Geochemistry of Strontium in Layered Intrusions: Inconsistency with Predictions of Orthomagmatic Model

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It is assumed that a process of magma chamber fractionation is recorded in layered intrusions. Primary homogeneous liquid must possess some resource of Sr and the main host mineral, plagioclase, must extract Sr from it in accordance with ctystal/liquid partition coefficient which is always much more than 1.0. It must inevitably make residual liquids, late derivates and plagioclase progressively poorer in Sr. Cryptic variation (cryptic layeing) must reflect this expected tendency.

As established for Uralian complexes of ophiolitic and "zoned" type, whole-rock Sr concentrations within natural gabbro series, usually layered or taxitic, have linear correlation with amount of plagioclase which has hereat *constant* Sr concentation (Sr_{Pl}) not depending on amount of plagioclase (Efimov, 1989). Hence Sr concentration in this mineral phase was determined not by Sr concentation in given volume but by level of chemical potential of Sr which was common for the series. Consequently, layered gabbros were equipotential, open Sr-systems; their parts (layers, domains) were in thermodynamic communication each with other. Sr was redistributed in proportion of plagioclase amount in each given point. Unfortunately systematic stidies on Sr geochemistry for layered intrusions such that by A.Morse (1982) are very rare.

Ioko-Dovyren layered complex (North Near-Baikal region, East Siberia) forms a subvertical lens-like body 28 km in lenght and up to 3.5 km in width. It is assumed as a product of fractional crystallization of picrite-like magma in primarily subhorizontal magma chamber. Whole-rock Sr content increases upsection from 30-40 to 300 ppm and in general correlates with plagioclase amount. Sr content in lower dunite-"plagiodunite" zone is very low. The next mainly troctolitic zone (Sr_{Pl} about 250 ppm) is connected by a sharp 200-m gradient with overlying zone composed mainly of olivine gabbro (Sr_{Pl} about 350 ppm). Values of Sr_{Pl} up to 500 ppm are fixed in zone of "upper gabbros" which is not well expressed. There are no indications of upsection decreasing whole-rock Sr content and Sr_{Pl}. In rough approximation all the gabbroic series forms single linear ($r > 0.9$) trend with average Sr_{Pl} near to 350 ppm. However strontium levels corresponding to main stratigraphic units are distinguished in the section. In each of them Sr whole-rock concentrations are approximated by linear function of amount of plagioclase with constant Sr_{Pl}. The doubt arises if stratigraphic units of the massif have been formed by fractionating of magma. This doubt is supported by data from some other layered complexes.

In the more than 6000 m of visible width section of the Freetown Layered Complex (Sierra Leone) composition of main mineral phases varies at a very narrow rate. In all the section correlation plagioclase amount vs whole rock Sr content is close to ideal linear. All the rocks are as if they are a mixture of femic minerals practically containing no Sr and plagioclase with constant Sr_{Pl} (650 ppm). Cryptic variation is absent (Umeji, 1983). W.P. Meurer and A.E. Boudreau (1996) studied the Middle Banded Series of the Stillwater Complex (Montana, USA) in very detail. In spite of great variations in mineral proportions there are no distinct stratigraphic or lateral trends of mineral composition in the section. Cryptic variation is also absent. Whole rock Sr concentrations are strictly correlated with plagioclase amount; almost ideal linear trend demonstrates constancy of Sr_{Pl} (about 200 ppm). Authors consider these facts as the result of significant modification of rocks by postcumulative processes which obscured their primary genetic features. The special study by A.Morse (1982) is dedicated to geochemistry of Sr in Kiglapait Complex (Labrador, Canada). The PCS (per cent solidified) vs Sr plot demonstrates the absence of any distinct trend of Sr in the section. Average whole rock Sr content is 330 ppm; values for the Lower Zone vary ±100 ppm and for the Upper Zone ±150 ppm around this figure. Lower Zone plagioclase contains 532 ppm; Sr_{Pl} increases to 680 ppm in the Upper Zone before decreasing to 310 ppm at the top. There is a very distinct linear trend ($r = 0.93$) in the lower part (90% of the section) which composes mainly of troctolites; it demonstrates here constancy of Sr_{Pl} (about 450 ppm) at any plagioclase amount. In the Kivakka Complex (North Karelia, Russia; Koptev-

Dvornikov et al., 2001) whole rock Sr concentrations are in a satisfactory correlation with plagioclase amount and vary in gabbroic part of the section mainly from 250 to 370 ppm at approximate average level about 300 ppm. They do not detect any stratigraphic direction or upsection decreasing. The average trend is close to linear; one can assume the average Sr_{Pl} to be about 400 ppm.

Thus for all these examples Sr distribution does not subordinate to predictions of ortho-magmatic model. Consequently some other process is recorded in considered sections.

The 1st important conclusion is: there are no indications to the tendency of decreasing Sr upsection predicted by orthomagmatic crystal-lization of a magma basin. The 2nd important conclusion is: at least in a part of layered complexes in all the section or in some significant stratigraphic units of the section whole-rock concentration of Sr is a linear function of amount of plagioclase containing constant concentration of Sr. This most important fact can not be plausibly interpreted by fractionating of a magmatic liquid. However the same fact can have a fully correct thermodynamic interpretations: constant concen-tration of a component in a phase which does not depend on phase amount symbolizes equality of chemical potential of this component at the moment of generation of all the sequence. Hence the following conclusion: all the great number of layers was in state of chemical equilibrium and composed a single whole, a some equipotential system (a reservoir, a kind of thermo- and barostate) where all the layers were formed simultaneously but not one after another as predicted by the classical interpretation.

There are another independent evidence that confirm these conclusions.

(1) Phenomena of solid state (plastic) flow in gabbroic rocks which makes dynamo-metamorphic nature of layering and structural pattern of massifs very likely. (2) Precise micro-probe studies do not confirm existence of two generation of crystals, cumulative and inter-cumulative. The degree of idiomirphism can not be convincing. (3) Phenomena of metamorphic differentiation. The petrology forbids existence of plagioclase liquids but in Ioko-Dovyren Complex extension structures of "horsetail" type are filled by anorthosite consisting of the same plagioclase as in the host troctolite (Efimov, 1989). In Stillwater Complex, discordant bodies of anorthosite and leucocratic troctolite are interpreted as result of replacement (Meurer et al., 1997) but indication of the last process are not very convincing. There are reasons to interpret them as fill segregations that compensate viscous gaps of layered mass by diffusion along pressure (chemical potential) gradient in order to diminish a contrast between host and gaps. (4) Experimental data of special importance for An-Fo system (Kushiro, Yoder, 1966) precludes orthomagmatic origin of troctolite: troctolitic liquid produces aluminous spinel (but never anorthite-olivine association) which never occurs in natural sequences as well as spinel cumulates. These data are usually simply ignored (Efimov, 1985). (5) At last, the marine geo-physicists community came to the conclusion that there are no great magma chambers postulated by petrologists in modern spreading zones such as mid-ocean ridges (Kent et al., 1993). This fact is in a sharp contradiction with cumulative interp-retations of 3rd layer of modern oceans and gabbroic member of the ophiolite suite.

Thus Sr distribution data together other independent evidence lead to a conclusion that orthomagmatic evolution of at least some of layered intrusions seems to be doubtful. However this conclusion does not answer question about nature of primary substance of these geologic objects. We can not discuss here this global problem. A hypothesis which connects ophiolitic gabbroic rocks with decompression of high pressure basic rocks of the upper mantle (Efimov, 1984) seems to be rather consequent and acceptable for this case.

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