Archean high-MgO volcanism in East Fennoscandia

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High-MgO volcanogenic rocks, such as komatiite and high-MgO basalt, are an essential part of Archean greenstone belts in East Fennoscandia (Russia). They provide a significant source of evidence for their endogenic evolution and the physicochemical environment in which mantle magma was formed.

The Karelian craton covers an area of ca. 300 000 km^2. Distinguished within the craton are seven large greenstone belts that incorporate over 25 greenstone domains in which high-MgO volcanic rocks vary in age from 3.4 to 2.8 Ga. The 3.05-2.90 Ga komatiitic associations are characteristic of the central part of the craton (Central Karelia, Russia). The greenstone belts extend approximately north-south in Central and West Karelia and northwest in East Karelia, have a length in excess of 300 km (Vedlozero-Segozero, Sumozero-Kenozero and Parandovo-Tikshozero belts) and a width of over 50 km. They are separated by TTG granite-gneiss domains with ages of 3210±12 to 2760±20 Ma (Lobach-Zhuchenko et al. 1993).

In East Fennoscandia, high-MgO associations formed asynchronously during several stages, as suggested by available geochronological data (Sm-Nd from whole rock and cross-cutting dyke zircon geochronology). The oldest high-MgO volcanic rocks described from the Vodlozero and Lake Kamennoye structures, East Karelia, have Sm-Nd ages of 3391±76 (Puchtel et al. 1993) and 3054±84 Ma (Samsonov et al. 1996), respectively. For Central Karelia (Vedlozero-Segozero greenstone belt), the Sm-Nd age of the komatiitic association is 2921±55 Ma (SvetovHuhma 1999). The formation of the greenstone belts (domains) can thus be split into several periods: 3.4-3.05, 3.05-2.9 and 2.9-2.8 Ga, the age of associations clearly younging from east to west. Overlapping in space in Archaean greenstone belts are geodynamically contrasting rock assemblages, such as high-MgO volcanic rocks with oceanic characteristics, island-arc BADR series, active continental margin andesites, and terrigenous-sedimentary sequences formed in various palaeogeographic settings. The periods of andesitic volcanism were simultaneous with komatiitic volcanism at 3.05-2.9 Ga (island-arc BADR series in Central Karelia) and 2.90-2.85 Ga (CMA-type andesites).

The reconstructed thickness of the komatiite-basaltic associations varies from several hundred metres (over 100 m in Vodlozero) to 2.8-3 km (Koikary). The maximum total thickness of reconstructed Archaean sequences is 6 km. In the structures, high-MgO volcanic rocks are compact and cover areas of 2-4 to 30 km^2.

In the Central Karelian greenstone belts, komatiites are chiefly represented by lava facies, such as 0.2-25 m thick differentiated massive, pillowed, variolitic flows traced for several kilometers along strike. The flows vary laterally in thickness. Lava lakes are occasionally formed (Svetov 1997). High-MgO volcanics characteristically outflow as thick lava rivers (Hill et al. 1995, Hill 1999). The Koikary structure shows marginal lava river facies with numerous wedging-out fractured magma injections that gave rise to 0.4-2 m thick, compositionally fractionated flows resting on each other in peripheral zones (in a 0.4 m thick flow, a cumulate zone is 0.2-0.3 m thick).

Magmatic differentiation is most conspicuous in the structure of 0.6-12 m thick lava flows, as evidenced by the occurrence of flow-top breccia (A1), spinifex- structured (A2-5) (differently oriented, radiated-structured, packet and parallel types) and cumulate-structured zones (B1-3). The abundance of pillow lava suggests submarine eruption. In some cases, volatile saturation of lava in a closed environment gives rise to metastable low-temperature (1170-1300°C) liquation differentiation of komatiitic melt with the release of andesitic melt globules. Variolites typically occur as globules ranging in size from microvarioles to spherulitic varioles, up to 12 cm in diameter. Clusters of lens-shaped liquants, conformable with the strike, were produced by residual currents in the core of lava tunnels.

Eruptions exhibited an explosive pattern. In the Archaean greenstone structures discussed, pyroclastic facies make up not more than 3-5% of rock volume and are represented by pelite- to agglomerate-sized tuffs. Pyroclastics occurred originally in greater volumes and were later eroded, as shown by thick piles of MgO-, Cr- and Ni-rich volcanogenic graywacke. Tuffites, iron formation, cherty schist and graphite schist are encountered between lava flows. Volcanic activity was accompanied by intrusive magmatism, such as the intrusion of comagmatic dunite and high-MgO gabbro.

The rocks of Archaean komatiite associations were metamorphosed to greenschist to amphibolite grade. Protomagmatic minerals, replaced by secondary ones, such as actinolitic hornblende, anthophyllite, tremolite, serpentine, chlorite, talc, carbonate, epidote, magnetite, plagioclase, retain their structural and textural rock characteristics.

Based on a geochemical study of Archaean komatiites in East Fennoscandia, they are defined as Al-undepleted types with the following geochemical characteristics:

1. 3.4-3.05 Ga – East Karelia (Vodlozero and Lake Kamennoye structures). The MgO content of East Karelian komatiites and basalts varies from 8 to 34 wt% and that of the chill zone (A1) from 26 to 29%. TiO_2 concentration is less than 0.35-0.48 wt%. Characteristic relations are $0.7 < CaO/Al_2O_3 < 1$ (0.91 ± 0.11 in Vodlozero and 0.75±0.33 in Lake Kamennoye), $20 < Al_2O_3/TiO_2 < 24$ (22.10±2.03 in Vodlozero and 22.76 ± 4.37), $2 < Zr/Y < 4$. Intermediate differentiates between peridotitic and basaltic komatiites do not typically occur in the Vodlozero structure. Maximum quantities of Ni in the cumulate zones of peridotitic komatiite flows are 1889-2000 ppm and those of Cr are 2700-3781 ppm. In some parts of the Lake Kamennoye structure ca. 100 m thick komatiite rivers show liquation Ni occurrences. The komatiites exhibit a poorly fractionated REE pattern: $(La/Sm)_n = 0.85 \pm 0.07$, $(Gd/Yb)_n = 1.02 \pm 0.03$, $(Ce/Yb)_n = 0.85 \pm 0.07$ at $\Sigma(HREE)_n = 1.4\text{-}1.8$.
2. 3.05-2.9 Ga – Central Karelia (Vedlozero-Segozero greenstone belt). Central Karelian komatiites contain 9.4-32 wt% MgO, 0.2-0.7 wt% TiO_2; $CaO/Al_2O_3 < 1.17 < Al_2O_3/TiO_2 < 30$. The ratios $80<Ti/Zr<130$, $Zr/Y = 0.3$, $(Nb/La)_n = 0.7\text{-}3$, the nonfractionated REE spectra poorly depleted in the LREE range: $(La/Sm)_n = 0.68 \pm 0.25$, $(Ce/Yb)_n = 0.89 \pm 0.16$ $(Gd/Yb)_n = 1.05 \pm 0.21$ make the komatiites similar to N-MORB basalt. Komatiitic tuffs are identical in the percentages of petrogenic elements to lava, but are poorer in Al_2O_3 (<8 wt%), richer in CaO (7-11 wt%) and poor in alkalies (less than 0.5 wt% NaO_2 and less than 0.04 wt% K_2O). Maximum concentrations of Ni (1862 ppm) and Cr (6395 ppm) were reported from Sovdozero peridotitic komatiites.
3. 2.9-2.8 Ga – Northwest and North Karelia (Gimoly-Kostomuksha greenstone belt and Hisovaara greenstone structure). In Northwest Karelia, MgO-rich volcanics typically vary in MgO content from 6.5 to 32-35 wt%. The chill zones of lava flows contain 25-28 wt% MgO. $CaO/Al_2O_3 < 1.19 < Al_2O_3/TiO_2 < 30$. The Kostomuksha komatiites differ considerably in Zr/Y ratio from Hisovaara komatiites (0.68±0.04 and 2.44±1.14, respectively). The Kostomuksha komatiites typically exhibit a nonfractionated HREE distribution pattern: $\Sigma(HREE)_n = 1.1\text{-}2.0$ at LREE depletion $(La/Sm)_n = 0.42 \pm 0.06$, $(Gd/Yb)_n = 0.92 \pm 0.30$, $(Ce/Yb)_n = 0.87 \pm 0.23$.

Based on modern geochemical, petrological and experimental studies of natural systems carried out on the basis of the chemical composition of high-MgO volcanics, the thermodynamic conditions of magma generation and melt flow can be determined. Primary komatiitic magma is transported rapidly (1 to over 10 m/s) onto the day surface. Because it is poorly viscous (0.1-10 poise), it flows out as turbulent flows (Huppert & Sparks, 1985) at temperatures of 1550-1600°C.

If komatiitic magma was hydrated, their maximum generation temperatures for East Fennoscandia at 1750-1850°C (P = 6-8 GPa), upper mantle sources melting partially at depths of ca. 230-270 km. The thickness of the Archaean protooceanic crust above mantle plumes is estimated at 45-70 km. Modern studies show that komatiites can be restricted to contrasting geodynamic regimes: continental (intracratonic rift structures: Schau 1977), oceanic (spreading and oceanic plateau zones: DeWit 1991, Puhtel et al. 1998) and transitional - subduction and suprasubduction settings (Parman et al. 1999).

Available geologic and geochemical data on the “ophiolite-like” komatiitic associations known in Central Karelia (Vedlozero-Segozero greenstone belt) suggest that they were generated during spreading in a back-arc oceanic basin. The beginning of the spreading was timed to the uplift of a deep-seated mantle plume, which melted in its axial portion to produce komatiitic melts.

Comprehensive analysis of geological samples from the greenstone belts and domains in Central Karelia has shown that they were all formed at convergent “protoocean-protocontinent” boundaries and that their evolution falls into two phases: an early accretion stage and a late collision stage. As a result, rocks formed in different geodynamic regimes overlap each other in the sequence, some rock associations drop out of it laterally and the greenstone domains are structurally asymmetric. In this case, the western margin of the Vodlozero block acted as a “protocontinent” and the oceanic crust was accreted from west to east. The model proposed for the evolution of the Archaean greenstone belts in Central Karelia (3.05-2.9 Ga) agrees with the geodynamic reconstructions made for the greenstone belts in the eastern part of the Karelian craton (Puchtel et. al.1999) and North Karelia (Kozhevnikov 2000).

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