analyses of glasses from melt inclusions in fergusite minerals, wt %

	1	2	3	4	5	6	7
SiO_2	52.7	50.0	46.2	50.6	49.7	53.9	56.6
TiO_2	1.06	1.13	1.62	0.59	0.50	0.67	0.0
Al_2O_3	13.9	14.2	13.3	15.0	17.2	17.9	22.2
FeO	6.3	6.4	7.8	5.2	5.2	3.9	0.7
MgO	1.9	0.9	2.8	2.2	1.9	0.8	0.02
CaO	8.0	6.2	9.6	7.1	5.8	2.9	0.2
Na_2O	2.9	3.6	4.1	3.7	5.0	2.5	2.0
K_2O	7.3	8.8	9.3	11.5	10.9	12.7	14.0
P_2O_5	0.09	0.08					
BaO	0.68	1.35	1.25	0.83	1.55	0.34	1.51
SrO	0.15	0.53	0.68	0.27	0.41	0.10	0.0
Cl			0.31	0.24	0.55	0.30	1.93
Total	95.0	93.2	97.0	97.2	98.7	96.0	99.2

Note: (1–7) melt inclusions in pyroxene, leucite, and apatite; (1–2) after [*Sharygin and Pospelova,* 1994]; (3–7) after [*Solovova et al.,* 1996].

ter paper used the temperatures of 1100–1350°C for glasses in leucite, yet, these temperatures are believed to be too high and are explained by technical errors. The highest melting temperatures were obtained for inclusions in sphene, the lowest for those in biotite and some sanidines. Since there are no glasses corresponding in composition to fergusite, the temperatures of melt inclusion homogenization seem to characterize the intermediate and closing phases of alkaline-basic magma evolution. The fergusites showed many coexisting silicate and carbonate inclusions [*Solovova et al.,* 1996].

Rare-element geochemistry. The rocks of the series discussed are enriched substantially in lithophile rare elements (Table 4, Figure 4). The undoubted fact is the geochemical kinship of the alkaline basic rocks and the syenitoids, even though the latter are slightly more enriched in Th, Zr, and Rb and impoverished in Ba, B, and Cs.

One of the few lithophile elements, which showed a negative speciation, is Nb, its deficiency correlating with the low Ti content of the rocks (Figure 4). It is obvious that the low Nb and Ti contents in the studied rocks, and primarily, in fergusite, reflect their deficiency in the primary melt and in the rocks from which the melt forming material had been derived.

It is known that closely associated with Ti and Nb in alkaline rocks is Zr whose solubility in melt grows, as proved by experimental data, with the growth of their alkalinity [*Kogarko et al.,* 1988]. As to the Pamir alkaline basic rocks, the Zr content in them is fairly high, being even higher in syenite, this being accompanied by the violation of the Zr-Ti association [*Mogarovskii et al.,* 1996].

Barium and strontium are the indicator elements of mantle alkaline rocks. In terms of their concentrations, the alka-

Table 4. Average trace elements composition of the Dukeldyk Complex rocks, ppm

	1	2	3	4	5	6	7	8
	III	IV	I	II	II	IV	IV	IV
F, %	0.31	0.62	0.49	0.49	0.41	0.82	0.62	0.63
B	24	26	12	23	23	5	15	13
Li	41	51	40	45	86	172	40	46
Rb	306	349	437	402	339	391	390	428
Cs	24	9	8	10	19	8	26	8
Ba, %	1.15	1.31	0.70	0.51		0.96	0.40	0.11
Sr, %	0.43	0.40	0.14		0.40		0.40	
Zr	300	600			800		600	
Th	56	67	>100	>100	>100	72	>100	93
U	8.4	>10	>10	9.3	>10	8.5	>10	>10
Tl	3.6	4.2	2.7	4.3	4.8	3.1	5.4	8.1
Sn	6	5	16	6	7	5	5	6
Be	10	8		19	2	3		3
n	7	9	14	14	26	5	5	6

Note: (1–2) fergusite, (3–8) syenitoids: (3,4) and (6–7) syenite porphyry and syenite, (5) tinguaite, (8) granosyenite porphyry; (I and II) are the North (I) and South (II) dike belts; (III) diatremes; (IV) subvolcanic rock massif; (n) the number of samples. The average contents of elements (ppm) in fergusite (n=7): (Y) 110, (Nb) 3, (Pb) 140, (Cl) 4900 [*Dmitriev*, 1976; *Mogarovskii et al.,* 1996]. The analyses were made using flame photometry (Li, Rb, and Cs), X-ray fluorescence (Ba, Sr, Zr, Th, Y, and Nb), spectral method (B, Tl, Pb, Sn, Be), chemical method (F), electron microprobe method (F, Cl), and luminescence method (U) in the laboratories of the Institute of Exploration Geophysics, the Institute of the Geology, Petrography, and Geochemistry of Mineral Deposits (Russian Academy), and the Institute of Geology (Tadjik Academy), using geochemical standards. The average contents of elements (pmm) in the syenite porphyry (n=3) and in tinguaite (n=35) from the Southern dike belt are given here after [*Puzankov et al.,* 2000]: 0.9 and 1.4 (Ta), 5 and 20 (Nb), 11 and 34 (Y), 244 and 305 (La), 413 and 507 (Ce), 177 and 176 (Nd), 35 and 30 (Sm), 7.6 and 7 (Eu), 24 and 20 (Gd), 3 and 2.6 (Tb), 2.9 and 47 (Yb), 0.34 and 0.58 (Lu).

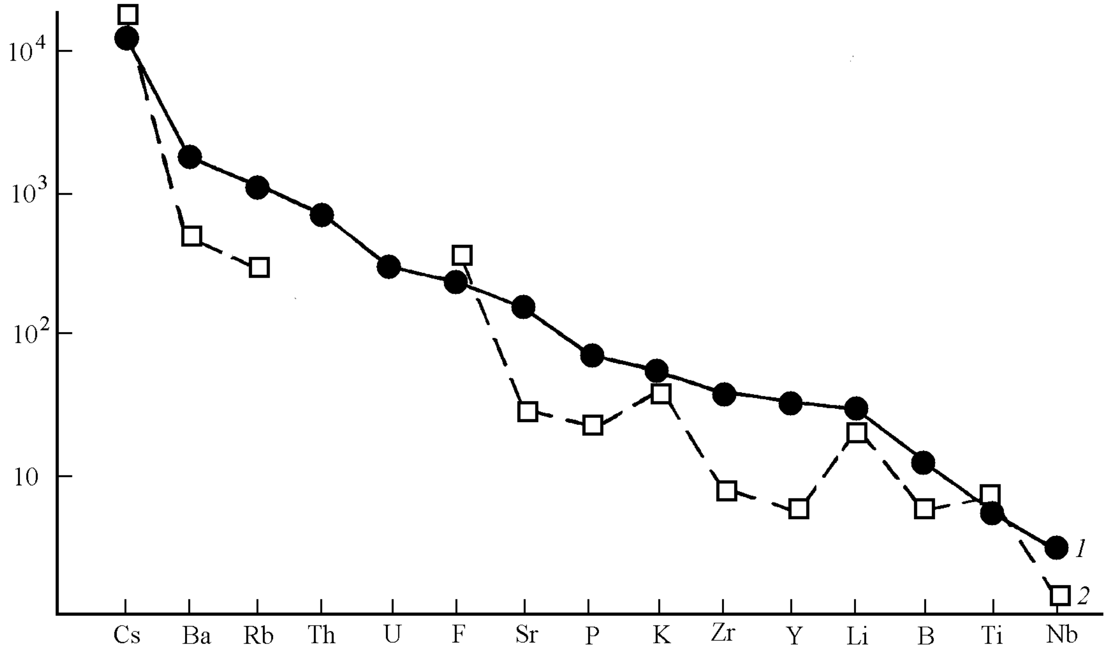

Figure 4. Distribution of incoherent elements in the fergusites (1) and in the xenoliths of the phlogopite pyroxenite-glimmerite (2), normalized to the primitive lherzolite [*Jagoutz et al.,* 1979; *Venke et al.,* 1987]. There are no data for any U or Th contents in the xenoliths.

line basic rocks investigated in this study exceed the clarkes of the potassic alkaline basalt, growing closer to the high-K alkalic rocks of the modern Italian volcanoes, the monchikitite of the Kola Peninsula [*Borodin et al.,* 1976] and to the potassic alkaline rocks of continental rifts [*East African Rift System,* 1974]. In contrast to the lamproites reported in [*Bogatikov and Kononova,* 1991] with their high Ba and low Sr contents, the rocks investigated in this study show substantially high contents both of Ba, tending to be associated with K, and of Sr associated with Ca and alkalis. This is reflected in the contents of SrO in the apatite (2–3.5%) and perovskite (1.4–1.7%) [*Sharygin and Pospelova,* 1994; *Solovova et al.,* 1996]. The high concentrations of BaO were found in biotite (1.5–7.5%) and sanidine (2–6.8%) [*Solovova et al.,* 1996]. The Sr contents varies poorly from alkalic basic rocks to sienite, the contribution of Ba declining notably. This might have been associated with the settlement of biotite (or sanidine, to a lesser degree), and also with carbonate-silicate liquation when Ba goes predominantly to the carbonate melt [*Solovova et al.,* 1996]. The fergusite and syenite are comparable in terms of their Ba/Ca and Sr/Ca ratios, this proving their genetic association.

One of the specific features of the Pamir alkalic basic rocks is their high Y content, comparable with that of the rifting-associated carbonatites. This might have been associated with the high content of Y-bearing garnet in the source rocks, and also with the process of carbonate-silicate liquation. At the same time, the fergusite shows the high concentrations of light lanthanoids, this, in particular, being reflected in the apatite composition (Ce_2O_3 = 0.2–2%; La_2O_3 = 0.5–1.2%), the syenite porphyry and tinguaite being also enriched in REE (Table 4).

Another specific feature of the alkaline basic rocks is their enrichment in volatiles, especially, in F. The main F concentrators were biotite, apatite (2.9–6.6% F), and fluorite, the Cl concentrations in these minerals ranging between 0.02% and 0.08% [*Faiziev and Iskanderov,* 1992; *Sharygin and Pospelova,* 1994; *Solovova et al.,* 1996]. At the same time, the Cl contents in the glasses of the fergusite and syenite melt inclusions were found to be 0.45–0.49% [*Solovova et al.,* 1996]. In some syenites and carbonitites, fluorite is a rock-forming mineral, its contents ranging from 2–7 vol % to 30–35 vol % [*Faiziev,* 2002]. This fluorite contains Sr, REE, U, and Th admixtures and was derived from the F- and CO_2-rich carbonatite melt produced by the liquation of fergusite-rich magma. Moreover, during the magmatic phase F was the constituent of fluorite, rather than of the silicate (the temperature of the homogenization of melt inclusions in fluorite was as high as 1050°C). Fluorite continued to crystallize from the magmatic to the hydrothermal (460°C) phase [*Faiziev,* 2002].

The high contents of Li, Cs, and partially Sn in the alkaline basic rocks correlate with the general geochemical profile of the Pamir province. Their high concentrations of radioactive elements distinguish them from the general geochemical profile of the Pamir Province. Their high concentrations of radioactive elements distinguish them from the K-alkaline rocks of the other regions, their high Th/U ratio reflecting the general trend of the province [*Baratov et al.,* 1978]. In spite of some Rb growth from the alkaline basic

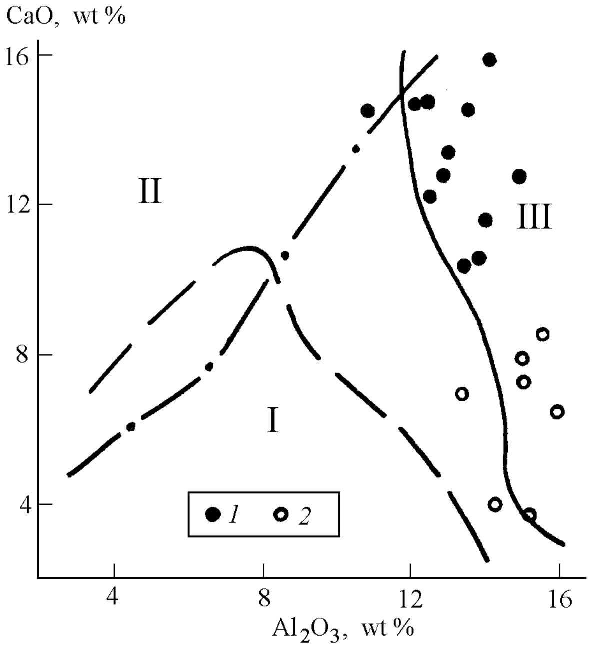

Figure 5. The CaO-Al_2O_3 diagram of the fergusites (1) and syenitoids (2). The potassic rocks are classified into the lamproite (I), kamafugite (II), and tephrite-leucitite (III) series [*Bogatikov and Kononova,* 1991]. See Figure 2 for the explanation of the other symbols.

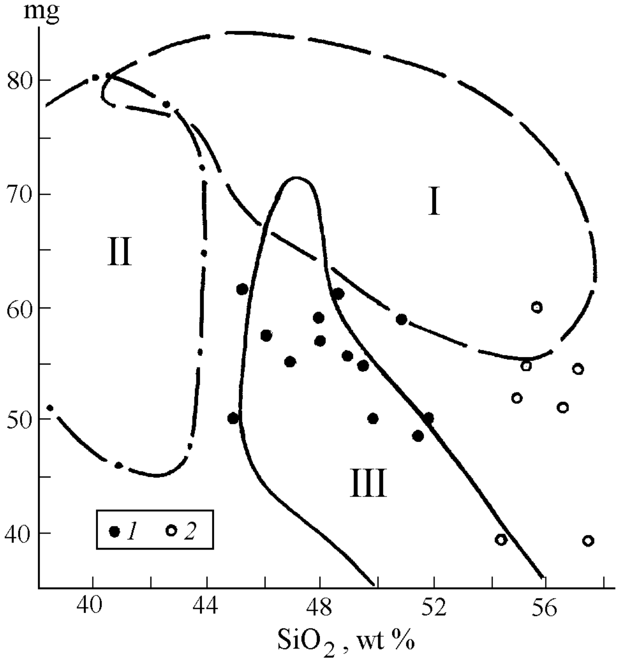

Figure 6. Ratio between the mg-value and SiO_2 contents in the fergusites (1) and syenitoids (2).
mg = 100 MgO/(MgO + Σ FeO)(mol %). See Figure 2 for the explanation of the other symbols.

rocks to syenite, the K/Rb value remains roughly the same (150–200).

Formation analysis. The problem of the formation classification of the fergusite-carbonatite-syenite series of the Pamir region is still a matter of discussion. Earlier, the transzonal bodies of the Neogene rocks of the Dunkeldyk Complex had been ranked as K-potassic gabbroids and basaltoids, associated with the epiplatform mountain-building of the young platform [*Dmitriev,* 1976]. Later, a view was advanced that the fergusite and syenite resemble, in their chemistry and mineralogy, some types of lamproite, yet being more close to the leucite volcanics of the kamafugite series of the East African Rift [*Sharygin and Pospelova,* 1994]. Later, *Solovova et al.* [1996] reported an analogy between the rocks of this series, the orogenic leucitite of Italy, and the post-collision volcanic rocks of Southwest England. Proceeding from their petrochemical data (the presence of a Ti-Nb minimum, the trends and ratios of some rare elements), it was proved that the rocks of the Dunkeldyk Complex occupied the intermediate position between the inter- and intraplate igneous rock associations [*Mogarovskii et al.,* 1996]. Later these rocks were correlated with the Pliocene-Quaternary volcanic rocks from the hot spots of Tibet and Afghanistan [*Budanov and Volkova,* 2003; *Puzankov et al.,* 2000].

The younger age of this rock series relative to the closing phases of the collision-related granite formation and the Cenozoic cataclasis and mylonitization zones, as well as the absence of late deformation traces in these rock bodies, suggest a connection between the formation of the Late Miocene fergusite-carbonatite-syenite series and the post-collision conditions. The structural control by deep faults (permeability zones) and the ultrapotassic alkaline-basic composition of the primary magma suggest the mantle origin of the rocks and their association with the partial melting of the "enriched" (metasomatized) mantle. The widely developed processes of the crystallization differentiation and liquid layering (carbonate-silicate liquation) of the mantle alkaline-basic melts in the Earth crust, including those operating in the intermediate-depth chambers of subvolcanic bodies, suggest their evolution under the conditions of relative tectonic quiescence and extension.

Let us compare the petrogeochemical features of the studied rocks (primarily, of fergusite which is most similar to the primary melt composition) with the known formation types of potassic alkaline-basic rocks (Tables 2 to 4, Figures 4 to 6). The rocks of this series show a peculiar petrogeochemical profile. Because of some characteristics it is difficult to classify them in terms of some definite formation type. Proceeding from the ratios of some elements (Ti-K, T-Zr, and Nb-Zr-Y), they fit the trends of interplate basic rocks [*Lutz,* 1980; *Meschede,* 1986], their main common feature being the distinct Ti-Nb minimum. Their high Ba, Zr, and Y contents and, partially, their Zr-Y ratios [*Pearce and Norry,* 1976] correlate well with the geochemical features of some rocks from continental rifts [*Grachev,* 1987]. However, they differ from rift-type, primarily, kamafugite rock associations by their higher K contents (K/Na) and by their lower Ti, Nb, and Ca concentrations. Similar differences can be found by comparing the rocks of this series with typical plume-type (prerifting) volcanic rocks [*Grachev,* 1999, 2000]. Yet, some indications suggest that a lower mantle plume (superplume) existed in Cenozoic time under the Tibet, Pamir, Himalayan, and Tuen Shan region [*Grachev,* 1999; *Pogrebnoi and Sabitova,* 2001]. In terms of its continental rift rocks this rock series is more close to the scarcely found ultrapotassic rock associations of melaleucitite, leucitic tephrite, and phonolite, as well as carbonatite [*Kovalenko,* 1987]. Yet, the study rocks differ from them by their higher potassium contents, by their potasiumphile trace elements, and by their low Cr, Ni, Ti, and especially Nb elements.

The alkaline basic rocks discussed in this paper have some features in common with the basic-intermediate leucite lamproite, such as, the ultrapotassic type of their alkalinity and their saturation in F, Rb, Ba, P, and other elements, yet, they differ markedly from the lamproite by their low contents of Mg, Ti, Zr, and Nb and by their higher contents of Ca, Sr, U, Th, and other elements. Somewhat closer to the study rocks are the low-Ti lamproites from the collision zones and from the structural features associated with them in the Western Mediterranean region [*Bogatikov and Kononova,* 1991]. However, the latter also show some differences from the Pamir alkaline basic rocks in terms of their different contents of Mg, Al, Ti, Sr, Nb, and other elements. Therefore, in spite of the fact that there are some common features in the geodynamic environment of the emplacement and composition of the Pamir high-K basic rocks and of some types of lamproite, the former and the latter belong to different formation types.

The study rocks differ from the "classical" igneous rocks of continental hot spots [*Kovalenko,* 1987] by their drastically higher K contents, by the high concentrations of K-philous elements (Rb, F, Ba, U, Th), and by their distinct Nb-Ti minimum. The correlation of the Dunkeldyk rocks with the N_2-Q volcanics of the Tibet "hot spot" [*Budanov and Volkova,* 2003; *Puzankov et al.,* 2000] is based merely on the high Ti content in one melt inclusion [*Sharygin and Pospelova,* 1994], which is classified as a primary melt analog. However, this inclusion contains merely 2% MgO, which suggests its association with alkaline-basic magma fractionation. Moreover, the high T-concentrations in melt inclusions have not been confirmed by their subsequent chemical analysis [*Solovova et al.,* 1996]. At the same time, the direct data available for the Ti and Nb distribution in the fergusite diatremes and in phlogopite pyroxenite xenoliths, the potential mantle sources of alkaline-basic magma, showed a distinct Ti-Nb minimum [*Lutkov and Lutkova,* 1998; *Mogarovskii et al.,* 1996]. Assuming the dike belts of the Dunkeldyk Complex to be some peculiar projections characterizing the motion of the Pamir plate over some mantle magma source, one has to admit that this plate moved first to the northeast and later, in the NWW direction, which contradicts quite a number of facts. Moreover, there is no evidence in favor of the Ar-Ar age growing younger from the southern bodies to the northern ones.

In terms of the Ca-Al and Mg-Si ratios (Figures 5 and 6), the rocks of this series tend to be closer to the tephrite-leucite association, being distinctly separated from the lamproite and continental rift-related (kamafugite) rock series. This agrees, basically, with above mentioned data for their rare-earth composition. There is some petrochemical similarity between the rocks of this series and some K-rich alkalic rocks in the collision zones of Iran, Tukey, and Italy, such as, leucitic tephrite, leucitite, alkalic trachyte, and carbonatite [*Kovalenko,* 1987], these rocks being also comparable with the post-collision K-volcanics of Southwest England [*Solovova et al.,* 1996].

Fergusite-carbonatite-syenite series as an indicator of geodynamic processes. The formation of the Late Miocene ultrapotassic rock series under the conditions of the Tibet Superplume operation reflected a substantial change in the geodynamic environment. The rock bodies of this series were intruded under the conditions of extension associated with mantle permeability zones which extended as high as the top of the asthenospheric layer. The character of the igneous rocks areas, the internal structure of the bodies, and the type of the magma evolution suggest the relatively quite tectonic (postcollision) conditions. This agrees with the lithological composition of the rocks of this series, which are comparable with some post-collision tephrite-leucitite (carbonatite and syenite) associations. The Late Miocene rock series differs from the typical plume-type rocks even in the broadest interpretation of this term (prerifting, rifting, and hot-spot conditions). The unusual rocks of this series can be explained, as mentioned above, by the combination of different geodynamic conditions and/or by a great variety of rocks representing the plume-type of magmatism [*Dobretsov et al.,* 2001].

The unexpected geodynamic consequences follow from the transzonal occurrence of the Late Miocene alkalic rock bodies which intersect, as mentioned above, the boundaries of the zones with different geologic histories and crustal structure, as well as the Alpine zones of cataclasis and mylonitization. It should be emphasized that the rock bodies of this series did not experience any later deformation. Their specific tectonic position, the youngest age compared to the igneous rocks of the region, namely, 11 Ma, as well as their lithology and genesis, suggest that the horizontal movement of the Pamir, or at least of its eastern block, must have ended, or at least slowed down, as early as during the Early Miocene or even somewhat earlier. If this stop were a temporary one, the renewal of this body motion must have caused the superposed deformation of the rocks developed over an area of >1500 km^2. This suggests the conclusion that the formation of modern structural style of the East Pamir terminated in the main during the Late Miocene. It should be noted that this hypothesis is contradicted by the instrumental measurements carried out at the Garm Geodynamic Site, which recorded the high velocity (up to 15–20 mm year^{-1}) of the Pamir and Tien Shan movement toward each other [*Pevnev et al.,* 1978], not to mention some other facts and geodynamic reconstructions.

The subsequent evolution of the Pamir and Tien Shan was marked by the growth of the accumulation rate and grain size of the terrigenous (molassoid) deposits [*Babaev,* 1984; *Lukina et al.,* 1985], this reflecting the growth of the relative contribution of tectonic movements from the Miocene (hundredth fractions of mm year^{-1}) to the Pliocene (tenth fractions of mm year^{-1}), and especially toward the end of the Quaternary (mm year^{-1}) [*Babaev,* 1975, 1993; *Grachev,* 2000]. The recent mountain buiding peak (N_2-Q) is associated mainly with vertical movements [*Nikolaev,* 1988]. As regards the Pamir region, it can be supposed, proceeding from the above considerations, that the vertical movements (N_2-Q) did not generally change the structural style of the region, which had been produced by the collision-related processes that operated up to the Late Miocene.

The genesis of this series rocks. Judging by the composition of the fergusite which seems to have been common for the primary or nearly primary magmas, their potential source might have been relatively poor in Mg with the potential absence of olivine. The high K and Ca contents in the alkaline basic rocks emphasizes the important role of phlogopite and clinopyroxene in the rocks. The source material was low not only in Mg, but also in Ti, Na, and, especially, in Nb. The high K concentrations, against the low-silica background, might have been produced by the presence of phlogopite which concentrates K, H_2O, F, Rb, Ba, and other K-philous elements.

The experiments made for the melting and crystallization of high-K alkalic-basic-ultrabasic magmas at high pressure [*Bogatikov and Kononova,* 1991; *Lloid et al.,* 1985] showed that in the case of their high water content phlogopite might be a near-liquidus mineral, whereas in the case of the leucite melt, similar to the Pamir alkaline basic rocks, garnet appears, along with clinopyroxene, at $P>35$ kbar. Generally, the growth of pressure broadens the field of pyroxene and garnet stability, and in the case of high water content, of phlogopite, whereas the region of olivine crystallization diminishes, the pyroxene + leucite paragenesis appearing at $P<15$ kbar. Our analysis of the subliquidus mineral associations of leucitite and lamproite showed that the mantle source of their high-K magma might have been phlogopite and garnet-phlogopite clinopyroxenite [*Bogatikov and Kononova,* 1991; *Lloid et al.,* 1985].

As will be demonstrated below, the mantle xenoliths in the Pamir fergusite include widely developed garnet-phlogopite and phlogopite clinopyroxenites (glimmerite), less common being websterite which originated at pressure as high as 35–40 kbar (115–130 km). These pressures suggest the minimum depth of fergusite melt generation. The above-mentioned requirements to the mantle sources of the Pamir alkaline basic rocks might have been satisfied by the garnet-phlogopite clinopyroxenite (±glimmerite) with carbonate and apatite. Their composition correlates with the fergusite chemistry (Figure 4). The xenoliths of these rocks are enriched in CaO, K_2O (3–7%), H_2O, CO_2, F (0.5–1.12%), Ba (up to 1.2%), Sr (500–1100 ppm), P (up to 4%), Rb (50–150 ppm), and are poor in Ti, Na, and Nb (<1 ppm) [*Lutkov and Lutkova,* 1998].

The studied basic rocks and their potential mantle sources are rich in volatiles: CO_2, H_2O, F, and Cl. The wide development of phlogopite in the metasomatized mantle rocks suggests the substantial role of H_2O and F in the primary melts. The direct determination of CO_2 inclusions in the pyroxene phenocrysts of the fergusite suggests the presence of carbon dioxide fluids also in the zone of magma generation [*Solovova et al.,* 1996]. The potential source of carbon dioxide was the carbonate of the phlogopite pyroxenite. The magma rise and pressure decline were accompanied by the growth of the CO_2/H_2O ratio, and part of water was removed along with mica phenocrysts and phlogopite pyroxenite cumulates. The relatively minor role of water-bearing minerals in the phenocrysts suggests the water pressure decline during the rise, differentiation, and crystallization of the subvolcanic bodies. Moreover, the results of experiments [*Bogatikov and Kononova,* 1991] suggest that the growth of the CO_2 and F contents in the melt narrowed the field of olivine crystallization, which has been observed in the basic rocks examined in this study. The presence of titanomagnetite in them is another indication of the CO_2/H_2O ratio.

As mentioned above, the homogenization temperature of melt inclusions in various fergusite minerals ranges from 1000°C to 1200°C [*Solovova et al.,* 1996]. Since the glasses usually have a syenite composition, it can be inferred that they record the temperatures of the intermediate and final (near-solidus) stages of the alkalic-basic magma crystallization. The fergusite of the diatrems which carry mantle nodules seem to have been associated with the relatively poorly differentiated mantle magma of mantle sources. The emplacement of the subvolcanic body and, especially, of the syenitoid dike belts was in many respects controlled by the differentiation of mantle magma in crustal (intermediate-depth) chambers [*Dmitriev,* 1976]. The separation of the carbonate melt from the potassic alkaline-basic magma was controlled by the effect of carbon dioxide that accumulated during the rise of the magma and its differentiation, its high alkali content broadening the field of magma incompatibility. The processes of carbonate-silicate liquation coincided in place and time with the crystallization and subsequent settling of phenocrysts at pressure of about 4 kbar [*Solovova et al.,* 1996].

5. Mantle and deep-crust xenoliths and models for the formation of the Cenozoic lithosphere in the Pamir region

The data available for the composition and PT conditions of the formation of mantle and crust xenoliths provide important information for the generation depth and composition of the melt sources of the alkali basic rocks, as well as for the crustal structure and evolution of the lithosphere in mobile belt areas. These data are especially important for the eastern segment of the Alpine-Himalayan Belt in connection of the problematic origin of the superthick continental crust there. The rapid removal of xenoliths to the ground surface ensures, in contrast to the exhumed high- and ultrahigh-pressure (HP-UHP) metamorphic rocks, the absence of retrograde metamorphism and the preservation of deep mineral associations. Since the compositions of the Pamir nodules are described in detail [*Dmitriev,* 1976; *Dmitriev and Lutkov,* 1983; *Ducea et al.,* 2003; *Lutkov,* 2003; *Lutkov and Lutkova,* 1998; *Lutkov et al.,* 2002; *Mogarovskii and Dmitriev,* 1975], we will concentrate here mainly on their thermobarometry

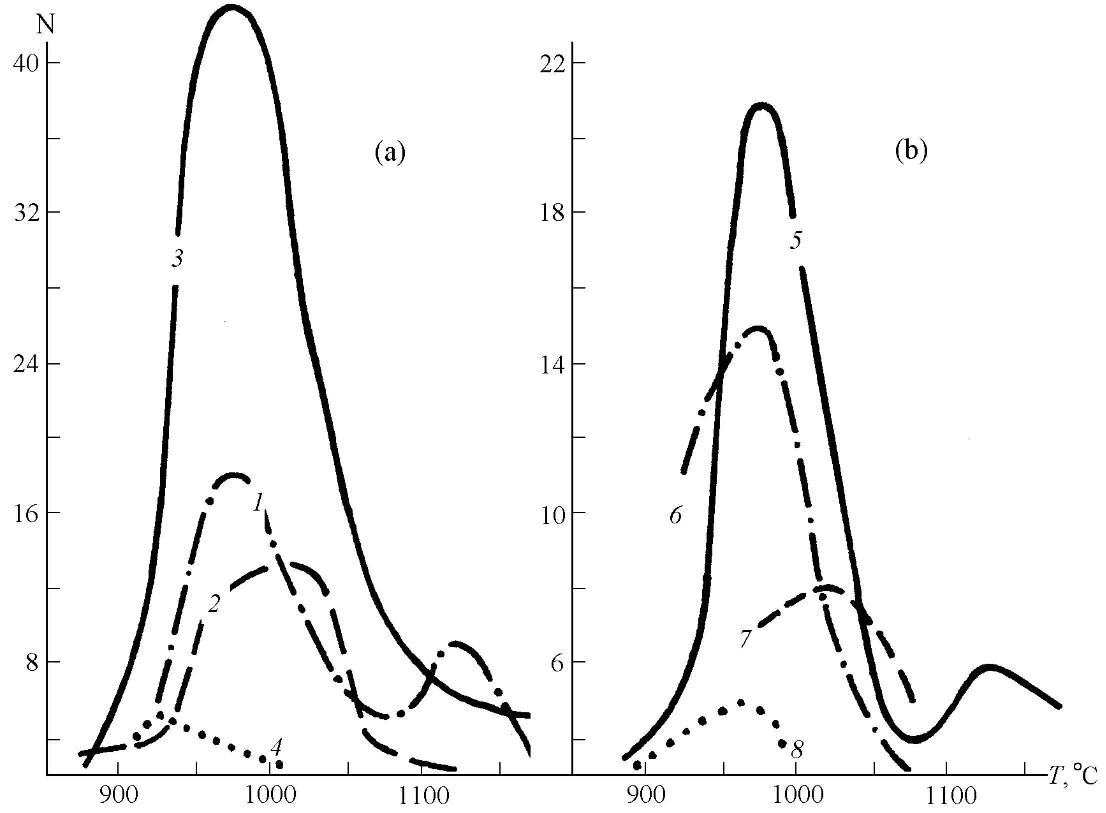

Figure 7. Variation curves for the distribution of mineral equilibrium temperatures of xenoliths in the Pamir fergusite. (A) Main types of nodules: (1) phlogopite-garnet websterite, (2) garnet clinopyroxenite, (3) eclogite, (4) garnet-orthopyroxene granulite; (B) eclogite types: (5) sanidine, (6) biotite, (7) bimineral, and (8) plagioclase eclogites. N denotes the number of T calculations.

and origin, these problems being directly associated with the topic of this paper.

The fergusite pipes contain the inclusions of eclogite, garnet and phlogopite pyroxenites, glimmerite, various eclogite-like rocks, and granulite [*Dmitriev,* 1976; *Lutkov and Lutkova,* 1998]. These rocks have some features in common, being different from the similar nodules in kimberlite and eclogite of the metamorphic rocks of elevated alkalinity and the wide development of sanidine and mica [*Lutkov,* 2003]. The garnets of the eclogite were found to contain relict (pre-eclogite) inclusions of K-feldspar, biotite, hastingsite, hypersthene, and other minerals [*Ducea et al.,* 2003] confirming the subalkalic type of their protoliths [*Lutkov and Lutkova,* 1998].

The most widely developed eclogites contain to two groups of minerals: (a) garnet, omphacite, and rutile (60–80%) and (b) sanidine ±K plagioclase no. 15–20 (grades to feldspar of high miscibility), kyanite, quartz, titanobiotite, amphibole, and some other minerals. The minerals of the (b) group compose intergranular spaces and veins of the leucosome type migmatite. They vary in composition from syenite (monzonite) to quartz syenite and K subalkalic and superaluminous granites. The appearance of plagioclase in the leucosome, the occasional corrosion relationships between the latter and the melanosome, and the elements of the mineral regressive zoning suggest that the melt had crystallized during the pressure decline [*Lutkov,* 2003]. The similar chemistry characterizes the primary inclusions discovered in all eclogite and granulite minerals [*Chupin et al.,* 1997].

In terms of their petrogeochemistry, the nodules combine two rock series: (a) a picrite (picrobasite)-shoshonite-latite series, closely resembling the similar Andean rocks of the Asian continental margin and mature island arcs, and (b) a subalkalic-alkalic Ti-bearing potassic picrite-basic rock series of the intraplate type. The rocks of both series are believed to have been associated with a mantle source [*Lutkov,* 2003].

The P-T conditions of the mineral equilibria in the xenoliths were estimated using 5 to 11 orthopyroxene-garnet barometers and 7 to 30 garnet-clinopyroxene, garnet-orthopyroxene, and two-pyroxene thermometers (TPF Program, Institute of Experimental Mineralogy, Russian Academy of Science), using 25 rock samples. Since it was difficult to estimate a priori the reliability of the thermobarometers used, and since the errors are leveled when a great number of the latter are used [*Carswell and Gibb,* 1980], the resulting data were averaged (Table 5, Figure 7). Moreover, we also used some approximate P and T values based on the parageneses and compositions of the minerals and on the homogenization temperatures of melt inclusions.

The temperature average values and modes were basi-

Table 5. Average crystallization temperatures of the Pamir deep nodules

Rocks	n1	n2	x̄, C°	S
Garnet-phlogopite websterite	2	50	1019±10	67
Garnet (±phlogopite) clinopyroxenite	5	36	995±8	50
Bimineral eclogite	3	21	1021±6	29
Sanidine eclogite	7	49	1033±12	83
Plagioclase eclogite	1	7	944±15	39
Biotite eclogite	5	34	968±6	34
Garnet-biotite-hypersthene granulite	1	8	956±20	57

Note: n1 is the number of the study samples, n2 is the number of individual calculations, x̄ is the arithmetic mean value, S is the standard deviation.

cally similar. This and the low data dispersion suggest a fairly uniform distribution of temperatures measured using different types of thermometers in the main types of the nodules (Table 5). Some temperature decline was recorded in the plagioclase and biotite eclogites and granulite. One of the xenoliths from the plagioclase-sanidine eclogite showed an abnormal temperature, namely, T_{av} = 1190° C. The temperatures of melt inclusion homogenization in sanidine-plagioclase eclogite and in kyanite-garnet granulite (1000–1050°C [*Chupin et al.,* 1997]) generally agree with the temperatures of garnet-pyroxene solid phase equilibria. This fact and the simultaneous occurrence of compositionally close melt inclusions in garnet and leucosome minerals confirm the proximity of the P-T conditions and time of metamorphism and partial melting. The highest pressures have been established for the garnet-phlogopite websterite (29–36 kbar), sanidine eclogite (22–28 kbar), and plagioclase-bearing eclogite and granulite (15–22 kbar) (Figure 8).

Worthy of mention is the proximity of the T_{av} values (950–1050°C) in the rocks of different compositions and formation depths (15–36 kbar) and the extremely high temperatures of some lower-crust sanidine-plagioclase eclogites (as high as 1200°C). These unusual T and P values can be expected in a subduction plate, where the normal isograde positions can be violated. At the same time a general agreement is observed between the composition (femicity) and the depth of the rocks in the lithospheric rock sequence, namely, from websterite (29–36 kbar) to intermediate-acid granulite (12–15 kbar). Compared to the HP-UHP rocks, the Pamir nodules are 150-300°C hotter and tend to the “eclogite+melt” field, being located in the vicinity of the “hot subduction” trend. The granulites show even higher T/P values tending to be located closer to the rift (collision) geotherm (Figure 8). These specific features seem to record the effects of mantle hot spots (plumes?).

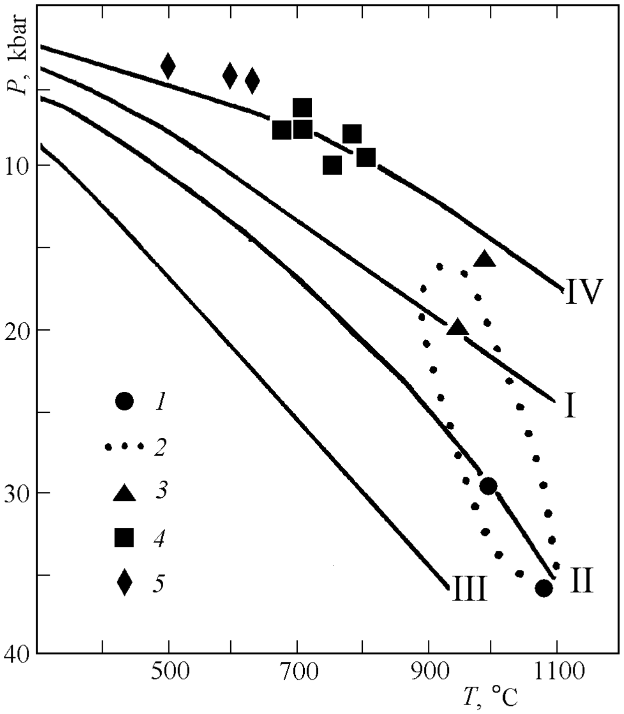

Figure 8. Paleogeotherms of the South Pamir Cenozoic lithosphere. (1–3) Xenoliths: (1) phlogopite-garnet websterite, (2) eclogite and eclogite-like rocks, (3) metabasic and metapelitic granulites; metamorphic rocks (4–5): (4) Precambrian rocks of granulite and amphibolite facies, (5) orogenic zoned rocks (KZ). Calculated geotherms: (I) oceanic [*Ringwood,* 1981], (II–III) shield-type (II after [*Ringwood,* 1981]; (III) 40 mB m^{-2} [*Pollack and Chapman,* 1977]; (6) South Pamir collision type [*Dobretsov et al.,* 2001] coincides with the rift-related geotherm of 90 mB m^{-2} [*Pollack and Chapman,* 1977].

The genesis of xenoliths, which is treated at the present time in terms of three models, is associated closely with the general problem of the Cenozoic lithosphere formation in this region. Model I suggests the differentiation and crystallization of the mantle subalkalic picrite-basic rock melts at different levels of the lithosphere and the downward growth of the South Pamir Precambrian crust during the Mesozoic-Cenozoic Period by way of magmatic underplating [*Lutkov,* 2003; *Lutkov et al.,* 2002]. Model II suggests that the igneous and sedimentary rocks (K_2-P_3) of the Kokhistan-Ladakh Arc and Karakorum were thrust under the South Pamir region, which involved their metamorphism and partial melting [*Ducea et al.,* 2003]. Model III suggests the rheologic layering of the lithosphere under the conditions of tangential compression and mantle diapirism, which resulted in the pressing and eclogitization of the South Pamir upper-crust blocks, metasomatism, and magma generation [*Vladimirov et al.,* 1992]. It should be noted that a universal model which would be able to interpret consistently the factual data available for the Pamir xenoliths, as well as, to correlate them with the evolution of the lithosphere of this region, is a matter of the future. At the same time, each of the above mentioned models offers some constructive elements which can be used in the discussion that follows.

It has been mentioned above that the dominating rocks of the region, namely, the eclogite-pyroxenites belong to two subalkalic picrite-basic rock series. The protoliths of the granulite xenoliths vary from basic rocks to intermediate-acid igneous rocks, and to pelite. The subsidence of a plate (or a block) into the mantle under the South Pamir to a depth of 100–120 km, that is, to the top of the asthenosphere, caused the metamorphism of the eclogite facies (25–36 kbar, $\geq$1000°C) and partial melting, obviously with the addition of K and other elements from the mantle. The operation of these mechanisms was accompanied by the beginning of gravitational differentiation which was controlled to some extent by the premetamorphic differentiation of the magmatic rocks (protoliths). The high concentrations of K and Si (sanidine, quartz, and biotite) in the bodies (crustal blocks) of sanidine and plagioclase-sanidine eclogite and granulite stimulated the growth of syenite-granite melts in them (with the potential separation of magma and garnet-pyroxene restite) and ensured their positive buoyancy and potential rise up to the ancient crust bottom. As mentioned above, the thickness of the latter was 40–45 km. These processes, generally corresponding to underplating and operating in Miocene time (the histogram peaks of the U-Pb age of the zircon marginal zones in xenoliths showed 15–17 Ma [*Ducea et al.,* 2003]), seem to have caused the growth of the crustal thickness in the eastern part of the Pamir region to 70–75 km.

This activity was accompanied by the subsidence of garnet-pyroxenite and/or garnet-pyroxenite restite blocks. The high density of the South Pamir mantle (V_p = 8.2–8.6 km s^{-1}) at depths as great as 200–300 km might have been caused only by eclogite, and the growth of V_p from the Moho discontinuity to the subasthenospheric layer, by the growth of the garnet content relative to that of pyroxene. The thick asthenospheric layer (V_p = 7.1–7.5 km s^{-1}) was the potential source of fergusite magma which transported garnet xenoliths to the ground surface in late Miocene time.

To sum up, the superthick crust was formed in the collision orogenic belt of the South Pamir under the conditions of the complex combination and interaction of collision-subduction and plume activity.

The remarkable feature of the upper mantle of this region, which is still waiting for its explanation, is the absence of peridotite, and of any olivine-bearing rocks, in general, the latter being proved by xenolith studies and geophysical measurements. The South Pamir region is known to include small bodies (20–30 m in size) of ophiolite-type ultrabasic rocks in association with continental and rifting-related (prerift) subalkalic Ti-rich K-Na picritic (basaltic) rocks of Permian-Triassic age. These bodies may characterize some relict Early Mesozoic ultrabasic mantle of the region, yet, the mechanism of the replacement (?) or displacement of the ultrabasic mantle by this pyroxenite-eclogite material remains to be unknown.

The Early Mesozoic and Paleogene growth of the continental crust in the Paleozoic structural features of the North and South Tien Shan took place also at the expense of the mantle material, yet, under the conditions of high heat flow and was controlled by a different mechanism. This mechanism can be roughly described as the melting of subalkalic and alkalic Ti-rich picritic and basic magmas with the development of the newly formed lower crust ("core-mantle mixture"), composed of plagioclase pyroxenite, hornblendite, biotite-kaersutite gabbroids, and the like, associated with the evolution of lower mantle plumes and underplating phenomena [*Grachev,* 1999, 2002a; *Lutkov,* 2000].

6. Conclusion

The Cenozoic history of the Pamir Mountains and of the Pamir-Himalayan region as a whole was controlled by the interaction of two main factors: the India-Asia collision and the Tibet superplume as a gigantic mantle anomaly [*Grachev,* 2000; *Pogrebnoi and Sabitova,* 2001].

Our study of deep-crust and mantle xenoliths in the Pamir alkaline basic rocks allowed us to suggest a potential model for the formation of a superthick crust in this region. The continental subduction involved the plunging of the crust protolith (subalkalic potassium picrite basic rocks and, to a lesser extent, sedimentary rocks) under the South Pamir to a depth of 100–120 km (top of the asthenosphere). This caused their eclogite facies metamorphism (25–35 kbar, 950–1050°C to 1200°C) with the additional potassium flow from the mantle and partial melting. Compared to the common high-pressure rocks, the HP-UHP rocks of the study xenoliths are 150-300°C hotter, reflecting the effect of mantle (plume?) sources. The gravitational differentiation and rising of the partially melted metabasite bodies in the Miocene(15–17 Ma) toward the Moho discontinuity resulted in the growth of the old continental crust thickness to 70–75 km.

The formation Late Miocene fergusite-carbonatite-syenite series (11 Ma) in the South Pamir region suggests an abrupt change in the geodynamic environment. The association of the melt with mantle permeability zones, as deep as 120–130 km, and with phlogopite-clinopyroxenite rocks, as well as the specific internal structure of the rock bodies and the character of the crystallization differentiation and the carbonate-silicate liquation of the magma, suggest that they were emplaced under the conditions of a relative tectonic quiescence and local extension. This rock series differs, in terms of its composition, from the typical plume-type rocks and is comparable with the post-collision tephrite-leucitite association. The correlation of the tectonic positions of the Late Miocene ultrapotassic rock bodies with the structural features showing different crustal structure suggests that the horizontal displacement of the Pamir (or at least of its eastern block), and the formation of its present-day structural style, controlled, mainly, by the collision movements, was completed during the Late Miocene.

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