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GEOLOGY

Different-Depth Xenoliths from Devonian Intrusions of the Kola Peninsula: Key to Deciphering Paleogeodynamic Settings of Alkaline Magmatism

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One of the puzzles of intraplate alkaline magmatism is its spatial confinement to extensional structures (rifts), whereas manifestations of magmatism (massifs, diatremes, and dikes) are found in the areas characterized by horizontal compression [1]. It is also difficult to explain the fact that magmatic rocks of this type are usually related to different mantle sources. In particular, coeval kimberlite and tholeiite diatremes are known within the Arkhangelsk province [2]. The Kola province probably incorporates independent magmatic sources differently enriched or depleted in incompatible elements [3]. One of the possible mechanisms explaining the paradoxes of alkaline magmatism is represented by the model of low-angle normal faulting proposed for formation of continental rifts [4]. Processes of shock decompression in the course of normal faulting control areas of partial melting, while their footwalls govern areas of local compression (Fig. 1) [5, 6]. However, many problems of structural position of the magmatic sources, and especially their interaction in the low-angle normal faults, have not been investigated. The study of different-depth xenoliths may help in deciphering paleogeodynamic conditions in the crust–mantle section in the low-angle normal fault zones.

Diverse manifestations of the Devonian magmatism in the Kola alkaline province (central-type massifs, diatremes, and dikes) contain xenoliths of the host and deep-seated rocks. The xenoliths not only yield information on the composition of the lower crust and upper mantle studied in the numerous works [7], but also provide insights into the deep structure of the region. The presence or absence of xenoliths, their primary composition, and secondary alterations indicate the dynamic state of the Earth's crust and upper mantle during the period of alkali rock formation (according to recent data, a narrow range of 380–360 Ma [3]). We believe that the formation and preservation of xenoliths of the host rocks is related to the rapid effusion of the fluid-saturated magmas to the surface. The composition of fragments corresponds to the horizon (or horizons), which maximally prevented the ascent of the deep-seated matter. The absence of xenoliths indicates their assimilation in the intermediate chambers or the free outflow of the magma.

The shallowest xenoliths (garnet amphibolites) were found in a diatreme at the coast of the Kandalaksha Gulf in the Kachinny Cape area (Fig. 2) [8]. The diatreme intrudes garnet amphibolites lying at the base of granulite slices. The thickness of amphibolites is no more than 2 km. The absence of fragments of other rocks in the pipe suggests that the last barrier at the pathway of nephelinites (diatreme material) was located at a depth of no more than 2 km. Dikes with xenoliths of granite gneisses underlying the garnet amphibolites occur in the same area. “Boulder” dikes that developed at the Turiy Peninsula and near the town of Kandalaksha contain 70–90% diverse fragments (granite gneiss, amphibolite, and carbonatite), i.e., rocks known at the present-day erosion level. The matrix of fragments has a silicate–carbonate composition. Wide development of such dikes indicates a strained state of the upper crust at the moment of their formation, which is confirmed by the structural investigations [8].

The deeper xenoliths (acid granulites) occur in the Khibiny nepheline syenite massif. The acid granulites are not exposed near the massif. However, they are similar to those in the Lapland belt. The acid granulites formed at a depth of ~25 km and were exhumed at the end of Paleoproterozoic. Therefore, the Khibiny magma could entrain acid granulites from depths of 25–15 km. Xenoliths in the Khibiny Massif and dikes of Kachinny Cape are characterized by different

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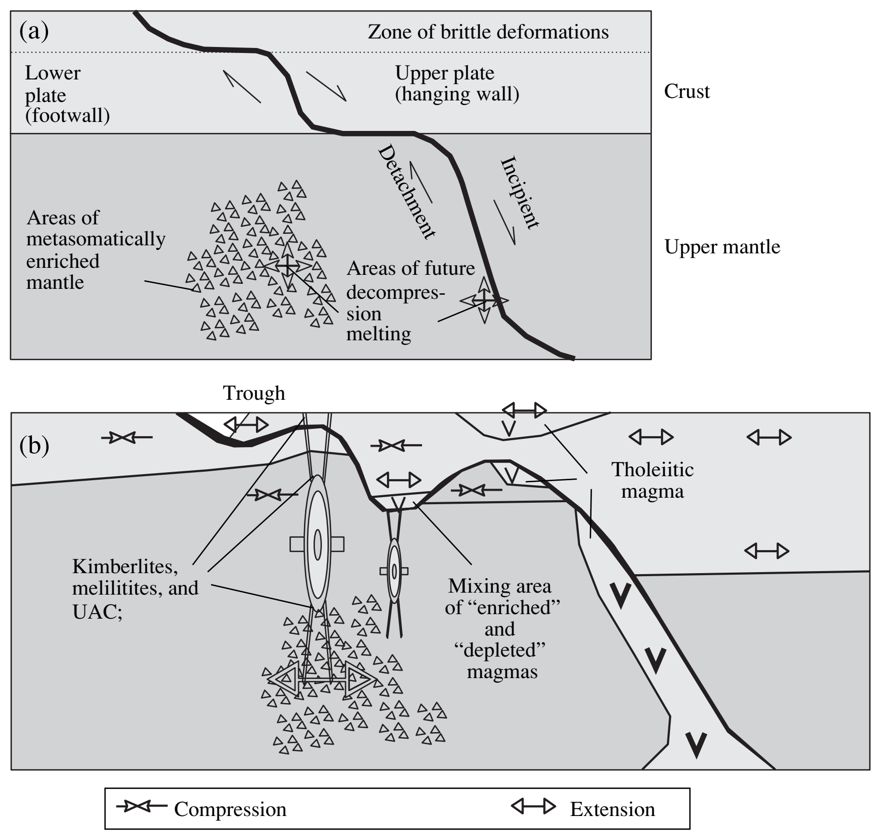

Fig. 1. Model of evolution of translithospheric low-angle normal fault (cross section) controlling the position of lithospheric compression and extension zones, as well as the formation and juxtaposition of diverse magmas (after [4–6]). State of the lithosphere: (a) before the regional extension, and (b) after the beginning of extension.

degrees of alteration. Xenolilths in dikes are angular (0.*n*–10*n* cm in size) and unaltered. One can also see a thin bleached band (2–3 mm) on the weathered surface along the edges. Xenoliths from the Khibiny Massif have large sizes (from a few meters to hundreds of meters). They are characterized by vague outlines, alterations, and the presence of corundum-bearing metasomatites [9]. This indicates both the greater depth of their entrapment (relative to granite gneiss dikes) and a higher degree (duration) of reworking by the alkaline magma. This conclusion is consistent with the concept of nepheline syenite formation due to the crustal contamination of deep-seated magma of ultramafic–alkali complex (UAC) [10]. Granulite xenoliths also occur within the Niva syenite massif (Fig. 2), with *PT* estimates of 13 ± 1.5 kbar and 750 ± 50°C, respectively [3]. They also include superimposed assemblages formed at 6–7 kbar. This suggests that the xenoliths were uplifted from a depth of about 20 km after metasomatic reworking, indicating the state of magma at this depth boundary.

The most known diatreme in Elovy Island is composed of melilitites (20%), angular fragments of the host granite gneisses and amphibolites (20–30%), as well as round xenoliths of garnet granulites (40–50%), as well as websterites, hornblendites, and micaites (5–10%). Different degrees of granetization of all deep-seated xenoliths [7] suggest their entrainment at a depth of no more than 25–20 km.

The Tersky Coast (southern Kola Peninsula) incorporates numerous explosive dikes and diatremes that crosscut the Riphean cover. The lower part of the vent is preserved in the largest diamondiferous (Ermakovka) kimberlite pipe. Xenoliths in kimberlite pipes are mainly represented by angular fragments and blocks of the Riphean sandstones [11]. Cognate counterparts of kimberlites (melilitites) compose diatremes or dikes in this area. Xenoliths from these pipes also mainly consist of sandstones. Xenoliths of basement rocks (granite gneisses and granulites) are less common. Fragments of the upper mantle mafic and ultramafic rocks (pyroxenites and eclogite-type rocks) are subordinate. Deep-seated xenoliths (coarse-grained spinel harzburgites) were found in the melanephelinite pipes that crosscut the Khibiny nepheline syenite massif (Fig. 2). It is suggested that the *PT* parameters of equilibrium phases at the moment of xenolith entrainment were 1000°C and 15 kbar, respectively [12]. Hence, the mantle reservoir of melanephelinites was located at a depth of ~45 km, i.e., at a deeper level relative to nepheline syenites.

The absence of deep-seated xenoliths in all UAC massifs also indicates dynamic conditions of their emplacement. All UAC massifs are surrounded by a

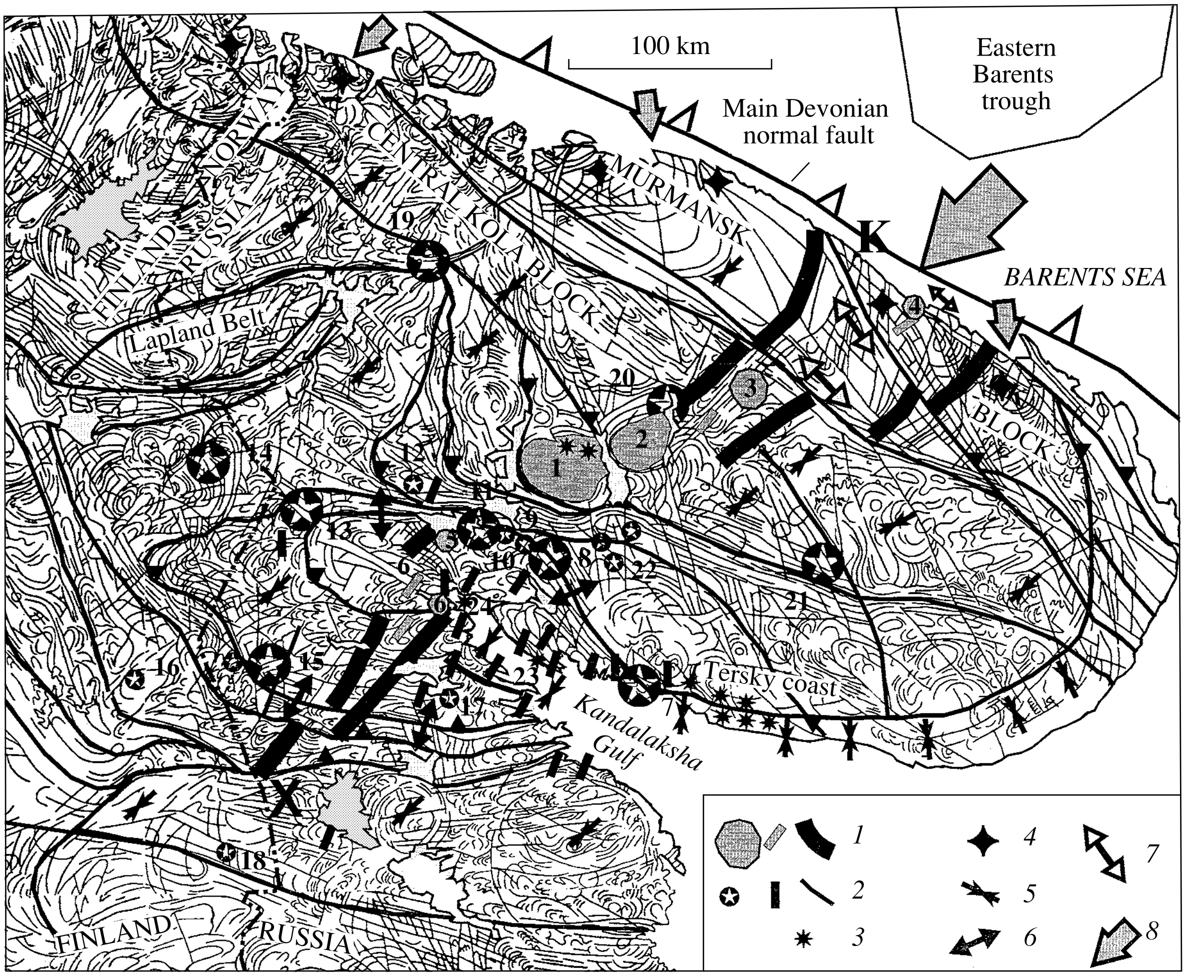

Fig. 2. Structural position of Devonian magmatism in the system of lineaments revealed from satellite and aerial photographs (Northeastern part of the Baltic Shield). (*1*) Massifs and dike fields of the nepheline syenite complex and faults controlling their location (numerals show massifs: (1) Khibiny, (2) Lovozero, (3) Kontozero, (4) Ivanovsk, (5) Niva, (6) Kandagubsk); (*2*) massifs and dike fields of the ultra-alkaline complex (UAC) and faults controlling their location (numerals show the massifs: (7) Turiy Cape, (8) Salmagorsk, (9) Lesnoi, (10) Khabozero, (11) Afrikanda, (12) Mavragubsk, (13) Kovdor, (14) Sokli, (15) Vuorijarvi, (16) Sallanlatvin, (17) Kovdozero, (18) Suoli, (19) Seblyavr, (20) Kurga, (21) Pesochnyi, (22) Inder); (*3*) kimberlite, melilite, or nephelinite diatremes: (23) Cape Kachinny, (24) Elovy Island; (*4*) centers of dike fields composed of tholeiitic basalts; (*5*) areas of surface horizontal compression; (*6*) areas of horizontal extension at depths of 0–20 km; (*7*) areas of horizontal extension at depths of 15–25 km; (*8*) conduits of tholeiitic magma in the Baltic Shield crust from the suboceanic basin. (Kh–K) Khibiny–Kontozero tectonic zone.

fenite zone up to several km wide [10]. They show regular changes in thickness. For example, the thickness of massifs in the Kovdor–Afrikanda–Ozernaya Varaka zone decrease from south to north, suggesting a centroclinal dip of faults bounding the Kandalaksha ring structure (Fig. 2) [4]. The presence of fenites and layered structure of the UAC massifs imply long-term storage of hot magma at one site. Study of the vertical structure of the UAC massifs revealed that they usually make up vertical stocks up to depths of 15–20 km, and thin conduits are only traced in deeper zones [13]. One can see all erosion levels ranging from the least eroded carbonatite massifs (e.g., Sokli Massif) to the near-bottom part of the magma chamber (Salmagorsk Massif) [14]. It should be noted that the Khibiny and Lovozero syenite massifs, which are significantly larger that UAC massifs, have no fenite halos, indicating fundamental differences in the mode of their formation.

Available isotope and geochemical data on the Kola alkaline province indicate that all these rocks can be derived by the mixing of enriched and depleted mantle sources [3, 8]. Reconstruction of the paleotectonic setting in the crustal sequence, based on analysis of xenolith distribution, makes it possible to outline the main structural aspects of generation and mixing of these magmas, as well as the formation of dikes, diatremes, and massifs.

Late Devonian rifting in the central Barents Sea produced tholeiites of suboceanic crust [15]. This magmatism is traced as dikes and sills along the entire Mur-

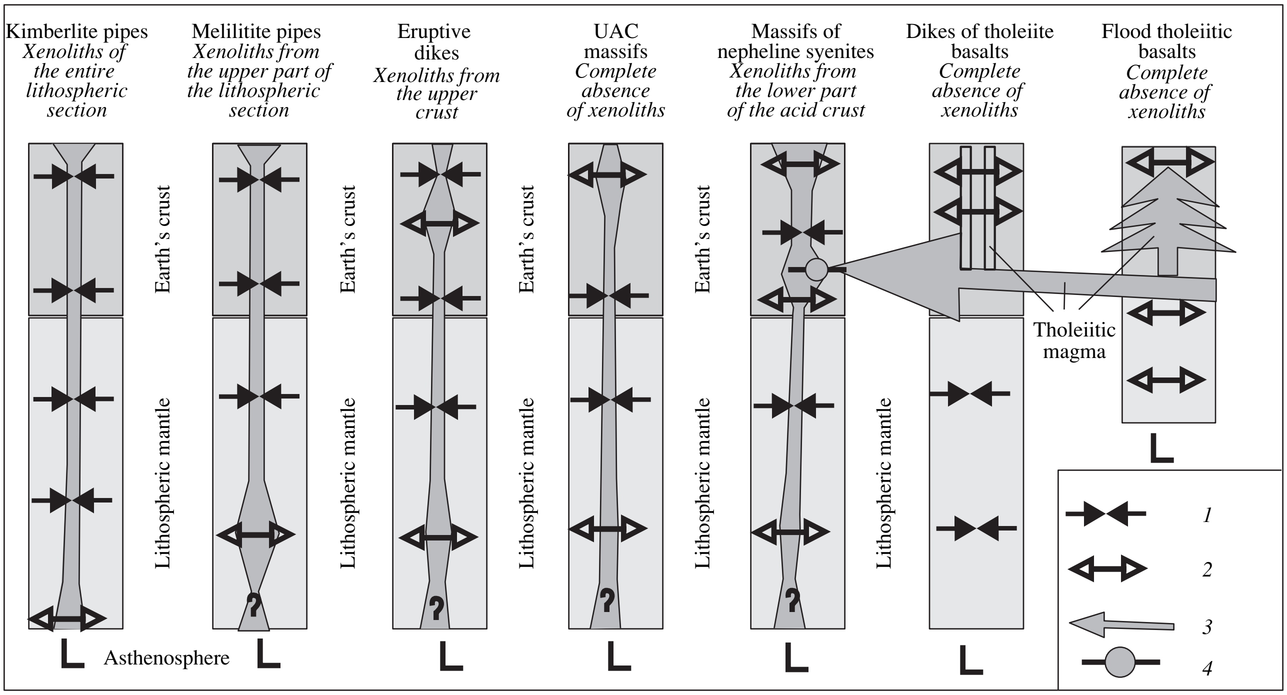

Fig. 3. Extension and compression zones in the Earth's crust and mantle in areas of Devonian magmatism in the northeastern Baltic Shield. (*1*) Compression areas; (*2*) extension areas; (*3*) direction of the tholeiitic magma movement toward the central Kola Peninsula; (*4*) mixing area of the tholeiitic and ultramafic–alkaline magmas.

mansk coast. The magma penetrated the Kola crust along the tectonic zones. The best conditions for this process existed within the Khibiny–Kontozero zone, where the initial (most depleted) alkaline magmatic rocks were formed [3]. Domains of metasomatically enriched mantle formed beneath the Kola Peninsula crust in the Paleoproterozoic. Its partial melting could be caused by decompression related to the formation of the East Barents Rift. Enriched (alkaline) magma or only its fluids ascended. They were mixed in different proportions with depleted magma and contaminated by crust. The presence of xenoliths in different rocks of the Kola alkaline province indicates a compression setting typical of the uppermost portion of the Earth's crust. Owing to compression, liquid jets of the alkaline magma could not easily reach the surface. Therefore, they formed eruptive dikes and breccia pipes. However, local extension could take place along a giant shear zone deciphered on the satellite and aerial photographs. This zone extends from the Umba Massif to the Kovdor Massif at depths of 2–20 km. This zone promoted the formation of large magma chambers that were favorable for the differentiation of material. Since the magma was stored in the upper crust, acid rocks of this zone were not assimilated by the alkaline magma and they were only subjected to fenitization. This was accompanied by complete dissolution of the deep-seated xenoliths. Presumably, such areas of local crustal extension also exist at depths of 2–20 km in other shear zones that govern the UAC massifs (Fig. 2). Nepheline syenite massifs formed in principally different dynamic setting. They are confined to the Khibiny–Kontozero zone, the northeastern termination of which controlled the opening of a suboceanic basin of the East Barents Depression with large-scale tholeiitic (depleted) magmatism [15]. The most acid alkaline rocks are confined to this zone, indicating the assimilation of acid crustal rocks. The presence of acid granulite xenoliths indicates the existence of an alkaline magma chamber at depths of 25–15 km, where the UAC magmas could assimilate acid crustal rocks. The depleted tholeiites could penetrate along the Khibiny–Kontozero fault (Fig. 3). These events were responsible for the formation of syenite–nepheline magma. Kimberlite and related melilitites formed diatremes with xenoliths of the entire crustal sequence; i.e., penetration of kimberlites through the crust was a very complicated process and their contamination by depleted magma and crustal materials was minimal.

Thus, distribution of different-depth xenoliths from Devonian intrusions of the Kola Peninsula suggests that the model of evolution of a low-angle translithospheric normal fault can be used to explain some paradoxes of alkaline magmatism, such as the existence of compression setting in the subsurface horizons of the normal fault footwall during regional extension and the appearance of principally different rocks in single magmatic complexes.

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