EVOLUTION OF THE BANSKÁ ŠTIAVNICA STRATOVOLCANO AND CORRESPONDING MAGMA CHAMBER (CENTRAL SLOVAKIA)

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Abstract: Banská Štiavnica Neogene stratovolcano evolved on a continental crust. Primary magmas generated in mantle wedge underplated under the crust where evolved to less denser basic magmas. In lower chamber took place high-pressure fractionation of olivine, clinopyroxene, amphibole ±Ca-plagioclase. Uprising basic differentiated magma from lower chamber stopped in the upper crust (6-10 km), interacted with surrounding granitic rocks and formed magma chamber. Mixing between basic and crustal partial melts, fractional crystallization and mixing between variably evolved magmas in magma chamber gave rise to the whole spectrum of andesitic rocks. Evolution of the magma is intimately linked with the collapse of the overlying ganitic rocks, intrusion of diorite and granodiorite, and final segmentation of the former unique magma chamber into several sub-chambers.

Keywords: andesite, magma chamber, differentiation, stratovolcano

Volcanic stages

The Štiavnica stratovolcano belongs to young Neogene-Quaternary volcanics, in the western part of Carpathian arc in the territory of Central Slovakia. Thorough previous investigations suggest sixs evolutionary stages. **(1) Pre-caldera stage I - Early to Middle Badenian:** build up of a large stratovolcano of px and hb-px andesites, including rare garnet-bearing and bi-hb-px andesites, **(2) Pre-caldera stage II - early Late Badenian:** erosion of the volcano and multiple phase emplacement of subvolcanic intrusive complex involving a large granodiorite/diorite bell jar pluton, granodiorite porphyry stocks and dyke clusters, and quartz-diorite to diorite porphyry sills and dykes, **(3) Caldera stage - late Late Badenian:** a large caldera subsidence, later filled by dome/flow complex of bi-hb andesites to dacites, **(4) Post-caldera stage - Early to Middle Sarmatian:** alternating explosive and effusive activity of px, hb-px, and bi-hb-px andesites in several pulses, mostly on slopes of the stratovolcano**, (5) Late stage rhyolites - Middle to Late Sarmatian:** resurgent horst uplift in center of the caldera accompanied by rhyolite volcanics, **(6) Late stage basaltic andesites - Pannonian:** dispersed dykes, necks and lava flows of high alumina basalts and basaltic andesites.

Comparison with different geotectonic settings

Trace elements used by Bailey (1981) discriminate the andesites according to geotectonic position. The elements K, Rb, Ba, La, Ce, Pb, Th, Zr, Hf, and ratios La/Yb, La/Y, Th/U, Zr/Y, Hf/Yb, Ni/Co systematicaly increase and Y, K/La, P/La, Sc/Cr, Sc/Ni decrease in profile from island arcs to thick continental margins. Štiavnica andesites exhibit crustal component. According to K, Rb, La, Ce, Y, Th, ∑REE, La/Yb, La/Y, K/La, they resemble andesites on thick continental margin but with lower Zr, Hf, Ba, Zr/Y (Tab).

REE patterns of andesites from stages 1-3 overlap. High LREE/HREE ratio reflects garnet in the source. More acid andesites of caldera filling and dacites tend to have higher LREE, HREE remain comparable. Small difference in LREE may be explained by clinopyroxene fractionation, since it has different distribution coefficient for LREE and HREE.

Inkompatible trace element patterns with Nb-Ta negative anomaly, depletion in P, Ti and strong poritive Pb anomaly are typical features of subduction-related magmas.

	1		2		3		4				
	island arcs				continental island arcs		thick continental margins				
	low K		high K							Štiavnica	
	R	range	R	range	R	range	R	range	trend	stratovolcano	afinity
K*	**0.51**	0,32-0,59	**1.20**	0,68-2,70	**1.37**	0,83-1,99	**1.95**	1,36-2,49	⇑	**2.21**	> 4
Rb	**8.3**	2.4-13	**28.0**	10-129	**44.0**	18-113	**66.0**	35-121	⇑	**88.1**	> 4
Ba	**152**	68-175	**318**	165-1850	**395**	243-875	**605**	360-1180	⇑	**498**	3-4
Sr	**220**	137-390	**434**	248-900	**400**	125-1100	**601**	265-860	⇑	**302**	1-2
Pb	**2.90**	2.3-4	**5.00**	2.85-12	**10.30**	5-21	**11.50**	11.5-12	⇑	**4.83**	2
La	**3.0**	2,35-3,7	**11.7**	8-36,3	**17.0**	10,8-25	**28.5**	19,2-44,8	⇑	**35.4**	> 4
Ce	**6.9**	5,9-14,1	**23.5**	15,5-88,5	**37.0**	25,5-65	**60.7**	42,2-99,8	⇑	**58.0**	4
Y	**25**	17-36	**20**	17-40	**22**	18-28	**15**	8-24	⇓	**19**	2
Th	**0.72**	0,27-2,57	**1.95**	0,5-5,5	**5.36**	3,64-7,8	**6.00**	4-8,2	⇑	**9.82**	> 4
Zr	**63**	38-110	**111**	35-250	**117**	100-250	**181**	88-230	⇑	**132**	3-4
Hf	**1.55**	0.92-2.6	**2.43**	2.1-4.5	**3.44**	1.9-4.6	**5.75**	4.5-6	⇑	**4.39**	3-4
∑REE**	**17.0**	-	**43.7**	-	**61.9**	-	**97.8**	-	⇑	**103.4**	4
La/Yb	**1.2**	0,92-1,26	**6.4**	3,5-11,9	**8.9**	79-158	**16.5**	12,2-21,4	⇑	**14.3**	4
La/Y	**0.11**	0,076-1,25	**0.58**	0,3-1,1	**0.93**	0,6-1,1	**1.46**	1,28-1,63	⇑	**2.04**	> 4
K/La	**1950**	850-2170	**1150**	354-2500	**814**	858-1180	**715**	450-1050	⇓	**551**	> 4
Zr/Y	**2.2**	1,5-3,8	**4.7**	0,88-10,3	**5.4**	4,3-10	**14.6**	6,6-30	⇑	**7.1**	3-4
Hf/Yb	**0.61**	0,4-0,84	**1.30**	0,72-2,45	**1.70**	1,05-2,11	**3.40**	2,8-4	⇑	**1.79**	3
Ni/Co	**0.29**	0,2-0,76	**0.52**	0,2-1,52	**0.95**	0,45-2,2	**1.40**	0,33-3,3	⇑	**0.61**	1-2
Sc/Cr	**3.80**	0,7-15,5	**0.80**	0,3-6,7	**0.61**	0,13-2,1	**0.36**	0,06-0,75	⇓	**0.93**	2
Sc/Ni	**3.40**	2,1->6,2	**2.00**	0,43-7,5	**1.10**	0,44-4,2	**0.55**	0,18-1	⇓	**3.48**	1

<u>Composition and differentiation of the magma</u>

Volcanic activity in Central Slovakia developed as response of subduction process. Low Sr/Y, La/Yb ratio, higher MgO, Yb indicates absence of melting of basaltic part of subducting slab. Enrichment in incompatible elements, higher Th/U, Ba/La ratio suggests influence of subduction-related fluids. Modelling of source on Zr/Yb vs Nb/Yb corrected on fractionation points to slightly enriched N-MORB source.

Uprising partial melts from mantle wedge have to stagnate under the crust. We suppose that underplating generated deep reservoir of basic magma. In deep reservoir, high-pressure fractionation took place. Under unhydrous conditions the fractionation is governed by assemblage oliv+aug+Ca-plag. Occurrence of relic olivine, plagioclase cores with An > 80, common augite in more basic andesites, low Ni, Cr are indirect indications of unhydrous high-pressure differentiation. With increasing water content at $P_{fluid}=P_{total}$ plagioclase is destabilized while stability field of amphibole expands. Fractionated assemblage then includes oliv+aug+amph in various proportions. High Al_2O_3 peak at 3.5 % MgO indicates rather fracionation under higher water content.

Magma evolves by fractional crystallization, assimilation of surrounding granitic rocks, contamination by partial melts derived from partially molten granites and mixing beween different batches of magma in chamber.

Fractionating assemblage may be recognized on modified PER diagram (4Ca+4Mg+0.5Fe+0.5Mg/Zr) vs (Al+Si)/Zr) by Bradshaw (1992). Incompatibility of Zr in melts with up to ~80 wt. % of SiO_2 suggests Zr as fractionation indicator. Štiavnica andesites give linear positive trend on PER. According to orientation and the length of the vectors of fractionating minerals we may conclude that main fractionating phases are clinopyroxene and plagioclase. Orthopyroxene and magnetite are subordinate. The role of amphibole is unclear, because it introduces only scattering on this type of PER diagram. High correlation factors may indicate supressed involvement of amphibole.

Modelling of fractional crystallization (FC) with K/Rb vs Rb fails. The variation is successfully modelled by assimilation and fractionation (AFC) and indicates pronounced role of assimilation in evolution of the magma.

Andesites from lower units in pre-caldera stage are intensively contaminated by granitic rocks, while later andesites are more fractionated. Granodiorite can be modelled as a mixture of partial melts derived from granitoids and evolved andesitic magma.

Late stage rhyolites on many diagrams (major and minor element diagrams) form a separate group suggesting origin by parial melting of crustal rocks. Rhyolites are not end member of andesite-dacite-rhyolite differentiation trend.

Late stage basalts on PER diagram show some scattering. Basalts do not lie at the beginning of the fractionation trend defined by andesites and clearly demostrate that they are not basaltic precursors of andesites. Moreover, basalts do not plot on one regression line implying that scattered occurences of individual basaltic rocks may come from different magma sources.

Two-pyroxene thermometry and Fe-Ti thermometry define temperature range to 850-1050 °C and oxygen conditions +1,5 $\log_{fO2}$ (FMQ) for andesites. Pl-Di-Q+Or plot (Baker & Eggler 1983) shows that andesitic magma had higher water content then 2-3 wt % and if we consider increased pressure to1,7-2,5 kbar the water contet was even higher. Plagioclase-melt pairs in martix give water content 3-6 wt % which corroborates with higher pressure. Estimated depth of magma chamber is 6-10 km.

Phenocryst assemblage reveals various states of disequilibrium, e.g. mantled opx cores by cpx, resorbtion of plagioclases, sieve-like plagioclase cores, reversal zonalities in pl and px, different fenocryst populations in one sample, whole-rock phenocryst disequlibria etc. The mixing between differently evolved magma batches is presumed as the main process that took place in the chamber. Mostly more magnesian pyroxenes in the matrix like phencrysts, higher two-pyroxene temperatures in matrix like in the cores of px phenocrysts indicate mixing of more silicious magma with less evolved. Just mixing with more basic magma is presumed to be a key process that could initiate or at least contribute to eruption activity.

Evolution of the magma chamber

In intial stage, the uprising, hot basic magma was confined in subvolcanic levels (6-10 km), where crystallized, releasing heat into surrounding granitic rocks. Partial melts from granitic rocks backwards-contaminated basic magma. Lower andesitic units are characterized by supressed fractionation and promoted contamination. Later new batches of uprising basic magma interacted with initially formed mixed magma and with granitic surrounding rocks resulting in formation of huge magma chamber. Fractionation became more preferred, but contamination was still strong. In a large magma chamber the influences like basic magma replenishment or wall rock contamination are effectively obscured.

Decrease of pressure in magma chamber at the end of pre-caldera stage initated collapse of the roof above the chamber. It started in central part and widen towards the edges of the chamber. More differentiated magma in the upper part of the chamber was confined within sinking blocks of granitoids. The less differentiated magma from the central part of the chamber evacuated through the cylindrical caldera faults and emplaced in subvolcanic level in a form of flat body (diorite intrusion). Melts from molten subsided blocks of granitoids mixed with interstitial magma and formed granodioritic magma, which intruded along cylindrical faults above the former diorite intrusion.

Granodiorite intrusion contains a lot of microgranular enclaves (MNE). The trace element chemistry of MNE is comparable with the lower andesitic units suggesting strong contamination of basic magma with crustal partial melts. Remnants of sinking ganitoid blocks came into contact with basic magma right above the cumulate horizont. Partial melts from granitoids mixed with basic magma producing lighter MNE magma that formed horizont between granodiorite and basic magma. As granodiorite magma flowed out from the chamber it collected pieces of hybrid MNE magma. Regular occurence of MNE in the whole granodiorite intrusion is indirect evidence for the presence of horizont of MNE magma.

Subsurfice collapse reflected on the surfice by formation of the caldera. A period of supressed surfice volcanic activity was used for rehomogenization of magma in the chamber. Pronounced fractional crystallization, mixing with small proportion of granodiorite magma and less efective wall-rock assimilation are indicators of standstill of inflow of basic magma in the chamber. Fractional crystallization led to more acid magma (dacite) and to enrichment in water. Later inflow of "fresh" basic magma on the bottom of the chamber iniciated strong eruption activity.

In post-caldera stage the subsurfice subsidence continued. Magma chamber was flattened due to the collapse and growing cumulate horizont. It lost the identity of one large chamber and was separated into few sub-chambers, which might only aperioadically communicate between them. The consequence is the presence of volcanic centers externally of the former caldera, individual geochemistry of each volcano, e.g. more basic and more contaminated magma vs more fractionated more silicic magma and probably simultaneous eruption of different magmas on different places.

Rhyolitic volcanism is coincidental with deep fault tectonic. The composition of rhyolites is on Ab-An-Or diagram confined in the field of granites. The whole rock composition is comparable with metling of metagreywackes. We suppose that underplating iniciated melting of lower crustal rocks, similar to metagreywackes. Longer period of melting is required, because more then 20 % melting is necessary for the ability of the acid melt to rise up. The uprise of rhyolitic melt was enhanced by deep fractures during extensional regime. Rhyolites emplaced in the N and NW of štiavnica caldera and few of them also within the caldera. No mixing between rhyolitic and andesitic magma in the chamber has been observed indicating solidified state of magma chamber.

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