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Layered intrusions as transitional magma chambers above the local plumes of large igneous provinces: Evidence from the Early Paleoproterozoic province of a siliceous highly magnesian rock series in the Baltic Shield

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Abstract. It is shown, using the example of the Baltic large Early Paleoproterozoic igneous province of the siliceous, high-Mg (boninite-like) series (SHMS), that the layered intrusions had been intermediate-depth magma chambers beneath thick lava flows. Operating in these chambers had been the processes of the accumulation of periodically entered mantle-derived magmas, their crystallization differentiation, and the mixing of the fresh and evolved magmas. As a result, the magmas uprising from these chambers to the surface, are usually modified to various degrees, and primary mantle magmas are extremely rare. The origin of the SHMS magmas is believed to have been linked with large-scale assimilation of the lower-crustal material by the hot mantle-derived magmas as the new magma chamber that had originated at the crust-mantle boundary "floated" upward. This floating seems to have operated by the mechanism of zone refinement, that is, by way of the melting of the roof's rocks with the simultaneous crystallization of the bottom. This "floating" ceased when the magma chamber reached to the essentially sialic upper crust, because a layer of light granite magma with its own convection system originated in the upper part of the chamber. Similar positions are occupied by layered intrusions in large igneous provinces (LIP) that had originated after 2 billion years ago, when a change in tectonic and magmatic activity occured. These intrusions had been formed as a result of solidification of intermediate magma chambers residing at different depths, the uppermost of which had resided immediately beneath lava plateaus and the lowermost at the crust-mantle boundary, forming up the lower continental crust from below (underplating). In all cases the LIP systems originated, irrespective of their composition, above protuberances (local plumes) on the surface of the superplumes, where the mantle material experienced melting. The character of the magma system evolution was controlled by the structure of the lithosphere, the heights of the plume rises, and the temperature of the mantle-derived magma. It is shown that the magmatic systems of the Moon highlands had been, apparently, of the same structure as those of the Earth.

Introduction

Layered intrusions continue to be among the most important objects of petrology, which can be used to study the processes of the origin and evolution of large magma chambers in the nature. These intrusions were emplaced during both the Precambrian and the Phanerozoic, however, were

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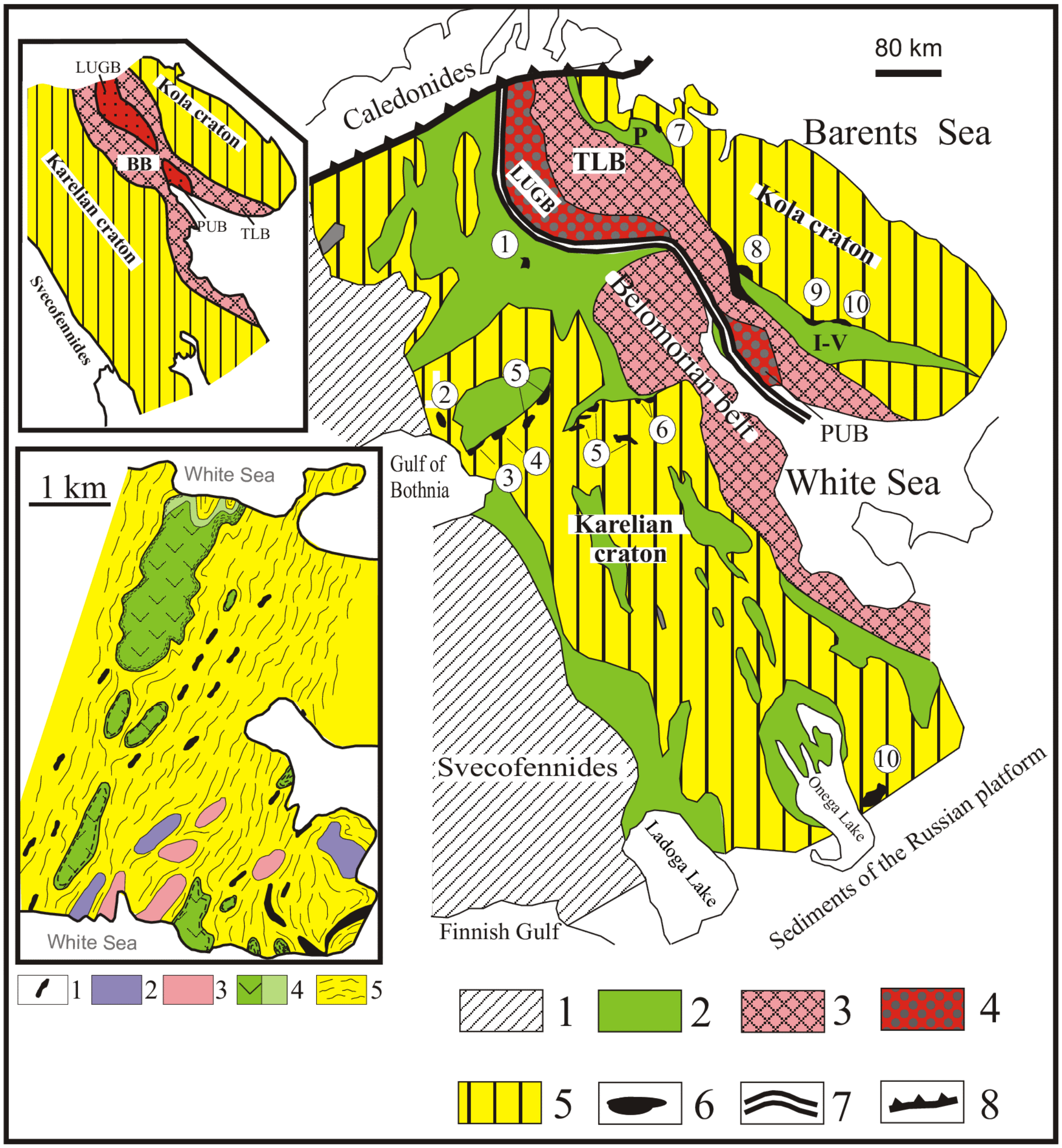

Figure 1. Early Paleoproterozoic Baltic Large Igneous Province of the siliceous high-Mg (boninite-like) series. (1) Svecofennides (Late Paleoproterozoic); (2) Paleoproterozoic volcanosedimentary belts with SHMS rocks at the base; (3) Early Paleoproterozoic transitional mobile belts: BMB – Belomorian Mobile Belt, TLB – Tersk-Lotta Belt; (4) Early Paleoproterozoic Lapland-Umba Granulite Belt (LUGB) with Porieguba-Umba block (PUB); (5) Archean basement of the Baltic Province; (6) largest layered intrusions: (B) Burakovka, (Kem) Kemi, (K) Koitilainen, (O) Olanga (Oulanka) group, (Pe) Penikat, (To) Tornio, (G) Generalskaya Mount, (Ko) Koilismaa, (Mo) Monchegorsk Complex, (Pa) Pana Tundra, (F) Fedorov Tundra, (Po) Portimo, (7) Late Paleoproterozoic Main Lapland Thrust, (8) suture zone of Caledonian nappes.

The upper inset map shows the reconstruction of the location of the main tectonic features in the Early Paleoproterozoic, the lower inset map is the schematic geological map of a typical area in the Belomorian Belt with small bodies of basic and ultrabasic rocks of the drusite complex (Northern Karelia, Pezhostrov I., Keretsky Archipelago, the White Sea): (1) small lenticular boudins of garnet amphibolite; (2) thick-layered bodies of plagioclase lherzolite and olivine gabbronorite with disrupted contacts; (3) indistinctly layered metamorphozed gabbronorite bodies; (4) metagabbro-anorthosite bodies: (a) coarse-grained rocks, (b) fine- and medium-grained rocks in inner contacts; (5) Archean plagiomigmatites.

most abundant in the Early Paleoproterozoic during the cratonic stage of the Earth's evolution [*Bogatikov et al.,* 2000]. A particular interest in layered intrusions is associated with the fact that they are known to be the important sources of ore deposits, in particular, of platinoids, the large deposits of which are known in the intrusive massifs, such as the Bushveld (South Africa) and Stillwater (USA) massifs. In this connection, the eastern part of the Baltic Shield, where similar massifs are abundant, is one of the largest potential sources of these ore deposits.

The main attention is given in this paper to the role of layered intrusions as the intermediate chambers of magmatic systems of the Early Paleoproterozoic Baltic large igneous provinces (BLIP) of the siliceous high-Mg (boninite-like) series (SHMS) as an example. These SHMS magmas seem to have originated as a result of the extensive assimilation of the lower crustal material by hot mantle-derived melts via ascending of magma chamber through the crust by way of zone refinement, that is, by the melting of the roof's rock with simultaneous crystallization at the bottom. This "floating" ceased when the magma chamber reached to the essentially sialic upper crust, because a layer of light granite melt with its independent convection system arose in its top. The aim of this paper is to discuss the structure of the largest intrusive bodies of the province, located within the rigid cratons, and also some small synkinematic intrusions in the intermediate mobile zones, as well as, to show the difference of the massifs of this province from those of other LIPs, and also to discuss the structure and operation of the Early Precambrian and Phanerozoic magmatic systems, as well as those of the Moon.

Structure of the Early Paleoproterozoic Baltic Large Igneous Province of the SHMS

This large igneous province of the SHMS, which had developed from 2.55 to 2.35 billion years (Ga) ago, is situated in the eastern part of the Baltic Shield, including the territories of the Kola Peninsula, Karelia, and Northern and Central Finland [*Sharkov et al.,* 1997]. Within the Kola and Karelian cratons the rocks of this province occur as volcanic sheets in the rift-related structures, swarms of gabbronorite dikes and large layered intrusions (Figure 1). In contrast to these areas, the Belomorian and Tersko-Lotta mobile belts, located between the cratons and the Lapland-Umba Granulite Belt which developed synchronously with the latter, are characterized by the SHMS dispersed igneous activity which had resulted in the emplacement of numerous small basic and ultrabasic intrusions.

At the present time the BLIP has an area of about 1 million km^2, though its initial area seems to have been much larger, because its southern and eastern extensions are hidden under the sediments of the Russian Platform, its northern extension is covered by the Barents Sea and by the nappes of the Norwegian Caledonides, and the younger Svekofennian domain of the 1.9–1.8 Ga in age being located in the west. Similar rocks of the same age have been traced in the basement of the Russian Platform, in Scotland, Greenland, in the Canadian Shield (Matachewan and Herst gabbronorite dike swarms and volcanic rocks at the base of the rock sequences in the Huronian basaltic plateau), and in the Wyoming Craton [*Heaman,* 1997]. As follows from paleomagnetic, geological, and stratigraphic reconstructions, these cratons had been the parts of the Laurentia-Baltica Supercontinent before they were separated during the Late Proterozoic. Accordingly, the initial size of this igneous province seems to have been not less than 2500 km long and 1500 km wide, that is, it had been much larger than the largest Phanerozoic trap regions.

Layered Intrusive Rocks of the Cratons

The Eastern part of the Baltic Shield is the world largest region of Early Paleoproterozoic layered basic and ultrabasic intrusions: more than 12 only big massifs have been mapped here (see Figure 1). In addition, at the basement of the lava sheets in the riftogenic structures layered subvolcanic sill-like bodies often occured, similar to the Imandra Complex in the Kola Peninsula [*Zhangurov et al.,* 1994], not to mention a great number of the small bodies of basic and ultrabasic rocks, emplaced in the mobile belts, such as the Belomorian one. All of these intrusions had been derived from SHMS magmas, have a similar structure and the fairly identical composition of their rocks, although often differ in structural details, in character of their cumulative stratigraphy, and in extent of ore mineralization [*Alapieti et al.,* 1990; *Sharkov and Smolkin,* 1998].

Large layered intrusions are usually found at the peripheries of the Paleoproterozoic volcanosedimentary graben-like structures (Pechenga-Varzuga Graben in the Kola Peninsula, Pana-Kuolayarvi in northern Karelia and northern Finland, and others), where they are usually located in the elevated shoulders of the grabens, and more seldom, in the basement highs between them. These rift-related structures evolved throughout the Paleoproterozoic, the lower parts of their volcanic rock sequences being formed by the Early Paleoproterozoic rocks of the SHMS series [*Sharkov et al.,* 2000].

The large intrusions have intrusive contacts with the Archean wall-rocks and tectonic contacts with the adjacent rocks of rift origin, expressed as the zones of their mutual schistosity and metamorphism, which resemble listric faults become flatter with depth. Evidently the intrusions had been pushed out from under the volcanic rock covers along a system of faults. As a result, the original sizes of the plutons are usually unknown and seem to be much greater compared to their outcrops. For example, the largest in the Europe Burakovka layered intrusion in Southern Karelia (about 720 km^2 in area) is the unique pluton occurring in isolated manner between the Onega and the Vetreny Belt volcanic plateaus. The volcanic rocks that had covered it, was eroded to expose the intrusion in its initial size. Thus, the spatial combination of the SHMS rocks in the form of the lava sheets and subvolcanic intrusions with large layered massifs, which were brought to the Earth's surface in the elevated shoulders of the grabens occurred in the cratons.

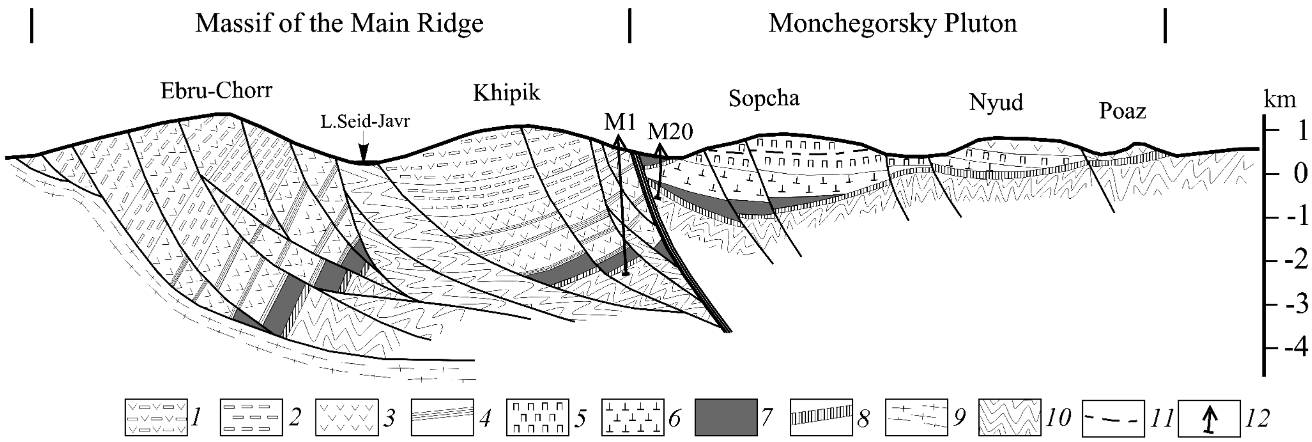

Figure 2. Sublatitude section across the Monchegorsk layered complex, Kola Peninsula. (1) Massive coarse-grained gabbronorite-anorthosite (Pl cumulates) with interlayers of pigeonite gabbronorite (Pl+Pig+Pig-Aug); (2) trachytoid gabbronorite-anorthosite with interlayers of leucocratic pigeonite gabbronorite; (3) norite and gabbronorite (Pl+Opx±Cpx cumulates); (4) zones of rhythmic alternation of basic and ultrabasic cumulates, including dunite (in the Main Ridge Massif); (5) bronzitite (Opx cumulate); (6) zone of rhythmic alteration of Ol+Crt, Ol+Opx±Crt and Opx cumulates in the Monchegorsk Pluton; (7) dunite (Ol+Crt) cumulates; (8) marginal essentially gabbronorite zones of the intrusions; (9) gneisses and migmatites of the Lotta Block; (10) granulites and diorite gneisses of the Kola Block; (11) ore bed of Sopcha; (12) location of structural wells.

All of the layered intrusions examined have the same structure and are composed of a dunite – harzburgite – bronzitite – norite – gabbronorite – anorthosite – magnetite gabbro-diorite series, although may differ from one another in details. Moreover, some of the large layered complexes may consist of two and more independent intrusive rock bodies with their own internal structures, which had been derived from similar magmas. For instance, the Burakovka Complex mentioned above consists of two intrusive bodies of different ages, Aganozero and Shalozero-Burakovka, which contact each other in their tops. The Aganozero body is approximately 50 million years younger than the Burakovka-Shalozero one, the age of the former being 2.37 Ga, and that of the latter, 2.43 Ga. Because these bodies were described in detail earlier [*Chistyakov et al.,* 2002], their description is omitted here.

A similar pattern has been established for the Monchegorsk Complex, ranking second in size, situated in the middle of the Kola Peninsula [*Sharkov et al.,* 2002]. It consists of two large bodies: the Monchegorsk Pluton of Ni-bearing ultrabasic and basic rocks and the substantially gabbro massif of the Glavnyi Range. In contrast to the Burakovka layered pluton, the Monchegorsk Pluton had been involved into the movements along the Late Paleoproterozoic Main Kola Fault and had been broken into blocks (Figure 2). Like in the previous case, these massifs are composed of the rocks of the same types, yet they differ in cumulative stratigraphy and in the amounts of their rock types. According to the geochronological data available, the rocks of the Glavnyi Range are 50 Ma years younger than the rocks of the Monchegorsk Pluton (2.45 and 2.5 Ga, respectively).

Minor Layered Intrusions in the Intermediate Mobile Zones

The large layered intrusions discussed above had been emplaced into the Kola and Karelian rigid cratons. The situation changed radically in the intermediate mobile belts, such as the Belomorian and Tera-Lotta ones, which are interpreted as the low-dipping zones of tectonic flow [*Sharkov et al.,* 2000]. Here, the SHMS igneous rocks, having the same age as those described above, are represented by numerous small synkinematic rootless intrusive bodies composed of the same rocks as the large layered plutons of the neighboring cratons (see Figure 1). In the Belomorian (White-Sea) Belt they are known as a drusite complex [*Sharkov et al.,* 1999]. In contrast to the highly differentiated plutons, here the main rocks occur as independent intrusions with the respective compositions of the quenching zones. They often show coarse and thin layering with the alternations of two and more, occasionally three, different rock types.

Layered Intrusions in Other Large Igneous Provinces

Late Paleoproterozoic Layered Intrusions in the Baltic Shield

The character of tectonomagmatic activity in the Baltic Shield changed abruptly 2.2–2.0 Ga ago, when the first evidence of plate tectonics was recorded. A Svecofennian Ocean had opened in the territory of its modern western part. The fragments of its lithosphere are preserved as the Jormua and Outokumpu ophiolites [*Kontinen and Peltonen,* 1998]. At the same time the Lapland collision zone was formed in the eastern part of the shield, with the Pechenga-Varzuga basin in its back [*Sharkov and Smolkin,* 1997]. Simultaneously, the region experienced a change in magmatic activity: the SHMS rocks were replaced by Fe- and Ti-rich picrite and basalt, typical of the Phanerozoic intraplate magmatism, and their analogs. These rocks produced a large igneous province with an age of 2.2–1.9 Ga, which coincided in space with the previous one. Moreover, new volcanic eruptions added their material to the sequences of the volcanic and sedimentary rocks in the same grabens.

Emplaced between them were dike swarms and layered intrusions, including the large ones, such as the Gremyakha-Vyrmes in the Kola Peninsula and the Elet'ozero in Northern Karelia, derived from the same melts [*Sharkov and Smolkin,* 1998]. In contrast to the Early Paleoproterozoic layered complexes, these intrusions are composed of the rocks ranging from olivinite, wehrlite, and clinopyroxene to gabbro, gabbro anorthosite, and alkaline gabbro (akerite and pulaskite). These rocks show high contents of titanomagnetite up to its ore concentrations. Both massifs have cores composed of nepheline syenite. The emplacement of the Gremyakha-Vyrmes intrusions was completed by the intrusion of essentially potassic alkaline granites. It appears that, like in the above cases, these intrusions had been intermediate magma chambers under the lava plateaus demolished by erosion.

Within more mobile Pechenga-Varzuga back-arc basin from such melts (Fe–Ti picrites and basalts) were formed small synkinematic coarse-layered intrusions of basic and ultrabasic rocks. Cu-Ni sulfide ore deposits are associated with them in the Pechenga structure [*Gorbunov et al.,* 1999]. It follows that here, too, the sizes of the intrusions had been controlled by their tectonic positions.

Layered Intrusions in Other Large Igneous Provinces of the World

It appears that all other layered intrusions of the World have the same geologic positions as intermediate magmatic chambers. For instance, the Early Tertiary (55–50 Ma) British Arctic province includes thick (up to 3–4 km) basalt sheets, dike swarms, and large layered intrusions (Skaergaard and those in the Ram, Skye, and other islands) [*Kerr,* 1995; *Larsen et al.,* 1989; *McBirney,* 1996; *Wager and Brown,* 1968]. Using the data available for lava the plateaus, *Fram and Lesher* [1997] performed the quantitative modeling of magma fractionation. They found that the primary differentiation of the magma had taken place at pressure of about 8 kbar, that is, at depths of about 25 km, and had been accompanied locally by magma differentiation at some moderate depths. The geochemical and isotopic data obtained by these researchers suggest that the basalts concerned might have assimilated up to 15–20% of the Archean gneiss material. These data suggest that in the course of their movement toward the surface the mantle magmas passed through a series of intermediate magma chambers (Figure 3), where the primary and evolved magmas experienced differentiation, and the partial assimilation of the wall rocks took place. As these magma chambers solidified, they transformed to layered intrusions which are observed now at the present-day erosion surface. The magma chambers had been connected with one another by the systems of dikes, the uppermost of them serving as channels feeding volcanic eruptions.

The large Late Cenozoic basalt provinces, were developed in the areas of continental rifting and intraplate magmatism and representing the uppermost levels of the former magma systems, show only volcanic sheets and dike swarms, as well as small trachyte stocks. As proved by the special study of moderately alkaline basalts in Syria, developed in the northeastern periphery of the Red Sea rift area, and of the basalts from the Baikal Rift, their primary differentiation, as well as that of the basalts in the British Arctic Province, took place at depths of 25–30 km [*Sharkov and Bindeman,* 1991; *Sharkov et al.,* 1987]. The structure of the magma systems under these lava plateaus can obviously be judged upon from the xenoliths contained in the basalts. For instance, the xenoliths contained in the basalts of Syria consist of mantle peridotite (mainly spinel lherzolite), fragments of cumulates from intermediate magma chambers (usually gabbro of various types, including olivine-bearing gabbro), and fragments of upper- and less common middle-crustal rocks; the xenoliths of the lower-crustal rocks being usually absent [*Sharkov et al.,* 1996]. A similar assemblage of xenoliths is found in other within-plate basalts worldwide. This suggests that (1) the tops of the mantle plumes had reached the base of the upper continental sialic crust, and (2) the intermediate chambers existed in the form of layered intrusions under the cover of volcanic rocks (see Figure 3).

Many areas of continental intraplate volcanism include substantially potassic trachyte, comendite, and pantellerite, which suggests a bimodal magmatic activity. According to *Yarmolyuk et al.* [1990], this stems from the fact that zones of sialic material melting appeared in the roofs of the intermediate crustal batches of basalt magma.

A close association of basaltic sheets and large layered intrusions has been reported from the Midcontinent Late Proterozoic rift province (Canada) with its Duluth Layered Complex residing under a lava plateau of a closely similar age [*Miller and Ripley,* 1996]. No large layered plutons have yet been found to be associated with the Permian-Triassic traps of the Siberian Craton. Here, layered sills are widespread at the base of basaltic sheets, including the famous Noril'sk and Talnakh sills containing unique deposits of Cu-Ni sulfide ores and platinoids [*Dyuzhikov et al.,* 1988]. A similar position is occupied by layered intrusions in alkaline rock provinces, for instance, in the Mesoproterozoic (1.35–1.13 Ga) Gardar Province in South Greenland with a great number of large layered alkaline massifs, the best known of which are Klokken and Ilimaussak [*Upton et al.,* 1996]. Associated with them are moderately alkaline and alkaline basaltic flows and dikes.

A similar situation is found in the Devonian Kola-Karelian alkaline province, where the Khibiny and Lovozero layered

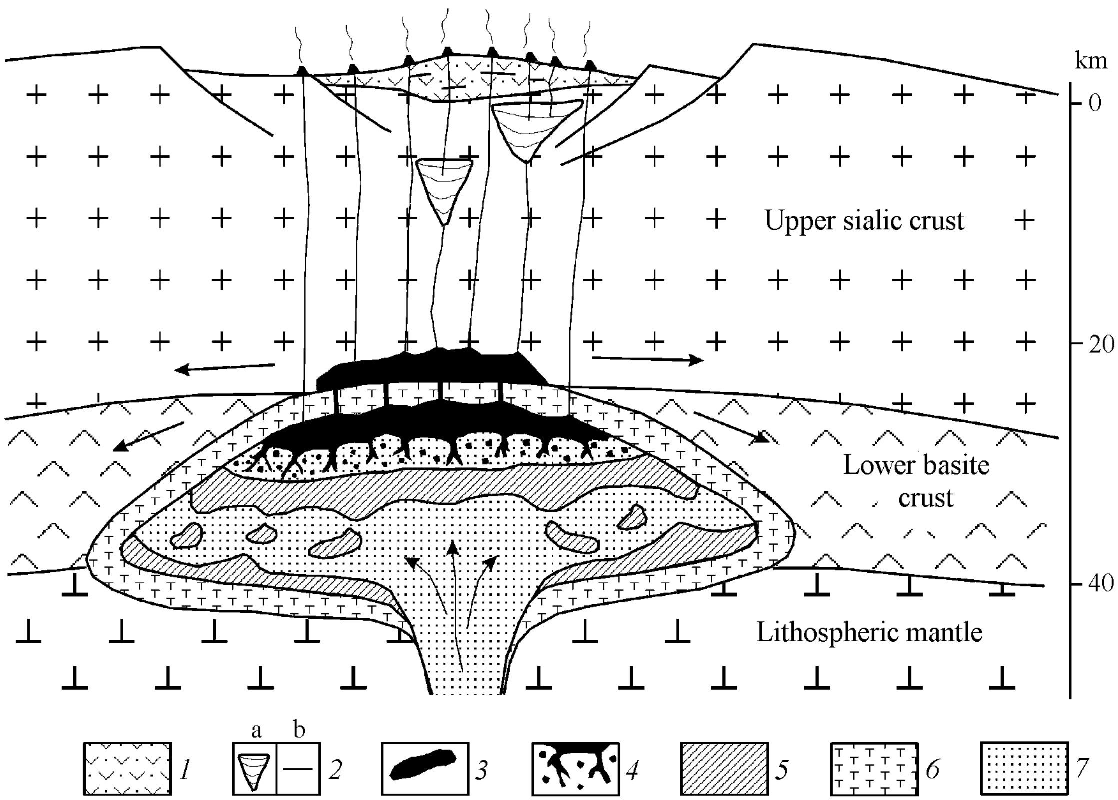

Figure 3. Structure of Cenozoic continental intraplate magma systems. (1) volcanic plateau; (2) layered intrusions: (a) in the crust, (b) sills in volcanic rocks; (3) major magma chambers in the mantle and in the base of the crust; (4) melting zone in the top of a mantle plume; (5) refractory restite; (6) cooled margin of the plume; (7) fresh plume material.

plutons of nepheline syenite are restricted to a graben-shaped structure filled with sediments and alkaline lava flows and surrounded by swarms of compositionally similar dikes [*Kogarko et al.,* 1995]. These plutons, especially the Khibiny one, are distinguished by an extremely complex structure, which suggests the long-term existence of an evolving magma center beneath them.

Magmatic Systems of the Moon

It is known that the main morphostructures of the Moon are ancient continents (*highlands*) and newly formed sea basins (*maria*), the floors of which are flooded with basalt. The igneous rocks developed on the Moon are similar to the rocks typical of the Paleoproterozoic rocks of the Earth without any analogs of the terrestrial Archean rocks or the Phanerozoic subduction environments [*Sharkov and Bogatikov,* 2001]. The magmatism of the *continents* is represented by magnesian suite, 4.45–4.0 Ga old, intruded into the Moon's primordial anorthosite crust [*Snyder et al.,* 1995]. These are volcanic rocks (low-Ti picrobasalts and olivine and alumina basalts) and their intrusive analogs similar to the cumulates of the Early Paleoproterozoic layered intrusions of the Earth (dunite, harzburgite, pyroxenite, troctolite, norite, and anorthosite, more magnesian compared with the primordial crustal ones). It appears that similar rocks had composed layered intrusions that had been formed in the lunar crust and were brought to the surface as tectonic blocks in the marginal mountains around the maria (Figure 4).

The lunar maria that had developed 3.9 to 3.0 Ga ago as large depressions with a thin crust and intensive basaltic magmatism resemble the oceanic segments or trap provinces of the Earth. Judging by the data available, the formation of the maria had been associated with ascending of mantle plumes, whereas the existence of dense rock masses (mascons) beneath them (mascons) had represented the solidified spreaded heads of these plums [*Sharkov and Bogatikov,* 2001]. It appears that the magmatic systems of the lunar maria had been structurally similar to the systems of the terrestrial trap provinces.

Discussion

As follows from the data presented in this paper, irrespective of their composition, layered intrusions are the very important elements of various large igneous provinces (LIP).

However, their origin is still a matter of debate and calls for special discussion.

Formation of Large Layered Intrusions

It is known that during the early periods of the study of layered intrusions it was believed that their crystallization had taken place simultaneously throughout the magma chamber, whereas the origin of layering had been associated with the gravitational differentiation of the newly formed crystals. However, at the present time, most of geologists agree that the solidification of the inner parts of the plutons proceeded by way of the upward moving a comparatively thin (3–4 m) crystallization zone, whereas their marginal parts solidified inward from the edges. In this respect, the emplacement of intrusions does not differ from the formation of large industrial casts, which is a well known process. It is known that the upper border of a crystallization zone (front of a solidification onset) coincides with the isotherm of the melt liquidus, and its lower boundary (front of a solidification end) coincides with the isotherm of melt solidus, the directional character of solidification being controlled by convection [*Chalmers,* 1968]. Our previous detailed study of layered intrusions suggests that this solidification model is valid for solidifying plutons [*Sharkov,* 1980].

It is known that layered rocks are formed of two groups of grains: the volumetrically predominant subidiomorphic grains of cumulus minerals, which compose the framework of the rock, and the xenomorphic grains of intercumulus minerals located in the interstices between them [*Wager and Brown,* 1968]. It is obvious that the former were produced at the moving front of the initial solidification, and the latter, at the front of the solidification end from the crystallization zone melt which had remained between the crystals. The bulk of the remaining melt was forced out of the crystallization zone, as the settling crystals grew more compact, and mixed with the bulk of the melt, the composition of which was equalized continuously by convection. The rhythmic layering was an accessory consequence of this directed solidification, caused by the accumulation of the residual melt at the front of the initial solidification [*Sharkov,* 1980].

Thus, in the course of the directed solidification of an intrusion the highest temperature phases were removed from the magma, while the bulk of the melt was enriched continuously in low melting components, this process leading to a change in the settling solid phases and in the formation of compositionally different layers, that is, in layering. In terms of physical chemistry this means that the crystallizing melt moved along the cotectics of the physicochemical system with the separation of respective mineral phases with phase changes during the transitions from one cotectic to another. In this approach, each cumulate horizon in a layered intrusion is the consequence of the melt moving along one of the cotectics, and the association of its cumulus minerals reflects the composition of the resulting solid phases.

Our detailed study of the layered rocks revealed that the layers had not been composed of any incidental assemblage of minerals, sorted out by their physical properties. We found that each layer had been, in fact, composed of a cumulus mineral association representing one of the parageneses of cotectic mineral phases, and that their succession in the rock sequence records the successive separation of these phases during the fractional crystallization of the parental melts [*Sharkov,* 1980], as should follow from the suggested model. For instance, the paragenetic sequence of cumulative phases in the lower parts of the sections of the Early Paleoproterozoic intrusions which had originated from the silica-rich melts of an SHMS series could be described in a framework of the forsterite-anorthite-quartz system by *Andersen* [1915]: Ol→Ol+Opx→Opx→Opx+Pl. Later, as a highly contaminated, alumina-rich melt arrived into the intrusive chamber (see below), the crystallization trend left this system. The sequence of cumulate phases in layered intrusions derived from undersaturated tholeiite basalt: Ol→Ol+Sp→Ol+Sp+Pl→Ol+Pl→Ol+Pl+Cpx is described by a forsterite-diopside-anorthite system.

It was believed earlier that large layered massifs had originated as a result of the one-act intrusion of huge magma volumes into the crust. However, our detailed geological, petrological, geochemical, and isotope-geochronological studies of the Burakovka and Monchegorsk layered plutons [*Chistyakov et al.,* 2002; *Sharkov et al.,* 2002], as well as of other layered rock complexes in the Kola and Karelia regions, revealed that all of them had been formed by the multiple replenishment of individual portions of fresh magma into the solidifying intrusive chambers. (If?). Where the new melt had a higher density than that in the intrusive chamber, it was spread over the temporal bottom of the latter displacing the previous melt upward and producing a new independent layer (Figure 5). Where it was close in density to the old melt, a newly formed layer had a complex structure and in-

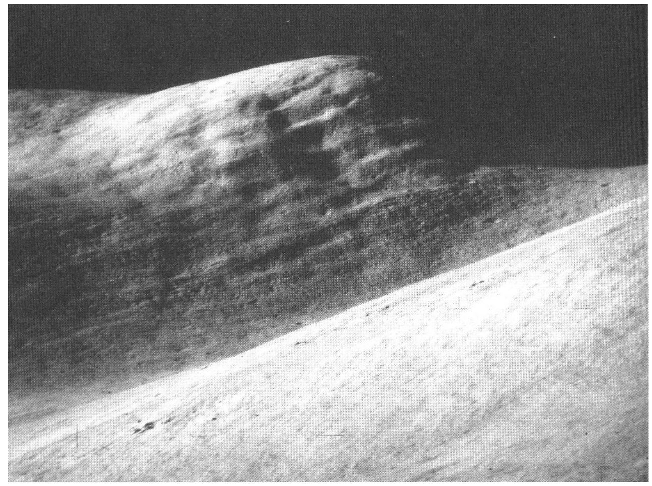

Figure 4. The Moon. Rhythmic layering in a block of intrusive rocks from middle-low lunar crust, which was moved out to the surface. Telephoto view of the mountains at the Apollo 15 landing site, Silver Spur Ridge. This cliff is over 600 m high (Spudis, 1996).

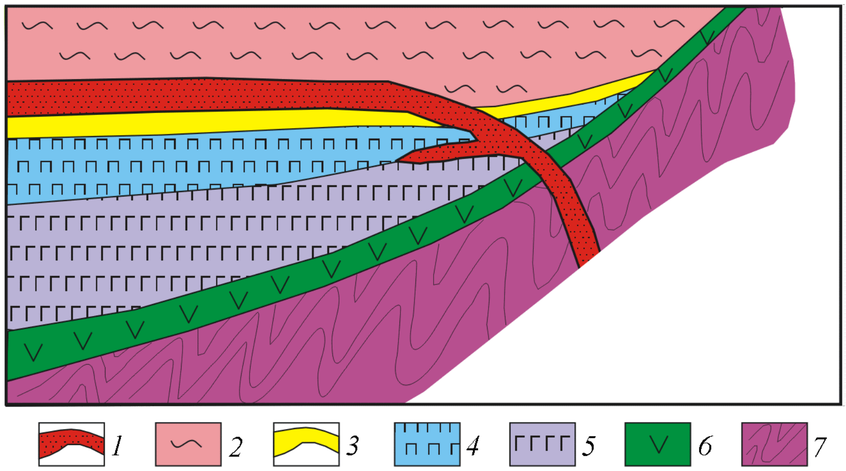

Figure 5. Replenishment of fresh magma into a crystallizing intrusive chamber (with reference to the "Sopcha ore bed" in the Monchegorsk Pluton. (1) Fresh magma; (2) evolved magma in the intrusive chamber; (3) zone of crystallization; (4) orthopyroxene cumulate; (5) peridotite cumulate; (6) lower marginal zone; (7) Archean wall rocks.

equigranular texture with nests and schlieren of pegmatoid rocks, numerous disorderings of layering, the traces of slumping of crystals precipitate, and the like, as it has been found in the Lukkulaiswaara Massif in Karelia [*Sharkov and Bogatikov,* 1998]. These new magma portions had been small enough, within a few per cent of the total volume. For this reason the equilibrium in the chamber had been recovered fairly rapidly, and the crystallization resumed its previous trend.

It follows, therefore, that in the course of their emplacement the intrusions must have grown slowly in volume at the expense of fresh melt portions added to the solidifying magma chambers, their final sizes being controlled by the long existence of the lower feeding portions of the magmatic systems.

Another important factor which has been emphasized above is the fact that large layered complexes might have consisted of two and more independent intrusions derived from similar melts but distinguished by their cumulative stratigraphy, and also by some features of their geochemistry and isotopy. Examples of these intrusions are the Burakovka and Monchegorsk ones.

To sum up, the large layered intrusions had been long-lived magmatic centers, obviously residing above the local protrusions at the tops of the spreading leading parts of the superplumes responsible for the existence of the provinces themselves. The intrusive chambers of these centers had existed as large intermediate magma chambers where magma had accumulated, experienced its crystallization differentiation, and where fresh and evolved magmas had mixed. The melts flowing from these intermediate chambers to produce lava sheets had been differentiated to various degrees, the primary mantle melts being very rare in such sheets.

Formation of Intermediate Magma Chambers

Large layered intrusions represent one of the main but not the only variety of intermediate magma chambers playing an important role in the transformation of primary mantle magmas. At least three depth levels of such magma chambers can be distinguished. The deepest level was at the boundary between the crust and the mantle (at the cooled surface of the plume). The processes operating there are known as underplating. The second level is characterized by the development of layered intrusions, and the third more shallow one, is represented by subvolcanic sills located immediately beneath lava plateaus and/or in their basements.

The development of these magma systems seems to have been associated with the fact that extension zones had originated above the spreading heads of the mantle plumes, which were accompanied by the formation of fractures, along which melts might have ascended. The main driving force of this process was the excessive pressure of the melt, produced by the volumetric effect of the melting and a density difference between the liquid and solid phases [*Popov and Bogatikov,* 2001]. For instance, where the melt generated at depth level A fills a vertical channel with height h_2, the upper edge of which has a depth h_1 below the ground surface, and the density of melt (ρ_2) is lower than that of melt (ρ_1), then the excess pressure at the A level is $\Delta P = P_1 - P_2 = \rho_1 g(h_1 - h_2) - (\rho_1 g h_1 + \rho_2 g h_2) = (\rho_1 - \rho_2) g h_2$. The greater is the vertical length of the melt column, the higher is the excess pressure of the liquid phase. Consequently, the separation of a magmatic liquid and its rise had been self-developing accelerating processes. The excessive melt pressure had favored the opening of fractures, which had accelerated the process of the magmatic system formation. The fissures filled with the melt had been transformed to dikes as the melt had solidified.

During the rapid rise of the magma, it had no time to cool off at the expense of its heat exchange with the sidewall rocks. Some temperature decline was associated only with the adiabatic expansion, which resulted in 0.6°C/km cooling. Under these conditions, the depth to which the magma could rise was controlled not by the cooling of the magma, but by some other factors, the most important of which were the productivity of the magma source, the ratio between the densities of the liquid and solid phases, and the extent to which the magma had been superheated relative to the solidus temperature. Where the amount of the new melt had been small, it would have been not enough to fill the channels measuring tens of kilometers, this being a normal situation for mantle magmas produced beneath the continental crust. In this case magma can reach the ground surface via a system of intermediate magma chambers, where melts accumulate to ensure their further advance.

To sum up, in the ideal cases, where the faults had reached the surface of the Earth, and where the volume of the newly formed melt in the mantle source had been sufficient to fill the feeder throughout its length, the primary mantle melts might have flowed to the ground surface, this being evidenced by the presence of komatiite and picrite lavas. However, judging by the structure of the lava plateaus, this happened very rarely, the most common mechanism being a multistep rise with magma accumulation in a series of intermediate chambers. Their formation seems to have been associated with the wide development, especially in the upper crust, of a great number of various inhomogeneities, such as, folds, gently dipping faults, interformation and stratigraphic boundaries, etc. For this reason, the fissures (feeders) often ceased their upward propagation, as they reached structural traps of this kind, and began to accumulate in them, producing intermediate magma chambers (intrusions). One of the main traps of this kind is the crust-mantle boundary, where melt accumulation is most intense.

As these magma chambers evolved and grew larger, they intercepted the neighboring magma feeders. The obvious consequence of this interception was the development of ruptures in the roofs of the chambers and the formation of new pathways for the melts arriving from these chambers. As these melts travelled farther upward, they might come across new, more shallow traps and produce intermediate, more shallow magma chambers, and so on. Thus, as magma rose toward the surface of the solid Earth, it traveled through a system of intermediate crustal magma chambers, where it was subject to various kinds of transformations.

Structure of Magma Systems in the Baltic SHMS Province

Very unusual magmas participated in the formation of this province. It is known that in Phanerozoic time these magmas had been generated only in island-arc situations, whereas in this region they had been generated, as follows from the geological data available, as intraplate formations similar to traps. The Baltic Shield is not an exception. This type of tectono-magmatic activity in the Early Paleoproterozoic is typical of all Precambrian shields, being a specific feature of the cratonic stage of the Earth evolution [*Bogatikov et al.,* 2000]. This suggests that the origin of the boninite-like SHMS magmas had not been associated with subduction zones.

As follows from their petrologic, geochemical and isotopic characteristics, these magmas had a mixed origin with the participation of both the material of the highly depleted ultrabasic mantle, and the basic material of the lower crust. The origin of these magmas seems to have been associated with the extensive assimilation of crustal material by high-temperature mantle magmas (1600–1700°C; [*Girnis and Ryabchikov,* 1988]), as they ascended ("floated up") through the crust to the ground surface by way of zone refinement [*Sharkov et al.,* 1997] (Figure 6). Apparently, it is thanks to this mechanism that the high contamination of the mantle melt by the crustal material had been achieved. The newly formed basic melts were involved into the general convection system ensuring the rise of the magma chamber through the crust. Judging by the appearance of high-temperature cumulates, among the low-temperature ones, in the layered intrusions, these magma sources had been replenished by hot mantle melts, this controlling the long periods of their existence. Where this replenishment ceased, the system degenerated rapidly.

This "floating" seems to have terminated at the boundary with the substantially sialic crust, where light acid melts were generated and accumulated in the upper parts of the chambers without being involved in the convection (Figure 7) [*Huppert and Sparks,* 1988; *Sharkov,* 1999]. This terminated the existence of particular SHMS magmatic systems. This turning of events can indicate that abundant granite, substantially potassic, magmatism operated at the late phases of the emplacement of Early Paleoproterozoic rocks. The best known examples are the "red granites" cutting and overlying the rocks of the Bushveld layered complex (South Africa), the Sumian (Early Paleoproterozoic) granites of Karelia, cutting across layered intrusions or located in the direct vicinity of them, and "red granites" cutting the rocks of the drusite complex in the Belomorian Mobile Belt.

A particular problem is the potassic composition of these granites, because the Archean sialic crust is composed mainly of plagiogranites (tonalite, trondhjemite, and granodiorite). This seems to have been associated with the coexistence of granitic and basaltic melts in the such magma chambers: the layer of the granitic melt heated from below by the basaltic melt might have started to solidify only after the solidification of the latter. As follows from experimental data, intensive diffusion exchange of alkalies takes place under these conditions between these melts, caused by the migration of potassium from the basaltic melt to the granitic one, and of sodium in the reverse direction [*Bindeman and Davis,* 1999]. It appears that this mechanism explains the potassic speciation of the granites in all the magmatic systems considered above, irrespective of the ages and compositions of their parental magmas.

The ordinary spatial association of the layered intrusions with the volcanosedimentary structures and dike complexes

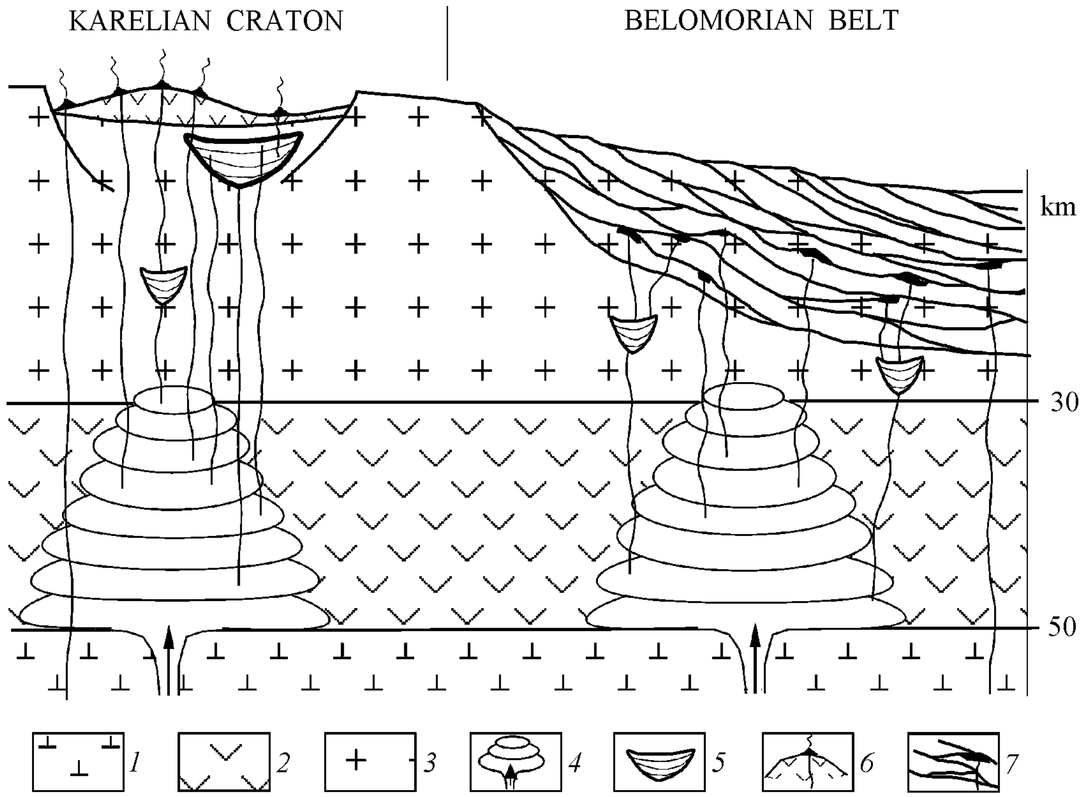

Figure 6. Structure of magmatic systems in the large Baltic SHMS Province as a function of tectonic conditions. (1) Ancient lithospheric mantle; (2) ancient lower crust; (3) ancient sialic crust; (4) paths of magma batches ascending through the crust by the mechanism of zone refinement; (5) transitional chambers (layered intrusions); (6) volcanosedimentary deposits in rift-related structures; (7) zone of tectonic flow into the Belomorian Mobile Belt.

suggests that they might have acted as intermediate intracrustal magma chambers beneath the lava plateaus. As have been shown above, it is in these magma chambers processes of accumulation and mixing of melts, as well as crystallizing differentiation occurred prior to their ascending to the surface in form of volcanic eruption.

As follows from the periodic input of high-temperature melts into the solidifying intrusive chambers, magma was generated in the mantle for a long period of time. This activity might include the development of new paths for the mantle magmas resulting in the formation a new magma chamber in the vicinity of the pervious one. As have been demonstrated above, examples of this activity are fairly common. For this reason it can be concluded that this structural diversity of the magma systems might have been responsible for the compositional diversity of the intrusions and differences in their metallogeny.

In contrast to the cratons, where intrusions were emplaced under rigid media which controlled the specific localization of the melt flow paths and melt accumulation in particular chambers, the situation was substantially different in the intermediate mobile belts of the Belomorian type. Here, magma rose into the mobile environment, where solitary melt portions might have been localized only in small chambers, the formation of which had been controlled by local inhomogeneities (folds, local detachment faults and extension zones, etc.) produced by the tectonic flow of the enclosing rocks (see Figure 6). Moreover, these magma chambers changed their positions in space precluding the accumulation of melt in one place to produce large bodies. As a result of this, numerous small, individualized, rootless intrusive bodies, undifferentiated or poorly differentiated in composition, were emplaced. They show a distinct trend of their localization along the directions coinciding with the direction of the main deformations in the Belomorian Mobile Belt during the Early Paleoproterozoic time [*Sharkov et al.,* 1997].

Specifics of Petrologic Processes of the Early Precambrian and the Phanerozoic Magmatic Systems

With an obvious general similarity there were substantial differences between the structures of the Precambrian and Phanerozoic magma systems associated with the heights of the plumes, their compositions, and the composition and thickness of the crust.

Host rock assimilation was most typical of the magma chambers of the lower depth level and varied greatly in time. The Early Paleoproterozoic mantle superplumes, responsible

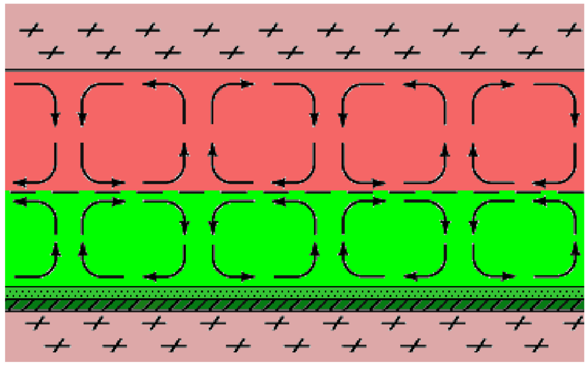

Figure 7. Schematic structure of a layered magma chamber originating during the melting of the sialic roof above a basalt melt sill [*Sharkov et al.,* 1999].

for the formation of large SHMS igneous provinces, consisted of a highly depleted ultrabasic material. It appears that local plumes did not ascent there higher than the base of the lower crust. Because their primary melts were extremely hot, the magma chambers of this lower depth level might have floated through the crust by the mechanism of zone refinement, facilitating the extensive assimilation of the rocks of their roofs, and resulting in the origin of SHMS melts themselves. These melts rose along dike systems to produce intermediate melt chambers at the medium depth levels of the crust in the form of large layered intrusions and shallow subvolcanic sills at the upper and shallow-depth crustal levels. The evolution of these magmatic systems seems to have terminated as the rising magma chambers had achieved the depths of the substantially sialic crust, where the mechanism of zone refinement ceased to operate.

At the boundary of 2.2–2.0 Ga the first plumes of a new generation were formed [*Bogatikov et al.,* 2000]. As follows from the modern views, their origin was associated with the fluid components rising from the liquid core at the base of the silicate mantle [*Artyushkov,* 1983; *Dobretsov et al.,* 2001]. Thanks to its fluid content the material of these plumes was lighter than that of the previous plumes, and they were able to rise to more moderate depths. The spreading of their heads was already able to cause breaks in the old continental crust and the formation of new oceanic crust, the fragments of which have been recorded as ophiolites beginning from the time of 2 billion years.

That period of time marked the origin of large igneous provinces where the leading role belonged to tholeiite and moderately alkaline basalt. The examples are Phanerozoic rift and trap areas. Local plumes might have risen there to the depth of the upper sialic crust, this leading to substantial changes in the structure of the magma systems. The chambers of the lower depth level, which generated on the cooled surface of the plume heads were often located in the granite crust. For this reason the assimilation of the crustal material by the mantle melts declined drastically, because the arising light granite melt layers precluded the development of a zone refinement mechanism. All other assimilation mechanisms were limited being blocked rapidly by quenching at the contacts with the enclosing rocks, and the mantle melts were isolated rapidly from the cold wall rocks along their pathways (dikes) and chambers (intrusions).

At the same time the Cenozoic intraplate continental basalts are often contaminated by the crustal material (up to 15–20%, see above). This contamination seems to have been associated with the heating of the roofs of the deeper intermediate-depth magma chambers, as the cold partially resorbed crustal material plunged into the underlying basalt melt and was dissolved in it. As it was shown above,this process was completed after the formation of a light granite melt layer impassable for new melt portions from the mantle magma generation source. They accumulated at the bottom of this layered chamber merely to enlarge its basic part. As a result, the early evolution phases of Phanerozoic LIPs were often marked by the emplacement of acid moderately alkalic K-bearing volcanic rocks, such as rhyolite, comendite, pantellerite, and the like [*Yarmolyuk et al.,* 1990]. Surface basalt flows might have resumed only after the removal of the acid melt from the top of the layered magma chamber or after the solidification of the whole magma chamber and the formation of extension fissures in its top, that is, of new intracrustal magma removing channels. This seems to explain the two-stage development of continental rifting: the general rise of the territory during the week basalt magmatism at the prerifting phase and the great intensification of volcanism during the rifting stage proper [*Grachev,* 1987].

In the course of the further evolution of such systems local magmatic centers originated with deep magma differentiation in their intermediate chambers, as it is demonstrated by the examples of the Late Paleoproterozoic Gremyakha-Vyrmes and Eletozero layered complexes. Judging by the emplacement of alkali granites as the final phases there, the evolution of these magma chambers was also completed by the formation of two-layer magma chambers with acid magma layers.

The above data suggest that within magmatic systems, irrespective of the magma composition a series of intermediate magma chambers originated, beginning with the large layered complexes in the crystalline basement (the Paleoproterozoic large igneous rock provinces of the Baltic Shield, the Mesoproterozoic ones of the Canadian and Greenland shields, the Devonian Kola-Karelian alkaline province, and the Tertiary British-Arctic Province, to name but a few) and ending with the layered sills at the bases of the lava plateaus, as it is demonstrated by the example of the Siberian traps.

The lowest and largest of these layered intrusive complexes seem to have been formed on the cooled tops of mantle plumes. This is proved by the studies of xenoliths from the basalts of volcanic plateaus and by the results of the quantitative modeling of magma fractionation in the British Arctic Province, which proved that the primary differentiation of these magmas had taken place at depths of some 25 km (see above). Similar results had been obtained earlier for the Late Cenozoic plateau basalts of Syria and the Baikal Rift. All this agrees well with the idea of underplating, that is, with the intrusion of basaltic magma along the crust-mantle boundary, which had been responsible for the formation of the lower continental basic crust [*Rudnick,* 1990].

A particular place in this series is occupied by Early Paleoproterozoic igneous rocks. As has been mentioned above, the origin of the siliceous high-Mg series magmas, typical of that time, was associated apparently with the extensive assimilation of the Archean rocks of the lower crust in the course of the rising of high-temperature mantle magma through it by the mechanism of zone refinement (see Figure 6). In essence, this is another version of underplating, yet operating in a different way because of the very high temperature of the primary mantle magma. As follows from the results of studying lower crustal xenoliths beneath the BLIP, the basal layers of the crust consist mainly of garnet granulite and granulite eclogite. These granulites had been initially cumulates that had originated simultaneously with the formation of this province from the same magmas [*Downes et al.,* 2002; *Kempton et al.,* 1995], and their metamorphic transformation was caused by the processes of high-temperature plastic flow.

It appears that the structure of the magmatic systems considered above is the general rule for the solid planets of the Earth's group. In fact, layered intrusions have been proved in the Moon, where they had been brought to the surface as tectonic sheets in lunar mountains. These intrusions are the deep analogs of the volcanic rocks of the ancient (4.4–4.0 Ga) magnesian suite, which intrude the primordial anorthosite crust. In terms of their composition the rocks of this suite are very close to the rocks of the terrestrial Early Paleoproterozoic SHMS. Its origin, like that of the latter, is believed to have been associated with the large-scale assimilation of the primordial material of the lunar crust by high-temperature mantle-derived melts [*Snyder et al.,* 1995].

It can be concluded as a result of this study that the magmatic systems of the large igneous rock provinces of the continents had a structure of the same kind from the Early Paleoproterozoic to the Late Cenozoic. They seem to have originated above protuberances (local plumes) at the surface of the spreading heads of mantle superplumes. Melting regions originated in the upper parts of these plumes as a result of adiabatic decompression. The resulting melts were added periodically to intermediate intracrustal magma chambers which solidified to produce layered intrusive complexes. The largest of them operated as long-lived magmatic centers, where the rising melts accumulated, their sizes being controlled by the duration of the given system's existence. The bulk of the magmatic melt rising from these sources to the surface along the system of dikes varied in terms of its evolution.

At the same time, each of the magma systems concerned had its own specific features which were controlled primarily by the structure of the lithosphere, the height of the mantle plumes ascending, and the temperature of the primary magma. For instance, the early Paleoproterozoic magmatic systems originated above the mantle plumes which rose as high as the base of the lower basic crust. The temperature of the newly formed mantle-derived magmas was high enough for melting the material of the latter and for the "floating" of the magma chamber through it by the mechanism of zone refinement with the formation of SHMS melts. The process terminated as the magma chambers reached the essentially sialic crust where as a result of its melting two-layer magma chambers began to form with independent convection systems, and where the mechanism of zone refinement ceased to operate.

The situation changed at the time interval of 2 Ga ago in connection with the origin of mantle plumes of a new generation, which were able to rise to the base of the sialic crust. In contrast to the previous systems, here, the period of zone melting terminated significantly more rapidly, omitting the formation of specific SHMS-type melts. Bimodal volcanic rock series were formed, typical of the Phanerozoic intraplate magmatism.

Conclusions

1. Using the example of the early Paleoproterozoic Baltic large province of the siliceous high-Mg series(SHMS), it is shown that the layered intrusive rock complexes operated as long-lived magma chambers beneath thick lava sheets. The processes operating there were the accumulation of periodically rising mantle magmas, their crystallization differentiation, and the mixing of the fresh and evolved melts. As a result of these processes, the magmas rising toward the ground surface via a system of dikes had been usually modified to different extents, the primary mantle melts being extremely rare.

2. The magma systems of that time originated above the local plumes at the surface of the spreading heads of the mantle superplumes, where the mantle material melted as a result of adiabatic decompression. The SHMS melts themselves seem to have originated at the expense of the high assimilation of the lower crust material by mantle melts, which operated in the form of magma batches "floating" through the crust by way of zone refinement, that is, by the melting of their tops with the simultaneous crystallization at the bottoms. This "floating" ceased as the chamber reached the substantially sialic upper crust with the formation of a light granite melt with an independent convection system in its upper part.

3. In the large igneous rock provinces of the continents, which originated after 2 billion years ago, when the composition of the mantle plumes had changed, the general character of the magma systems remained the same, although

the early, assimilation, stage of their evolution was highly reduced. Layered intrusions originated during the solidification of intermediate magma chambers of different depths, the uppermost intrusions being located immediately below the lava sheets, the lowermost ones, at the crust-mantle boundary (on the cooled top of the mantle plume), incrementing the lower continental crust from below (the process known as underplating). Since the magma chambers were located in the granite crust, the contamination of rocks in their roofs was a subordinate process because it terminated immediately after the origin of a thick granite layer.

4. Granite melts that terminated the evolution of particular magma systems were potassic because of mass exchange processes in two-layer magma chambers between the thick layers of basic and acid melts, where K diffused from the basic to acid magma, and Na diffused in the opposite direction.

5. This structure of magma systems seems to be characteristic of other solid planets of the terrestrial group, in particular, of the Moon, where layered intrusions have been proved, being the deep-seated analogs of the volcanic rocks of the oldest magnesian rock series intruding the primary anorthosite crust. In terms of their composition and origin, the rocks of this series are very close to the rocks of the Early Paleoproterozoic siliceous, high-Mg series of the Earth.

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