GEOLOGIJA *39*, 159-191 (1996), Ljubljana

Lithofacies characteristics of the Smrekovec volcaniclastics, northern Slovenia

Litofacialne značilnosti smrekovških vulkanoklastitov (severna Slovenija)

Polona Kralj
Geološki zavod Ljubljana
Inštitut za geologijo, geotehniko in geofiziko
Dimičeva 14, 1000 Ljubljana, Slovenija

Key words: andesite volcaniclastics, volcaniclastic turbidites, zeolites
Ključne besede: andezitni vulkanoklastiti, vulkanoklastični turbiditi, zeoliti

Abstract

The Smrekovec mountains are characterised by a widespread occurrence of volcanic rocks of the Upper Oligocene age. Their development is closely related to volcanic activity which resulted in the formation of a submarine stratovolcano complex, emplaced onto pre-Tertiary carbonate basement and locally, on Upper Oligocene marine marls and silts. Magma composition varied with time during volcanic activity. The original tholeiitic magmas very likely underwent a differentiation due to low pressure crystal fractionation, resulting in the development of andesitic and finally rhyodacitic magmas. The early stage of volcanic activity was dominantly non-explosive; the main style of fragmentation was autoclastic, related to chill and quench processes that affected lavas and high-level intrusive bodies. During the late-stage of volcanic activity, explosive volcanism was also present, being most probably related to magmatic and combined magmatic-hydrovolcanic activity. Explosions also seem to have generated or triggered volcaniclastic debris flows and turbidity ash flows.

Shallow intrusive bodies (syn-volcanic sills and feeder dykes) were a local source of heat that generated hydrothermal/geothermal conditions in the enclosing, water-saturated volcaniclastic sediments. Consequently laumontite, analcime, clinoptilolite, heulandite, thomsonite, yugawaralite, prehnite, pumpellyite, albite, apophyllite, epidote, sphene, chlorite and mixed-layered clay minerals developed as replacements of the primary constituents, interstitial fillings and vein minerals.

Kratka vsebina

Smrekovško podgorje grade vulkanske kamnine zgornjeoligocenske starosti. Njihov nastanek je vezan na razvoj vulkanskega masiva, sestavljenega iz enega ali več stratovulkanov, ki so delovali v morskem okolju. Podlaga sestoji iz mezozojskih karbonatnih kamnin, ponekod tudi iz zgornjeoligocenskih laporjev in meljevcev. Sestava magme se je med vulkanskim delovanjem spreminjala. Prvotna sesta-

va magme je bila toleitna, vendar se je, najverjetneje zaradi kristalne frakcionacije, diferencirala, sprva v andezitno in nato v riodacitno. V zgodnjem obdobju je prevladovala neeksplozivna vulkanska dejavnost. Tedaj je bil najpomembnejši način fragmentacije avtoklastičen, vezan na procese nenadnega ohlajanja lave v vodnem mediju oziroma magme ob intruzijah v plitvo ležeče vlažne sedimente. V poznejšem obdobju vulkanskega delovanja so se pojavile tudi magmatske in magmatsko-hidrovulkanske eksplozije. Najverjetneje so le-te povzročile tudi nastanek vulkanoklastičnih debritnih in turbiditnih tokov.

Plitvi intruzivi (sin-vulkanski silli in dyki) so predstavljali lokalni izvor toplote, zaradi katere so v okolnih, z morsko vodo prepojenih sedimentih iz pornih vod nastajale tople raztopine s povečano vsebnostjo raztopljenih mineralnih snovi. Zaradi njihovega delovanja so začeli kristalizirati zeoliti laumontit, analcim, klinoptilolit, heulandit, thomsonit, yugawaralit in avtigeni silikati: prehnit, pumpellyit, albit, apofilit, epidot, sfen, klorit in glineni minerali z zmesno strukturo vrste klorit/montmorillonit. Avtigeni minerali nadomeščajo prvotne sestavine kamnin ali pa zapolnjujejo pore in razpoklinske sisteme v kamnini.

Introduction

The Smrekovec mountains, located in northern Slovenia (fig. 1), are characterised by a widespread occurrence of coherent volcanic rocks and volcaniclastic deposits. The complex encompasses an area of approx. 15 sq. km and includes three major mountain peaks, Komen, Krnes and Smrekovec, reaching of 1684 m, 1613 m and 1577 m respectively. The Smrekovec volcanic complex represents a part of a wider volcanic belt, named the "Smrekovec series", extending along a distance of about 100 km towards the southeast (Mioč, 1978, 1983; Mioč et al., 1986). The Smrekovec volcanics are of Upper Oligocene stratigraphic age, as determined on the basis of foraminifera fauna, encountered in locally underlying marine marls and siltstones (Rijavec, 1966).

An early publication on the Smrekovec volcanics appeared at the end of the previous century, when Teller (1898) elaborated the first geological map of the area. Following works are mainly related to the period after the Second World War (Hinterlechner-Ravnik; Pleničar, 1967; Mioč, 1978, 1983; Mioč et al., 1986; Osterc, 1976; Kovič & Krošl-Kuščer, 1986; Kovič, 1988).

The basement consists mainly of Mesozoic carbonates, occurring as tectonically uplifted blocks on the NW and SE margins of the Smrekovec volcanic complex. A NW-SE trending deep-seated fault of the peri-Adriatic lineament separates this complex from the Karavanke tonalite (Mioč, 1983), which is in "sensu stricto" quartz diorite (Zupančič, 1994).

The present, rather complicated geological situation in northern and north-eastern Slovenia is closely associated with global tectonic processes of subduction and collision of the continental African and oceanic European plates and their segmented parts, Apulia and the Pannonian fragment (Oberhauser, 1980; Royden, 1988; Dercourt et al., 1986). In early Tertiary, Apulia and Europe collided in south-north direction. In early Miocene the Pannonian fragment separated from Apulia and began to escape eastward from the collision zone, whereas the movements of Apulia were directed westwards. The plate movements were accomodated by the peri-Adriatic lineament (Royden, 1988).

The details about the extent and directions of displacements along the peri-Adriatic lineament in the territory of Slovenia are still uncertain of Slovenia. It also remains undefined whether the Smrekovec volcanism is related to an active continental margin or to one of the collision combinations: island arc – active continental

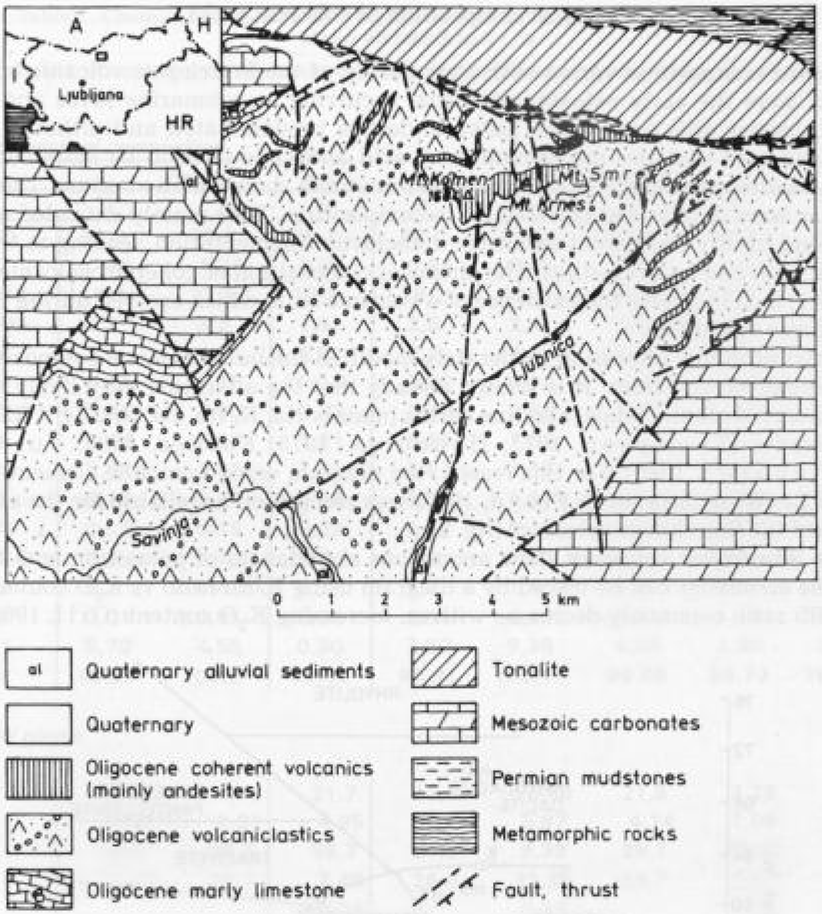

Fig. 1. The Smrekovec volcanic complex: geologic sketch map (after Mioč, 1983)

Sl. 1. Poenostavljena geološka karta smrekovškega podgorja (po Mioču, 1983)

margin – passive continental margin. Andesitic volcanism may continue during the collision and after its separation from a trench, dipping seismic zone and the geophysical characteristics associated therewith (Gill, 1981).

Magma composition gives rather good indications of the tectonic environment. In the Smrekovec volcanic complex, coherent volcanic rocks mainly occur as high-level intrusive bodies and only subordinately as lava flows. Both, coherent and volcaniclastic rocks have undergone appreciable alteration, mainly upon hydrothermal conditions (Kovič & Krošl–Kuščer, 1986). The alteration undoubtedly puts severe constraints particularly on geochemical reliability of alkaline elements and alkaline earth abundances. Prior to a description of lithofacieses encountered in volcaniclastic deposits, I shall provide some general information on the chemical composition of magma and indicate some problems related to its interpretation.

Chemical composition of coherent rocks

Magma composition varied with time during of the Smrekovec volcanic activity. Basalts were the early volcanic products, occurring as submarine lavas and high-level intrusive sills and dykes. Later, andesites predominated and although both, basic and acid varieties are encountered, acid andesites seem to be more common. Acid andesites are mostly vitrophyric and sometimes show perlitic texture. The latest magmas were dacitic and rhyodacitic in composition. They mainly extruded as lava flows and locally underwent extensive autoclastic fragmentation, leading to the formation of in situ hyaloclastites. The chemical composition of coherent volcanic rocks (tables 1, 2, 3) indicates the existence of a volcanic suite which evolved during the the Smrekovec volcanism.

A hydrothermal alteration moderately modified the bulk chemical composition of the Smrekovec volcanics. It is known already that the alteration very likely affects the content of alkali metals, alkaline earths (mainly Na, K, Rb, Ba, Sr), light REE and iron oxydes (Thompson, 1973; Honnorez, 1978; Furnes, 1980; Furnes & El-Anbaawy, 1980). For this reason, the diagram using immobile elements SiO_2, Ti and Zr (Winchester & Floyd, 1977) was recognised as reliable for the classification of the Smrekovec volcanics (fig. 2).

The Smrekovec volcanics show anomalous abundances of potassium and rubidium. The anomalies can be traced by a diagram using K/Rb ratio vs K_2O content (fig. 3). K/Rb ratio commonly decreases with an increasing K_2O content (Gill, 1981) and

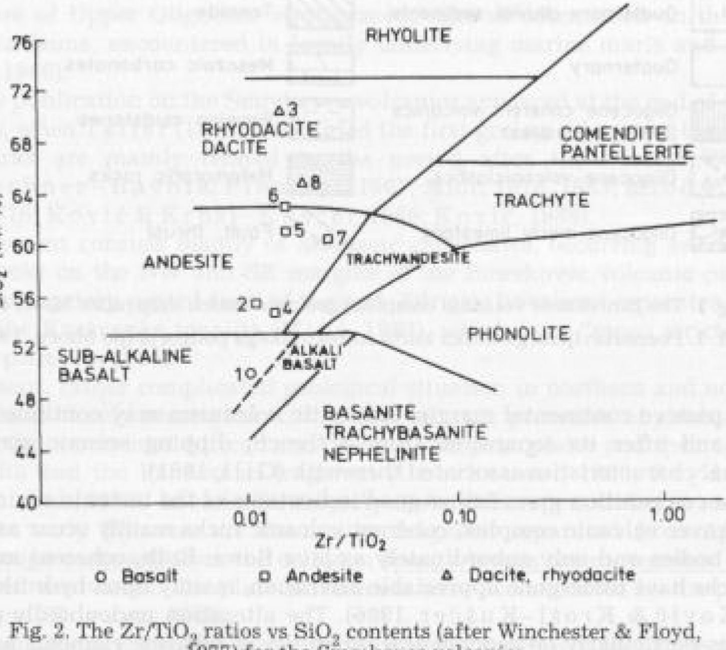

Fig. 2. The Zr/TiO_2 ratios vs SiO_2 contents (after Winchester & Floyd, 1977) for the Smrekovec volcanics

Sl. 2. Diagram odvisnosti med razmerjem Zr/TiO_2 in vsebnostjo SiO_2 (po Winchester & Floyd, 1977) za preiskane vzorce neeksplozivnih predornin smrekovškega podgorja

Table 1. Chemical composition of the Smrekovec lavas and high-level intrusives. Major elements in wt.%

Tabela 1. Kemična sestava smrekovških predornin. Glavne prvine v masnih odstotkih

Bulk chemical composition

	basic		acid	intermediate				
	1	2	3	4	5	6	7	8
SiO2	49,6	52,3	69,1	52,0	55,5	59,6	58,3	59,0
TiO2	0,88	1,06	0,89	0,84	0,89	0,80	0,69	0,89
Al2O3	16,9	17,8	15,2	16,2	15,5	15,5	18,5	14,6
Fe2O3	3,3	3,2	1,9	2,5	2,4	4,0	1,8	2,6
FeO	4,3	4,3	0,3	3,2	4,0	2,0	3,2	2,5
MnO	0,14	0,15	0,15	0,20	0,12	0,09	0,14	0,11
MgO	5,48	3,60	0,13	2,40	2,63	2,27	2,01	1,68
CaO	8,44	7,08	1,81	8,89	7,02	6,10	2,35	6,85
Na2O	3,64	4,32	7,01	2,87	1,11	3,45	8,51	1,42
K2O	0,19	1,17	0,82	1,59	1,01	0,70	0,18	0,93
P2O5	0,13	0,15	0,23	0,17	0,19	0,16	0,13	0,19
H2O+	5,6	4,7	0,7	5,8	7,8	3,7	2,5	8,1
H2O-	0,7	0,4	0,2	0,7	1,4	0,8	0,3	1,9
CO2	0,01	<0,01	<0,01	2,01	0,21	<0,01	1,14	0,02
L.O.I.	5,70	4,55	0,80	7,90	9,30	4,05	3,50	9,25
Sum.	99,27	100,2	98,40	99,21	100,1	99,08	99,73	100,5

CIPW norms

	1	2	3	4	5	6	7	8
q	4,38	4,41	21,7	13,3	26,88	21,8	3,29	
or	1,12	6,91	4,85	9,4	5,97	4,14	1,06	
ab	30,8	36,5	59,3	24,2	9,39	29,1	72,01	
an	29,22	25,7	7,48	26,6	32,85	24,7	3,6	
c			0,04		0,44		2,99	
di	9,14	6,51		2,85		3,44		
hy	9,41	5,95	0,32	4,66	6,96	4,06	5,59	
mt	11,76	11,2		8,53	9,98	4,42	7,74	
il	1,67	2,01	0,95	1,60	1,69	1,52	1,31	
hem	0,01	0,16	2,19	0,18		3,21		
ap	0,30	0,35	0,53	0,39	0,23	0,37	0,3	
cc	0,02	0,02		4,57	0,48	0,02	2,59	
ru			0,39					
an	49	41	11	52	78	46	5	

1. – basalt, northern slopes of Komen (sample Ko–3); *2.*– basalt, northern slopes of Smrekovec (sample Sm 34a); *3.* – rhyodacite lava flow, southern slopes of Komen (sample Sm 81/96C); *4.* – basic andesite, southern slopes of Krnes (sample Sm 83/96C); 5. – acid andesite, southern slopes of Krnes (sample Sm 83/96A); *6.* – acid andesite, the top of Krnes (sample Sm 16/88); 7. – acid andesite lava flow, southern slopes of Krnes (sample Sm 74/88); *8.* – hyaloclastite, southern slopes of Krnes (sample Sm 76/88); Analysed in XRAL Activation Services., Ann Arbor, Michigan

Table 2. Chemical composition of the Smrekovec lavas and high-level intrusives. Trace elements in ppm

Tabela 2. Kemična sestava smrekovških predornin. Sledne prvine v mg/g

Trace elements (ppm)	*basic*		*acid*	*intermediate*				
	1	2	3	4	5	6	7	8
Ag	<0,1	0,7	<0,1	0,2	<0,1	<0,1	0,5	0,5
As	0,2	0,5	1,6	3,4	5,0	0,5	3,4	2,2
Au (ppb)	<2	<2	<2	<2	<2	<2	6	<2
B	10	30	<10	10	10	10	<10	10
Ba	90	170	140	360	210	210	110	350
Be	1	1	1	2	2	2	1	2
Bi	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5
Br	3	2	<1	1	2	<1	<1	2
Cd	0,3	1,1	0,3	0,2	0,4	0,4	0,3	0,3
Cl (%)	0,010	0,01	0,01	0,00	0,010	0,01	0,01	0,00
Co	33	33	80	28	25	33	18	19
Cr	31	9	<2	18	12	8	<2	<2
Cs	<0,5	<0,5	<0,5	<0,5	1,8	2,3	1,6	1,3
Cu	66,9	30,4	16,7	33,5	39,7	16,7	29,7	13,1
Ga	13	16	12	16	14	15	10	15
Ge	<10	<10	<10	<10	<10	<10	<10	<10
Hf	<0,2	<0,2	<0,2	<0,2	7,8	<0,2	3,6	<0,2
Li	14	13	12	17	33	21	23	14
Mo	<1	<1	<1	<1	<1	<1	<1	<1
Nb	11	11	13	10	14	11	18	12
Ni	19	11	3	5	3	3	10	<1
Pb	<2	<2	<2	<2	<2	<2	<2	<2
In	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5
Rb	8	41	19	44	39	26	12	46
S (%)	0,008	0,00	0,00	0,19	0,341	0,00	0,00	0,03
Sb	0,2	0,2	0,4	0,4	0,5	0,3	<0,1	0,4
Sc	22,0	19,0	13,0	15,0	13,0	16,0	10,0	14,0
Se	<1	<1	<1	<1	<1	<1	<1	<1
Sn	6	6	7	6	8	7	8	7
Sr	168	152	90	157	100	344	76	1140
Ta	0,9	0,6	1,3	1,3	0,6	1,3	<0,5	0,9
Th	4,2	4,5	5,2	5,3	7,4	7,0	4,5	5,6
Tl	<0,1	0,1	0,1	0,3	0,5	<0,1	<0,1	0,1
U	1,2	2,0	1,8	1,9	2,6	2,1	1,5	1,8
V	190	170	43	110	73	130	55	71
W	150	330	1800	290	78	550	99	320
Y	20	22	37	27	37	29	37	34
Zn	68	95	75	71	72	60	76	62
Zr	100	130	180	140	220	180	310	210
Hg (ppb)	53	24	6	54	89	<5	29	6

Table 3. Chemical composition of the Smrekovec lavas and high-level intrusives. Rare earth elements in ppm

Tabela 3. Kemična sestava smrekovških predornin. Prvine redkih zemelj v mg/g

Rare earth elements (ppm)

	basic		*acid*	*intermediate*				
	1	2	3	4	5	6	7	8
La	9,5	11,3	16,2	13,2	18,1	15,0	20,2	15,0
Ce	20,9	23,8	34,7	28,7	41,0	33,9	45,7	32,5
Pr	2,7	3,0	4,5	3,6	5,1	4,5	5,8	4,2
Nd	11,6	12,9	19,4	15,0	21,9	19,2	25,0	17,6
Sm	3,4	3,8	5,5	4,3	6,1	5,1	7,2	5,2
Eu	0,88	0,91	1,39	1,03	1,22	1,07	1,19	1,28
Gd	3,9	4,1	6,2	4,5	6,4	5,2	8,1	5,3
Tb	0,6	0,7	1,0	0,8	1,1	0,9	1,3	1,0
Dy	4,3	4,0	0,8	5,0	7,0	5,0	8,2	6,2
Ho	0,89	0,94	1,49	1,11	1,51	1,22	1,69	1,38
Er	2,7	2,7	4,4	3,3	4,4	3,5	5,0	4,0
Tm	0,4	0,4	0,6	0,5	0,7	0,5	0,8	0,6
Yb	2,7	2,8	4,2	3,4	4,5	3,5	5,3	4,1
Lu	0,40	0,43	0,64	0,49	0,67	0,54	0,79	0,65

usually lies above, but parallel to Shaw's main trend (Gill, 1981). Values for K/Rb ratios vs K_2O content of the Smrekovec volcanics mostly lie under Shaw's main trend (Shaw, 1968), except in two samples. They even show an inverse trend compared to that observed in several suites of orogenic andesites.

Ewart (1982) reported that the abundances of Ce and the corresponding Ce/Y ratios are systematically related to the K abundances in many volcanic series from the south-western Pacific subregion. The data of Ce/Y ratios vs Ce abundances for

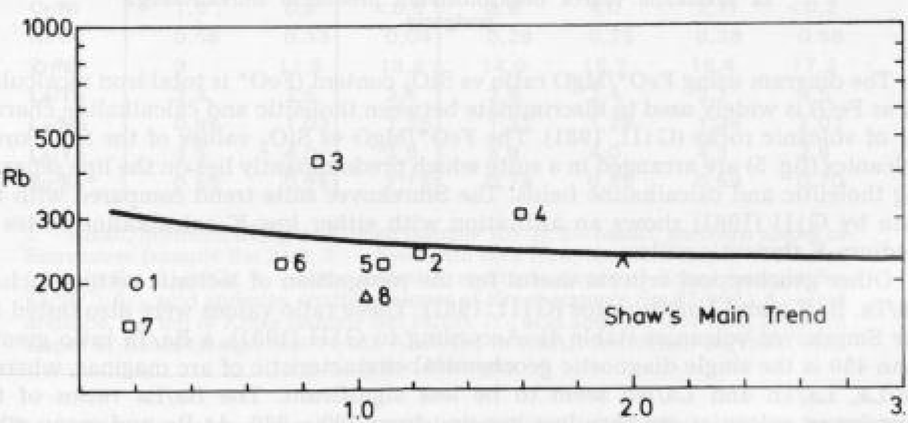

Fig. 3. The K/Rb ratios vs K_2O contents (after Gill, 1981) for the Smrekovec volcanics

Sl. 3. Diagram odvisnosti med razmerjem K/Rb in vsebnostjo K_2O (po Gillu, 1981) za preiskane vzorce neeksplozivnih predornin smrekovškega podgorja the Smrekovec volcanics (fig. 4) do not show such anomalously scattered values as the K/Rb ratios vs K_2O contents. As cerium and yttrium are assumed to be immobile upon zeolite facies conditions, and potassium being mobile and readily incorporated into the zeolite lattice, the anomalous K/Rb ratios vs K_2O content can be at least partially ascribed to the rock alteration.

In orogenic andesites, Th/U ratios likewise tend to increase with K_2O, being <2, 2 to 4 and >4 in low, medium and high-K suites, respectively (Gill, 1981). Th/U ratios in the Smrekovec volcanics range from 2.3 to 3.5 in spite of the relatively low K_2O abundances measured, but do not show any positive correlation with the increasing K_2O content.

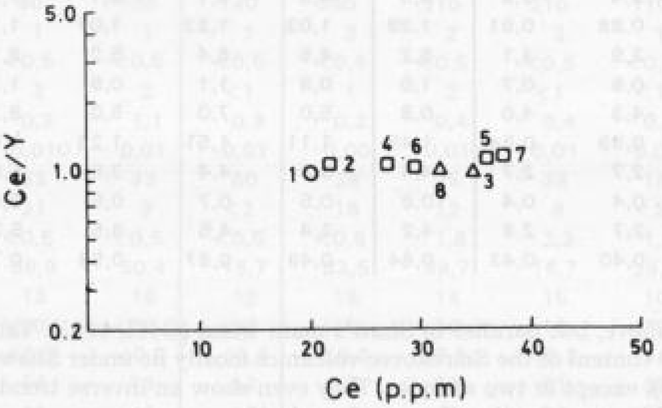

Fig. 4. The Ce abundances vs Ce/Y ratios for the Smrekovec volcanics

Sl. 4. Diagram odvisnosti med vsebnostjo Ce in razmerjem Ce/Y za preiskane vzorce neeksplozivnih predornin smrekovškega podgorja

The diagram using FeO*/MgO ratio vs SiO_2 content (FeO* is total iron recalculated as FeO) is widely used to discriminate between tholeiitic and calcalkaline character of volcanic rocks (Gill, 1981). The FeO*/MgO vs SiO_2 values of the Smrekovec volcanics (fig. 5) are arranged in a suite which predominantly lies on the line separating tholeiitic and calcalkaline fields. The Smrekovec suite trend compared with the data by Gill (1981) shows an affiliation with either low-K calcalkaline suites or medium-K tholeiitic suites.

Other geochemical criteria useful for the recognition of tectonic setting include Ba/Ta, Ba/La and La/Nb ratios (Gill, 1981). These ratio values were also tested for the Smrekovec volcanics (table 4). According to Gill (1981), a Ba/Ta ratio greater than 450 is the single diagnostic geochemical characteristic of arc magmas, whereas Ba/La, La/Th and La/Nb seem to be less significant. The Ba/La ratios of the Smrekovec volcanics are very low, ranging from 100 – 380. As Ba and many other LIL-elements can be mobile during alteration (Thompson, 1973), and on the other hand, Ta is assumed to be a fairly immobile trace element, the Ba/Ta ratios for the Smrekovec volcanics might have been modified by hydrothermal processes. The La/Nb ratios are consistent with the values characteristic of orogenic andesites.

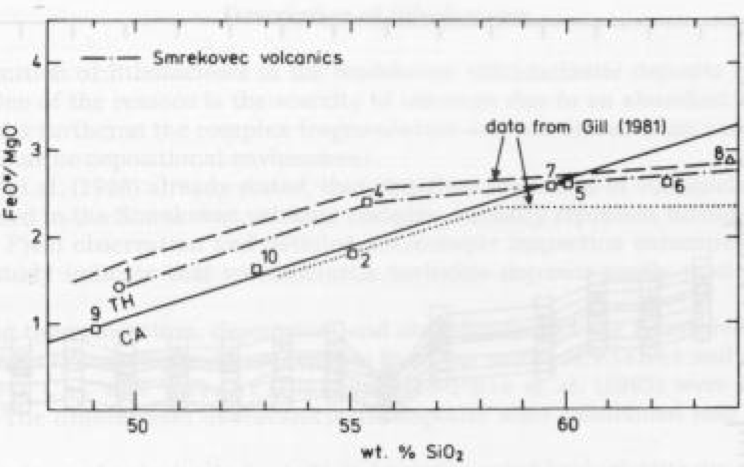

Fig. 5. The FeO*/MgO ratos vs SiO_2 abundances (after Gill, 1981) for the Smrekovec volcanics

Sl. 5. Diagram odvisnosti med razmerjem FeO*/MgO in vsebnostjo SiO_2 (po Gillu, 1981) za preiskane vzorce neeksplozivnih predornin smrekovškega podgorja

Table 4. Some trace element ratios in the Smrekovec lavas and high-level intrusives

Tabela 4. Razmerja nekaterih slednih prvin v smrekovških predorninah

	basic		*acid*	*intermediate*			
	1	2	3	4	5	6	7
K/Rb	200	244	385	323	236	235	133
Ba/Ta	100	283	108	277	350	162	220
Cr/Ni	1,6	0,8	<0,6	3,6	4,0	2,7	<0,2
Ni/Co	0,58	0,33	0,04	0,28	0,25	0,38	0,56
Zr/Nb	9	11,8	13,8	14,0	15,7	16,4	17,2
La/Th	2,3	2,5	3,1	2,5	2,4	2,1	4,5
La/Nb	0,86	1,02	1,25	1,32	1,29	1,36	2,02
La/Yb	3,5	4,0	3,9	3,9	4,0	4,3	3,8
Eu/Eu*	0,66	0,65	1,13	0,79	0,85	0,59	0,70

1. – basalt, northern slopes of Komen (sample Ko–3); *2.*– basalt, northern slopes of Smrekovec (sample Sm 34a); *3.* – rhyodacite lava flow, southern slopes of Komen (sample Sm 81/96C); *4.* – basic andesite, southern slopes of Krnes (sample Sm 83/96C); 5. – acid andesite, southern slopes of Krnes (sample Sm 83/96A); *6.* – acid andesite, the top of Krnes (sample Sm 16/88); 7. – acid andesite lava flow, southern slopes of Krnes (sample Sm 74/88); Analysed in XRAL Activation Services., Ann Arbor, Michigan

The distribution of rare earth elements, normalised to chondritic values by N a k a m u r a (1974), shows only moderate enrichment (fig. 6): for the basalt sample, LREE 20–12 × chondritic level, HREE 16–12 × chondritic level; for dacite and rhyodacite samples, LREE 50–17 × chondritic level, HREE 22–10 × chondritic level, and for andesite samples, LREE 62–16 × chondritic level, HREE 30–10 × chondritic level. The

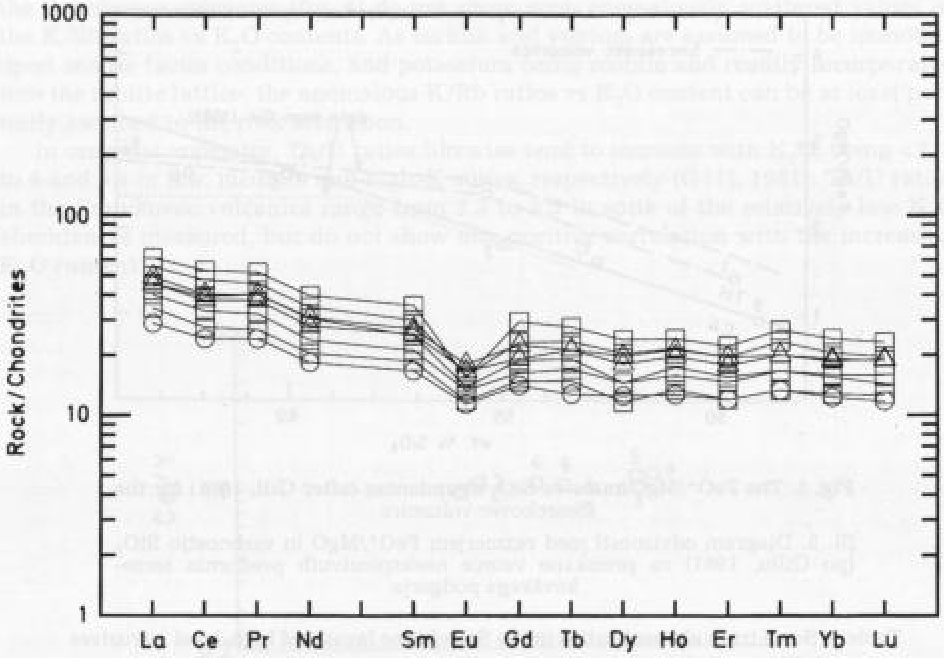

Fig. 6. The chondrite normalised (after Nakamura, 1974) REE patterns of the Smrekovec volcanics

Sl. 6. Razporeditev prvin redkih zemelj normalizirana na vsebnosti v hondritih (po Nakamuri, 1974) za preiskane vzorce neeksplozivnih predornin smrekovškega podgorja

REE distribution is very consistent for the whole suite and shows pronounced negative Eu anomaly (table 4). La/Yb ratios (table 4) are very low compared with the values for orogenic andesites (Gill, 1981; Lopez – Escobar et al., 1977; Poka, 1988; Panto, 1981), indicating limited REE fractionation.

Relatively flat REE chondrite-normalised patterns and a pronounced negative Eu anomaly (>10%) are not common in andesites (Gill, 1981; Lopez - Escobar et al., 1977), but are rather characteristic of tholeiites (Herrmann, 1972; Condie, 1982; Kay & Hubbard, 1978).

Although a petrogenesis of the Smrekovec volcanics is far beyond the scope of this work, and the available data rather insufficient, some general statements can be suggested. As plagioclases in residue mainly deplete the melt in Sr and Eu (Hanson, 1978), this model can be applied as an option in the case of the Smrekovec volcanics. Some dykes encountered in the Smrekovec volcanic complex are composed almost exclusively of feldspars and could therefore represent late-stage emplacements of the mentioned residual magmas. Some additional fractionation of potassium feldspar would, besides Sr and Eu, contribute to a depletion of K and Ba in the melt relative to the parent. Since REE distributions are very similar for the whole Smrekovec volcanic suite, the above mentioned feldspar fractionation would explain the anomalous K/Rb, Ba/Ta and Ba/La ratios observed.

Description of lithofacieses

Recognition of lithofacieses in the Smrekovec volcaniclastic deposits is far from simple. One of the reasons is the scarcity of outcrops due to an abundant vegetation cover, and a furtheron the complex fragmentation and resedimentation process going on in submarine depositional environment.

Mioč et al. (1986) already stated, that stratified sequences of volcaniclastic rocks encountered in the Smrekovec volcanic complex, actually represent turbidity current deposits. Field observation and detailed microscopic inspection encompassed in the present study indicate that volcaniclastic turbidite deposits vastly predominate in the area.

During the recognition, description and classification of the Smrekovec volcaniclastic deposits contemporary approaches from the works of Fisher and Schmincke (1984), Cas and Wright (1987) and Mc Phie et al. (1993) were taken into account. The lithofacieses of volcaniclastic deposits were subdivided into four main groups:

lithofacieses of autoclastic deposits and resedimented hyaloclastite deposits
lithofacieses of pyroclastic deposits (?)
lithofacieses of volcaniclastic debris flow and turbidite ash flow deposits
lithofacieses of reworked turbidite ash flow deposits

Lithofacieses of autoclastic deposits and resedimented hyaloclastite deposits

Autoclastic fragmentation is closely related to chill and quench processes when lavas enter an aqueous medium or move on a surface composed of water-saturated sediments (Cas & Wright, 1987; Fisher & Schmincke, 1984). Through such non-explosive fragmentation, autobreccias are formed (Mc Phie et al., 1993). Another group of autoclastic rocks are hyaloclastites, encompassing clastic aggregates developed by non-explosive fracturing and disintegration of quenched lavas (Honnorez & Kirst, 1975; Yamagishi, 1987), or parts of intrusions on contacts with wet, unconsolidated host sediments, the so-called intrusive hyaloclastites (Mc Phie et al., 1993).

Lithofacies Hb – hyaloclastite breccia

Marginal parts of the the Smrekovec coherent volcanic bodies were commonly affected by non-explosive fragmentation. Hyaloclastite breccias are related to fragmented lava flows – lithofacies Hb(l), and high-level intrusives – lithofacies Hb(i).

Lavas were readily fragmented when extruded into the submarine environment (plate 1, fig.1). The lava-sediment basal contacts, observed on a microscopic scale, show smooth and curviplanar boundaries; very frequently no obvious mixing of lava and sediment is present. Brecciated lateral and frontal parts of lava flows are composed mainly of larger hyaloclasts, amounting up to 20 cm in diameter. This juvenile lava hyaloclasts are blocky, with curviplanar and sometimes resorbed surfaces; vesiculation is very uncommon.

In the upper parts of lava flows, autobreccias might be developed. Autoclasts are locally slabby, flow foliated and have jagged ends.

Lateral and front parts of lava flows may contain minor amounts of matrix, consisting of finer-grained hyaloclastites and admixed underlying volcaniclastic sediment. Alteration upon zeolite facies conditions is common. Ocassionally, perlite fracturing is developed due to early hydration processes in the glassy groundmass. Plagioclases of hyaloclasts are readily replaced by fine-grained aggregates of albite and the groundmass is altered to microcrystalline quartz, chlorite, mixed-layered clay minerals and opaque oxides. Zeolites, predominantly laumontite, occur as interstitial fillings and vein minerals, rarely they also replace fine-grained clayey matrix of hyaloclastite breccias.

High-level intrusive bodies are appreciably more abundant among the Smrekovec coherent rocks. They commonly occur in subaqueous settings when the lithostatic pressure of sedimentary cover exceeds the confining pressure of ascending magma (Cas & Wright, 1987; Mc Phie et al., 1993). In such case, magma intrudes into the pile of sedimentary cover as syn-volcanic sill or feeder dyke. Sudden and intensive heat transfer leads to autoclastic fragmentation, which is particularly pronounced in marginal parts of intrusive bodies.

Hyaloclastite breccias related to high-level intrusive bodies are encountered on the top of Komen, as well as in its southern and northern slopes. Autoclasts range in sizes from a few dm to some tenths of mm. The sandy fraction, along with an extensively developed interstitial cement, forms the matrix of hyaloclastite breccias (plate 1, fig. 2). Autoclasts are blocky and commonly show curviplanar surfces similar to those produced in frontal and lateral parts of lava flows.

Authigenic mineralisation under zeolite facies conditions is particularly pronounced in hyaloclastite breccias (plate 1, fig 2), related to high-level intrusions. Primary constituents may be completely replaced by secondary minerals: plagioclases by albite, prehnite, laumontite, pumpellyite or analcime, and the glassy groundmas most commonly by chlorite or interlayered chlorite/smectite, microcrystalline quartz, sphene and albite. Laumontite, prehnite, analcime and thomsonite are fairly abundant minerals infilling pore space and crack systems.

Lithofacies Hv – hyaloclastites

Quench fragmentation of lavas and high-level intrusive bodies due to chilling effects of cooling marine water or water-saturated enclosing sediments may be very efficient producing sand- and granule-sized grains. Hyaloclasts are essentially non-vesicular glassy particles with a distinctly angular shape and curviplanar surfaces (Fisher & Schmincke, 1984; Cas & Wright, 1987; Mc Phie et al., 1993). Hyaloclastites developed "in situ" are strictly monomict and are neither internally organised nor stratified (Yamagishi, 1987; Honnorez & Kirst, 1975). Resedimented hyaloclastites may be internally graded and polymict.

In situ hyaloclastites developed in the Smrekovec volcanics are localised in close vicinity of lava flows and high-level intrusives. They are mainly monomict, although they may contain very small amounts (up to 8 vol.%) of lithics and pumice. Hyaloclasts are angular (plate 2, fig. 1), with curviplanar surfaces, glassy with very scarce plagioclase phenocrysts and predominanty non-vesicular. A texture of flow foliation in individual hyaloclasts is not uncommon. In many examples the glass is perlitic.

Reworked hyaloclastites occur in some cm to a few dm thick, ungraded layers, but they differ from in situ hyaloclastites in much higher content of the admixted component. Pumice may be particularly abundant attaining up to 40 vol.% of the bulk rock. Resedimented hyaloclastites are fairly eroded. Some scarce, erosional remnants are to be found on the top of the mountain range from Komen to Smrekovec, but also along the southern and northern slopes of the mountain range, at a distance of about 1 km from the mountain peaks. The layers have a declination angle of approx. 25°. Most commonly, resedimented hyaloclastites originate from glassy acid andesite lava flows (table 1, sample 8). Pumice lapilli of similar composition, encountered in resedimented hyaloclastites indicate the lavas possibly followed explosive eruptions, producing pyroclastic deposits.

In situ hyaloclastites are commonly altered upon hydrothermal and contact metamorphic conditions to contain laumontite, albite and quartz are the most pronounced new-formed minerals. In resedimented hyaloclastites clinoptilolite and heulandite are abundantly developed; along with smectite and crystobalite they replace volcanic glass in hyaloclasts, pumice and fine-grained matrix.

Lithofacies Bp – peperitic breccias

Upon an intrusion of magma into wet, unconsolidated sediments, quenched debris may be dynamically mixed with the enclosing sediment. As interstitial water in sediments boils due to magma intrusion, the dispersal of hyaloclasts by fluidisation occurs (Kokelaar, 1982; Cas & Wright, 1987; Mc Phie et al., 1993). Such mixtures of quenched debris with the enclosing sediments are called peperites or peperitic breccias (Cas & Wright, 1987).

Peperitic breccias developed in the Smrekovec volcanic complex are related to intrusions of high-level intrusives. They outcrop on the southern flanks of Krnes, W of the farmhouse Kugovnik and somewhat southwards, near the farmhouse Atelšek. The interpretation of rock formation was given by Jocelyn McPhie and Ray Cas (pers. comm.) during their visit to the Smrekovec mountains in September 1996.

Peperitic breccias consist of blocky clasts, characteristic of hyaloclastites, and matrix, composed of fine-grained volcaniclastic sediments (plate 1, fig. 3; plate 2, figs. 2, 3). The blocky clasts are composed of glassy acid andesite, with a fairly common perlitic texture (plate 2, fig. 3). The contacts of blocky clasts and sediment locally indicate that resorption and alteration processes were not uncommon. Clasts are essentially non-vesicular and sometimes show the texture of flow foliation.

The alteration mainly affected blocky clasts whereas the matrix remained poorly altered. Zeolites – most abundantly laumontite – replace volcanic glass and infill microfissures. The associated authigenic minerals are albite, prehnite, sphene, quartz, chlorite and interlayered clay minerals.

Lithofacies Vp – peperites

Peperites are mixtures of lavas and the enclosing sediment (plate 3, figs. 1, 2). Autoclasts commonly have patchy or globular forms and are very commonly altered to such an extent that their origin became obscured. The alteration is related to hydration reactions and intensive heat transfer from still hot autoclast to the surrounding sediment. It is characteristic of this type of alteration that it affected only autoclasts whereas the sediment remained fairly unaltered. Very common secondary minerals replacing autoclasts in peperites are zeolites.

Lithofacieses of pyroclastic deposits

Pyroclastic deposits should have both, distinct pyroclastic composition and the mode of transport (Cas & Wright, 1987). In the Smrekovec volcanic complex, pumice-rich tuffs of acid andesitic to dacitic composition are locally encountered (plate 3, fig. 3). However, there is no clear evidence of pyroclastic mode of transport and sedimentation, and the abundance of pumice lapilli only is not an evidence sufficient for the recognition of the origin of rocks. Some pumice-rich deposits occur in the sequences of volcaniclastic turbidity flow deposits (fig. 7). In comparison with a typical pyroclastic flow deposit, they lack of cross-bedded fine-grained unit; the coarse-grained unit can be massive or fainty stratified. The upper unit consists of a

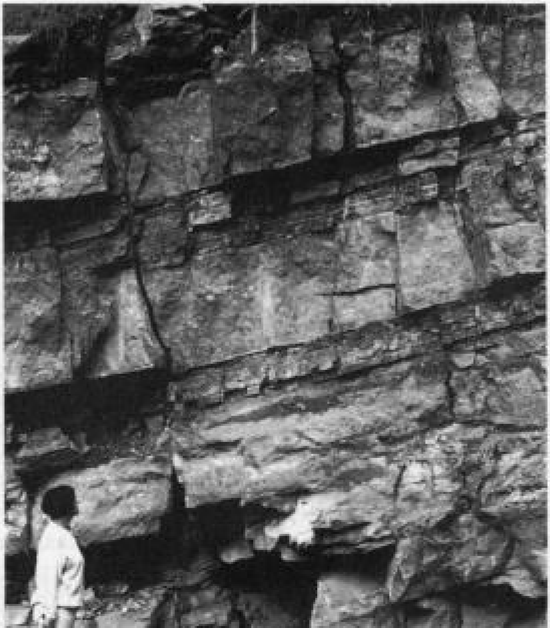

Fig. 7. Pyroclastic flow deposits (?) sealed in a sequence of volcaniclastic turbidity flow deposits, southern slopes of Krnes. Pyroclastic flow unit (?) can be seen in the lower left half of the photo

Sl. 7. Piroklastiti (?) med zaporedjem vulkanoklastičnih turbiditov z južnega pobočja Krnesa. Plasti piroklastitov se vidijo na spodnji levi polovici slike

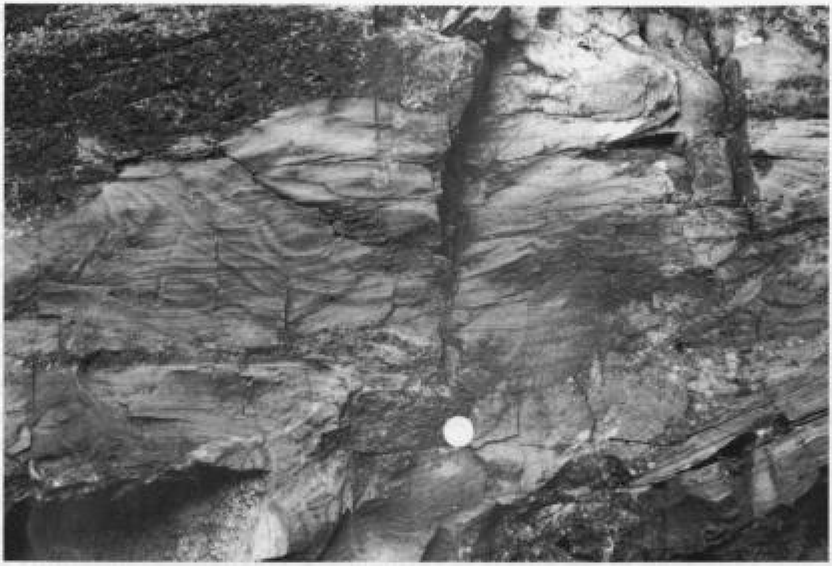

Fig. 8. Disturbed, fine-grained, horizontally an vaguely laminated tuffs, the upper pyroclastic flow (?) unit. A detail from the previous photo

Sl. 8. Porušeni, vzporedno in vijugavo laminirani drobnozrnati tufi v vrhnjem delu piroklastitov. Detajl iz prejšnje slike

fine-grained tuff, horizontally or vaguely laminated (fig. 8). The coarse-grained tuff contains tube pumice of coarse sand- to granule-size; the matrix is subordinate in occurrence and glass shards can not be recognised due to alteration processes. The deposit does not show lenticular geometry. It closely resembles subaqueous volcaniclastic mass-flow deposits (after McPhie et al., 1993). The flow very possibly started as a pyroclastic flow, and was converted to a volcaniclastic mass-flow during its movement in the submarine environment.

Lithofacieses of volcaniclastic debris flow and turbidity ash flow deposits

Volcaniclastic deposits formed by the settling of volcaniclastic debris flows and turbidity ash flows are particularly widespread on the southern slopes of the mountain range. Turbidity ash flow deposits overlie volcaniclastic debris flow deposits and are internally stratified, building fining-upward sedimentary sequences. In the vicinity of Komen, Krnes and Smrekovec peaks, volcaniclastic deposits comprise a considerably larger proportion of volcaniclastic debris flow deposits – often over 75 percent of the total sequence. At a distance of about 2–4 km from the top of the mountain range, volcaniclastic debris flow deposits become much thinner and may even be absent. The proportion of volcaniclastic debris flow deposits decreases to 50 percent or less of the total sequence. In these more distal settings, reworked turbidite deposits are also encountered.

The material contained in volcaniclastic deposits is mainly of autoclastic, subordinately of pyroclastic origin, and may be rather heterogenous according to the texture, composition and stage of alteration.

Lithofacies Bx – polymict volcaniclastic breccia with mud clasts

Polymict volcaniclastic breccia is abundantly encountered in the vicinity of the present outcrops of coherent volcanic rocks near the top of the Komen-Krnes-Smrekovec mountain range. It commonly occurs in the form of tabular bodies, attaining a thickness of a few metres to over ten metres.

The deposits are massive, containing angular fragments of coherent volcanics and rounded or angular clasts of mudstone, set in a coarse-grained tuffaceous matrix (fig. 9). The largest fragments may attain up to 5 dm in diameter, but usually they do not exceed 2 dm. The shape and size of larger coherent rock clasts indicate that they probably originate from hyaloclastite breccias and autobrecciated lavas. Juvenile material is very scarce in occurrence.

The tabular geometry of polymict volcaniclastic breccias suggest that they are deposits of cohesive volcanic debris flows or lahars. They could have been triggered by volcanic explosions or the effects of earthquakes, gravitational instability on the surface of repose or some larger-scale tectonic displacements. Volcaniclastic debris flows must have been the instrumental in the generation of turbidity ash flows. In

Fig. 9. Turbidite ash deposits; southern slopes of Komen. Horizontally stratified division – lithofacies T(h), overlain by volcaniclastic debris flow deposits, lithofacies Bx

Sl. 9. Sedimenti turbiditnega toka; južno pobočje Komna. Nad vzporedno plastovito enoto litofaciesa T(h) leže sedimenti vulkanoklastičnega debritnega toka litofaciesa Bx volcaniclastic sequences, polymict volcanic breccia commonly overlies turbidite ash deposits and comprises eroded clasts of mudstones from the uppermost turbidite ash division. Due to a lower velocity of volcaniclastic debris flow in relation to the turbidity current, the turbidite ash flow deposits underlie the deposits of volcaniclastic debris flow they evolved from (fig. 9).

Lithofacies Bt – volcaniclastic tuff-breccias

The rocks of this lithofacies type are also related to basal parts of the fining-upward sequences of turbidite ash flow deposits (fig. 10). The bed thickness varies from under 2 dm up to 4 m, but most commonly it ranges between 3–12 dm. The rock structure is massive and the basal contacts erosional. The main constituents are angular fragments of coherent volcanic rocks of diverse origin whereas pumice lapilli are subordinate in occurrence and may locally amount to up to 20% of the bulk rock composition. The matrix is sandy and with respect to the composition closely related to the coarser fraction. Fines are subordinate in occurrence; the rock is mainly grain-supported.

Lithofacies Tv(h) – horizontally stratified coarse-grained tuffs

The rocks of this lithofacies type are fairly widespread in occurrence throughout the Smrekovec volcanic complex. In well developed turbidity sequences, the division

Fig. 10. Distal volcaniclastic turbidite flow deposit; Primož, north-west of Ljubno. Each sedimentary cycle consists of lithofacieses Bt, T(h), F(h), F(v) and F(m)

Sl. 10. Distalni sedimenti vulkanoklastičnega turbiditnega toka; Primož nad Ljubnim. Vsak sedimentacijski ciklus sestoji iz litofaciesa Bt, T(h), F(h), F(v) in F(m) of horizontally stratified coarse-grained tuff overlies massive tuff-breccias of lithofacies Bt (fig. 10). The thickness of the coarse-grained tuff division is approx. 0.1–5 m. It may comprise several (over fifty) graded units, 1–20 cm thick. Very commonly one bedding set is composed of distinct subsets, defined by faint stratification. Gradation is for the most part normal. The tuffs vary, according to grain size, from very coarse, granule-rich varieties, to tuffs comprising a fair amount of fine ash.

Coarse-grained tuffs are mainly composed of angular rock fragments of diverse composition, texture and stage of alteration. Some sequences are characterised by the occurrence of pumice which may amount to up to 20% of the bulk rock composition, but glass shards are fairly uncommon. The tuffs are predominantly grain-supported; fine-grained matrix, if present, is subordinate and may consist of glassy ash or tuffitic material. Examples of pronounced cementation can be found. Zeolites are the most common cementing minerals that infill interstitial fillings and replace fine-grained matrix.

Lithofacieses F(h) and F(v) – horizontally laminated and vaguely laminated fine-grained tuffs

The deposits of this litofacies type occupy the uppermost parts of the turbidity sequence and are interpreted as deposits from dilute suspensions, trailing the turbidity currents. The lamination is fairly commonly diffuse. In the more ideally developed sequences, the horizontally and vaguely laminated rocks may attain a thicknes of 1–5 dm; syn-sedimentary structures of slumping and sliding occur locally.

Lithofacies F(m) – massive fine-grained tuffs

Massive fine-grained tuffs occupy the top position in turbidite ash deposits. The thickness varies between a few mm and 25 cm. In near-source deposits they may be absent, but in distal parts they are very common (fig. 11).

Lithofacieses of reworked turbidite ash deposits

Reworked, fine-grained turbidite ash deposits locally overlie distal, fine-grained turbidite ash deposits. They are related to shallower, possibly shoreline environment, indicated by cross-stratification, bioturbation, mud drapes and abundant organic matter. Compositionally they contain some non-volcanic component, very possibly originating from Upper Oligocene siltstones and mudstones.

Lithofacies Sv(m) – massive tuffaceous sandstones

The occurrence of massive tuffaceous sandstones is scarce. According to their grain-size, they range from fine-grained sandstones to silty sandstones. Locally they are bioturbated. The composition indicates some admixture of non-volcanic material – mainly illite and quartzite, derived from Upper Oligocene clastic sediments.

Fig. 11. Turbidite ash deposits alternating with reworked turbidite ash deposits; Primož, north-west of Ljubno

Sl. 11. Sedimenti turbiditnega toka, ki se menjavajo z lokalno presedimentiranimi sedimenti turbiditnega toka; Primož nad Ljubnim

Lithofacies Sv(t) – through-cross stratified tuffaceous sandstones

The deposits of this lithofacies type are related to distal settings. They overlie the horizontally and vaguely laminated fine-grained tuffs of lithofacies types F(h) and F(v). With respect to the grain-size, fine-grained sandstones and silty sandstones predominate.

The most common bedforms are antidunes and dunes (fig. 12). According to Cas & Wright (1987) antidunes are deposited by unidirectional current flows characterised by progressively increasing velocity. Many of the antidune and dune bedforms have thin mud drapes (fig. 12).

Mineral composition of the cross-stratified division indicates a partial incorporation of non-volcanic material, characterised mainly by the presence of illite and detritial quartz.

Lithofacies M – massive tuffaceous mudstones

Massive tuffaceous mudstones of reworked deposits are characterised by mixed, volcanic and non-volcanic mineralogy and local abundance of organic matter.

Fig. 12. Reworked turbidite ash deposits, through cross-stratified sandstone unit – lithofacies Sv(t); Primož, north-west of Ljubno

Sl. 12. Lokalno presedimentirani sedimenti turbiditnih tokov, litofacies navzkrižno plastovitega peščenjaka Sv(t); Primož nad Ljubnim

The succession of volcaniclastic deposits related to the settling from turbidite ash flows

Volcaniclastic deposits related to the settling from turbidity ash flows are organised in sequences comparable to Bouma's sequence for turbidites (Bouma, 1962; Cas, 1979). An ideal sequence comprises massive, coarse-grained basal layer (division a), planar stratified coarse sand (division b), wavy and ripple cross-laminated sand (division c), laminated mud and silt (division d) and massive mud (division e).

The development of a volcaniclastic turbidite sequence, encountered in the Smrekovec volcanic complex, is closely related to the distance of the deposition site from the assumed source. The main present outcrops of coherent volcanics on the mountain range top must have been located close to the source of turbidity currents. A widespread occurrence of polymict volcaniclastic breccias deposited from volcaniclastic debris flows or lahars in the vicinity of coherent volcanics also indicates a position was close to the source.

Turbidite ash deposits situated closer to the source (fig. 13) comprise coarser-grained massive tuff-breccias (lower division a, lithofacies Bt), horizontally stratified, coarse-grained tuff (division b, lithofacies T(h)), and laminated mud and silt (division d, lithofacieses F(h) and F(v)). The upper finely-grained unit (division d) is commonly missing. The stacking of sedimentation units results in the formation of amalgamated turbidites. Slumping and sliding structures are fairly common.

Distal turbidite deposits (located approx. 3–4 km further to the south-west are thinner, sometimes lacking the coarser-grained layers (division a).

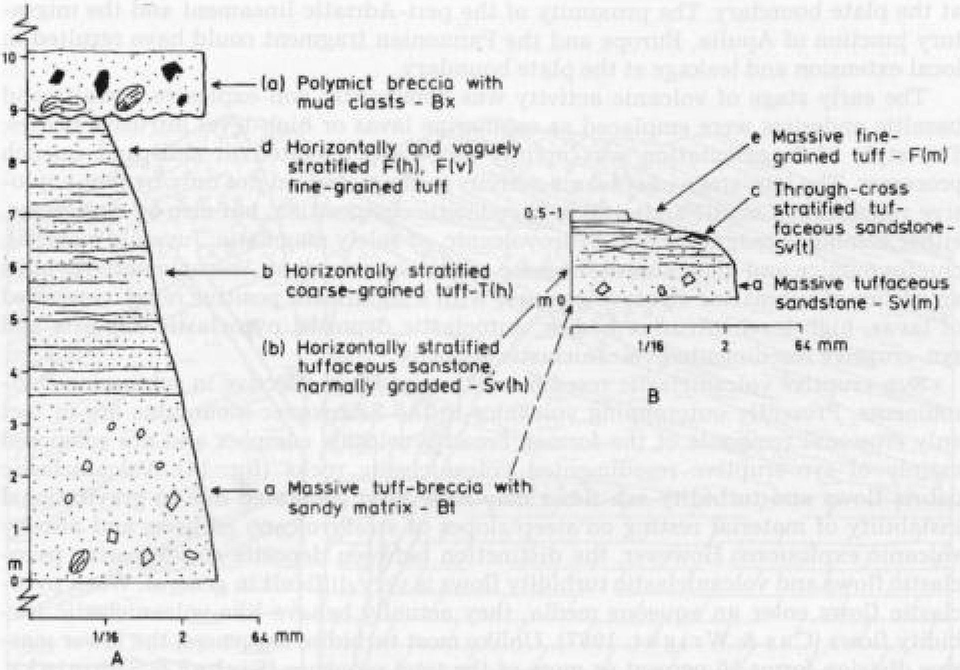

Fig. 13. Simplified graphic log of the Smrekovec volcaniclastic debris flow and turbidite ash deposit: A, proximal deposits and B, distal deposits interbedded with reworked turbidite deposits

Sl. 13. Shematski profil prek skladovnice sedimentov vulkanoklastičnega debritnega toka in vulkanoklastičnih turbiditnih tokov: A, sedimenti proksimalnih območij in B, sedimenti distalnih območij, mešani s presedimentiranimi turbiditi

Facies model of the Smrekovec volcaniclastics

The Upper Oligocene Smrekovec volcanic activity is recorded by the occurrence of coherent volcanic rocks, autoclastic deposits, volcaniclastic deposits and reworked volcaniclastic deposits. Among recently outcropping volcanics, volcaniclastic debris flow and turbidity ash flow deposits predominate. Among coherent volcanic rocks, high-level intrusive bodies are far more abundant than lavas.

Early magmas were of basaltic composition, extruding as submarine lava flows or forming high-level intrusive bodies. The chemical composition of trace elements, particularly of rare earths, indicates that basaltic magma most probably underwent a differentiation due to crystal fractionation. Consequently, basaltic andesites, acid andesites and finally rhyodacites evolved in time, forming a volcanic suite. Major element composition is slightly modified due to hydrothermal activity, but trace element proportions and REE distribution in the Smrekovec coherent volcanics of intermediate composition are not very characteristic of orogene andesites. For this reason the tectonic setting still remains ambiguous and may also be related to a setting different from convergent plate boundaries. The andesite and dacite occurrence in central California (Dickinson & Snyder, 1979 a, b) was attributed to local extension at the plate boundary. The proximity of the peri-Adriatic lineament and the migratory junction of Apulia, Europe and the Pannonian fragment could have resulted in local extension and leakage at the plate boundary.

The early stage of volcanic activity was dominantly non-explosive. Basalts and basaltic andesites were emplaced as submarine lavas or high-level intrusive bodies. The style of fragmentation was mainly autoclastic, related to chill and quench processes. The late-stage of volcanic activity is characterised not only by non-explosive volcanism of acidic andesitic to rhyodacitic composition, but also by explosions, either combined magmatic and hydrovolcanic, or solely magmatic. Juvenile material, chiefly pumice and glass shards, became relatively abundant. Volcanic activity built an edifice of submarine stratovolcano(es) with a significant positive relief, composed of lavas, high-level intrusive bodies, autoclastic deposits, pyroclastic deposits and syn-eruptive resedimented volcaniclastic deposits.

Syn-eruptive volcaniclastic resedimentation is rather effective in submarine environments. Presently outcropping volcanics in the Smrekovec mountains are in fact only erosional remnants of the former, broader volcanic complex and are composed mainly of syn-eruptive resedimented volcaniclastic rocks (fig. 14). Volcaniclastic debris flows and turbidity ash flows may have been generated due to gravitational instability of material resting on steep slopes of stratovolcano edifices, and also by volcanic explosions. However, the distinction between deposits of submarine pyroclastic flows and volcaniclastic turbidity flows is very difficult in general. When pyroclastic flows enter an aqueous media, they actually behave like volcaniclastic turbidity flows (Cas & Wright, 1987). Unlike most turbidite sequences, the lower massive division forms 50 percent or more of the total sequence (Fisher & Schminke, 1984). As single pyroclastic flow deposit commonly reaches several tenths to several hundred metres in thickness (Cas & Wright, 1987; Fisher & Schmincke, 1984).

The composition of Smrekovec volcaniclastic rocks is characteristically polymict. The main constituents are lithics which show strong affinity to the Smrekovec coherent volcanics and their autoclastic deposits, although textural and compositional differences may occur in the same sample; sometimes there is also a difference in their state of alteraton. For instance, it is possible to encounter in the same volcaniclastic rock sample relatively unaltered glassy fragments and lithics of high-level intrusive bodies with pumpellyite, prehnite, epidote or laumontite as authigenic minerals. Tuffs, comprising predominantly juvenile material are, very rare, and since they are fairly overgrown, it can not be established whether they have both, a demonstrable pyroclastic mode of fragmentation and transport.

In distal parts of the Smrekovec volcanic complex, turbidite ash deposits underwent a reworking process in a shallow-marine environment. in addition to minor admixtures of non-volcanic material, cross-stratification, bioturbation and mud drapes are also characteristic of rocks of this lithofacies.

Conclusions

The Upper Oligocene Smrekovec volcanic activity is recorded by the occurrence of coherent volcanic rocks, autoclastic deposits, volcaniclastic deposits and reworked volcaniclastic deposits. Besides extrusive rocks, settled in a submarine environment, high-level intrusive bodies were emplaced into unconsolidated, water-saturated volcaniclastic sediments.

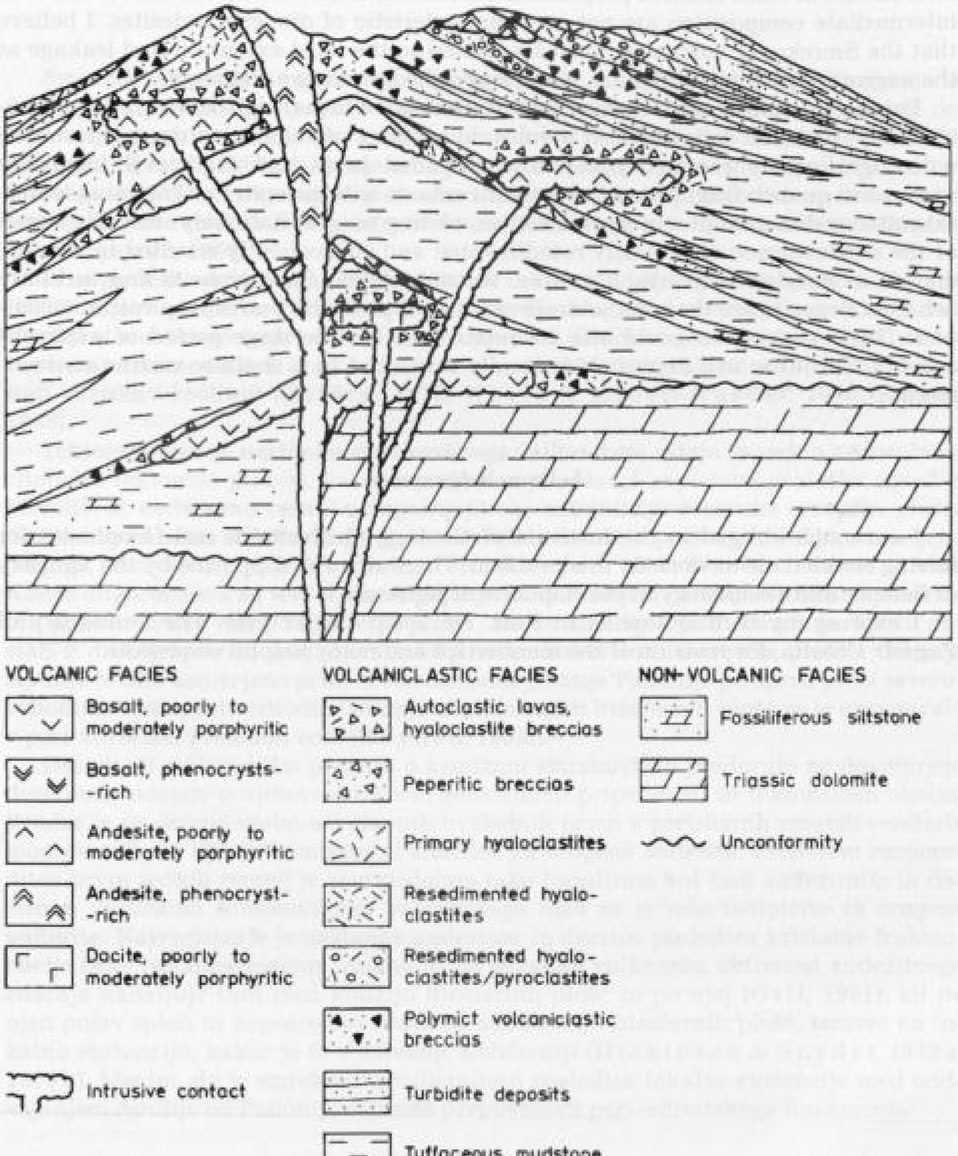

Fig. 14. Idealised facies model for the Smrekovec volcanics
Sl. 14. Idealizirani facialni model smrekovških vulkanitov

The chemical composition of coherent volcanics indicates that magmas varied with time from basaltic, basaltic andesitic and acidic andesitic to dacitic, forming a volcanic suite. Major element composition is slightly modified due to hydrothermal alteration, but trace element proportions and the REE distribution in the volcanics of intermediate composition are not very characteristic of orogene andesites. I believe that the Smrekovec volcanism must be related to the local extension and leakage at the migratory junction of Apulia, Europe and the Pannonian fragment.

During the Smrekovec volcanic activity, extruded lavas, high-level intrusive bodies and pyroclastic deposits built a volcanic complex of submarine stratovolcano(es) with significantly elevated relief. The extruded lavas and high-level intrusives underwent quench fragmentation on their contacts with seawater or enclosing water-saturated sediments. In situ hyaloclastites, resting on gravitationaly unstable slopes of the stratovolcano were easily resedimented and consequently resulted in the formation of resedimented hyaloclastites. Volcanic debris flow deposits and turbidity ash flow deposits are the most widespread rock type of the Smrekovec volcanic complex. Their generation could also be related to the late-stage period of explosive activity. Turbidite ash deposits are locally reworked in a shallow-marine environment.

Acknowledgements

I am much obliged to the Institute of Geology, Geotechnics and Geophisics for having enabled me to work on this problem. The study was supported by the Ministry of Science and Technology of the Republic of Slovenia.

I express my cordial thanks to Prof. Dr. Josip Tišljar from The University of Zagreb, Croatia, for revision of the manuscript and many helpful comments.

Litofacialne značilnosti smrekovških vulkanoklastitov (severna Slovenija)

Uvod

Smrekovško podgorje grade zgornjeoligocenske vulkanske kamnine. Raztezajo se na površini približno petnajstih kvadratnih kilometrov in predstavljajo osrednji del obsežnejšega vulkanskega pasu, imenovanega tudi smrekovška serija (Mioč, 1978, 1983; Mioč et al., 1986). Najvišje se vzpno vrhovi Komen (1684 m), Krnes (1613 m) in Smrekovec (1577 m). Zgornjeoligocenska starost predornin je določena na osnovi biostratigrafskih raziskav foraminiferne favne, vsebovane v meljastih sedimentih podlage (Rijavec, 1966).

Prvo geološko delo s tega področja datira iz konca prejšnjega stoletja, ko je Teller (1898) objavil geološko karto lista Prassberg. Po drugi svetovni vojni so tod delovali številni slovenski geologi, bodisi v okviru projekta Osnovne geološke karte I (Hinterlechner-Ravnik & Pleničar, 1967; Mioč, 1978, 1983; Mioč et al., 1986) kakor tudi raziskav zeolitov (Osterc, 1976; Kovič & Krošl-Kuščer, 1986; Kovič, 1988).

Tektonsko okolje nastanka smrekovškega vulkanizma ostaja še vedno nedorečeno. Globalni tektonski procesi, katerih posledica je sedanja zapletena geološka zgradba ozemlja, so nedvomno vezani na zgornjejursko subdukcijo oceanske evropske plošče pod kontinentalno afriško, ki pa je že v začetku terciarja prešla v kolizijo, usmerjeno od juga proti severu (Oberhauser, 1980; Royden, 1988; Dercourt et al., 1986). Konec oligocena sta za tektonsko dogajanje na današnjem ozemlju Slovenije pomembni predvsem dve manjši litosferni plošči, imenovani Apulija in Panonija, ki sta nastali z drobljenjem in spajanjem tako afriške kakor tudi evropske plošče. Gibanje Apulije je bilo usmerjeno proti severozahodu, gibanje Panonije pa sprva proti severovzhodu in nato proti vzhodu. Gibanje obeh manjših litosfernih plošč se je uravnavalo v peri-adriatski prelomni coni (Royden, 1988).

Dosedanji maloštevilni podatki o kemizmu smrekovških predornin ne dovoljujejo dorečenih sklepov o njihovem izvoru, geokemični pripadnosti in tektonskem okolju. Vendar je na osnovi vsebnosti glavnih in slednih prvin v preiskanih vzorcih vendarle mogoče reči, da njihov kemizem ni značilen za orogene andezite. Predvsem razporeditev prvin redkih zemelj je zelo podobna tako bazaltnim kot tudi andezitnim in dacitnim različkom smrekovškega vulkanskega niza in je zelo netipična za orogene andezite. Najverjetneje je nastanek andezitov in dacitov posledica kristalne frakcionacije neke bazaltne magme. Znano je, da se lahko vulkanska aktivnost andezitnega značaja nadaljuje tudi med kolizijo litosfernih plošč in po njej (Gill, 1981), ali pa njen pojav sploh ni neposredno vezan na subdukcijo litosfernih plošč, temveč na lokalno ekstenzijo, kakor je to v osrednji Kaliforniji (Dickinson & Snyder, 1979 a, 1979 b). Menim, da je smrekovški vulkanizem posledica lokalne ekstenzije med oddvajanjem Apulije od Panonije oziroma prepustnosti peri-adriatskega lineamenta.

Opis litofaciesov vulkanoklastičnih kamnin

Smrekovške vulkanoklastične kamnine so bile razporejene v štiri glavne skupine litofaciesov:

litofaciesi avtoklastičnih kamnin in lokalno presedimentiranih hialoklastitov
litofaciesi piroklastitov (?)
litofaciesi vulkanoklastičnih debritov in turbiditov,
litofaciesi lokalno presedimentiranih vulkanoklastičnih turbiditov.

Litofaciesi avtoklastičnih kamnin in lokalno presedimentiranih hialoklastitov

Avtoklastična fragmentacija je vezana na procese nenadnega ohlajanja, ko se lave izlijejo v vodo ali gibajo po površini vlažnih sedimentov (Cas & Wright, 1987; Fisher & Schmincke, 1984). Takšna neeksplozivna fragmentacija pa se pojavlja tudi na stikih plitvo ležečih intruzivov vulkanskega nivoja z okolišnimi vlažnimi sedimenti (McPhie et al., 1993). Plitvo ležeči intruzivi vulkanskega nivoja se pogosto pojavljajo v morskih okoljih tedaj, ko je teža sedimentnega pokrova in vodnega stebra večja od tlaka dvigujoče se magme (McPhie et al., 1993). Fragmentirani deli plitvo ležečih intruzivov vulkanskega nivoja se imenujejo intruzivni hialoklastiti.

Avtobrečirane lave (tabla 1, sl. 1) so med smrekovškimi predorninami sorazmerno redke. Mnogo pogosteje je mogoče najti avtoklastične kamnine intruzivnega porekla. Bolj debelozrnati različki so hialoklastične breče (tabla 1, sl. 2), ki vsebujejo hialoklaste z značilnimi, ukrivljenimi ploskvami. Osnova hialoklastičnih breč sestoji iz hialoklastičnega materiala velikosti 0.063–2.0 mm.

Hialoklastiti smrekovškega podgorja sestoje iz hialoklastov velikosti drobnih lapilov in vulkanskega pepela. Hialoklasti se od juvenilnih piroklastov ločijo predvsem po tem, da skorajda ne vsebujejo votlinic plinskih mehurčkov, oblike zrn so pogosto zelo oglate, ploskve pa ukrivljene in le malo nazobčane (tabla 2, sl. 1). Presedimentirani hialoklastiti niso strogo monomiktni, temveč vsebujejo primes plovca, ki znaša ponekod do 40 vol.%. Prav tako je v nasprotju razliko od pravih hialoklastitov, ki so notranje neorganizirani, v presedimentiranih hialoklastitih opazna plastovitost.

Hialoklastične breče, vezane na stike plitvo ležečih intruzivov z okolnimi vlažnimi sedimenti, prehajajo bočno v mešane sedimente, imenovane peperitne breče in peperiti. Peperitne breče sestoje iz hialoklastov, ki so pomešani z okolnim sedimentom (tabla 1, sl. 3; tabla 2, sl. 2, 3). Mešanje nastaja zaradi fluidizacije osnove okolnih vlažnih sedimentov, v katerih se porne vode zaradi bližine vročega intruziva močno segrejejo. Fluidizacija osnove tako omogoči disperzijo hialoklastov v okolni sediment (McPhie et al., 1993). Hkrati s fluidizacijo in segrevanjem pornih raztopin v okolnih sedimentih se pričenjajo ustvarjati lokalni hidrotermalni sistemi, ki povzročajo nastanek zeolitov. Peperiti (tabla 3, sl. 1, 2) se od peperitnih breč razlikujejo po nepravilni, krpasti ali kroglasti obliki hialoklastov (McPhie et al., 1993).

Litofaciesi piroklastitov(?)

Piroklastiti morajo vsebovati juvenilni material, hkrati pa morajo tudi jasno odražati piroklastični način transporta (Cas & Wright, 1987). Med smrekovškimi vulkaniti se pojavljajo plasti, bogate s plovcem (tabla 3, sl. 3), vendar pa teksture niso dovolj značilne, da bi jih lahko z gotovostjo opredelili kot piroklastite. S plovcem bogate plasti izdanjajo med zaporedjem vulkanoklastičnih turbiditov (sl. 7). V primerjavi z značilno zgradbo in zaporedjem sedimentov piroklastičnega toka v plasteh domnevnih piroklastitov smrekovškega vulkanskega kompleksa manjkajo spodnji, navzkrižno plastoviti deli drobnozrnatih tufov (McPhie et al., 1993). Debelozrnati tufi so masivno grajeni ali pa izražajo samo nakazano vzporedno plastovitost; zgornji deli sestoje iz vzporedno in vijugavo laminiranega drobnozrnatega tufa (sl. 8). Ti sedimenti so najverjetneje nastali s sedimentacijo iz tokov, ki so po izvoru piroklastični, vendar so se zaradi gibanja v vodnem mediju kmalu spremenili v vulkanoklastične turbiditne tokove.

Litofaciesi vulkanoklastičnih debritov in turbiditov

Vulkanoklastiti, nastali s sedimentacijo iz debritnih in turbiditnih tokov, so najbolj razširjena zvrst kamnin smrekovškega podgorja. Posebno razprostranjeni so na južnih pobočjih Smrekovca, Krnesa in Komna. Te vulkanoklastične kamnine grade skladovnice z zmanjševanjem velikosti zrn navzgor. V bližini omenjenih vrhov sestoje te skladovnice iz masivnih debritov v njihovih spodnjih delih ter iz plastovitih in laminiranih turbiditov v zgornjih delih. Debriti grade skoraj 75% celotne sekvence. V razdalji 2–4 km od gorskega grebena vrhov Smrekovca, Krnesa in Komna se zmanjša delež debritov v vulkanoklastični turbiditni sekvenci na manj kot 50%, pojavijo pa se tudi drobnozrnati sedimenti, ki so bili lokalno presedimentirani v plitvem morskem okolju.

Debriti so zastopani z masivno grajenimi vulkanoklastičnimi tufskimi brečami, ki se pojavljajo v obliki lečastih in ploskastih teles, debelih od manj kot 2 dm do največ 4 m (sl. 9). Stiki s podlago so navadno erozijski. Glavna sestavina vulkanoklastičnih tufskih breč so oglati fragmenti lave in plitvo ležečih intruzivov različne sestave, medtem ko je plovec le maloštevilno zastopan. Drobnozrnate osnove je zelo malo, zato ima kamnina pretežno klastno podporo.

Med turbiditi se pojavljajo vzporedno plastoviti debelozrnati tufi, vzporedno in vijugavo laminirani drobnozrnati tufi in masivno grajeni drobnozrnati tufi (sl. 10, 11). Sestava vulkanoklastičnega materiala je heterogena, v splošnem je vsebnost plovca nizka in le izjemoma presega 10 vol.% celotne kamnine.

Litofaciesi lokalno presedimentiranih vulkanoklastičnih turbiditov

Lokalno presedimentirani drobnozrnati turbiditi (sl. 12) so vzporedno ali navzkrižno plastovito grajeni, pojavljajo se drobne leče mulja (mud drapes), bioturbacija in ponekod tudi organska snov. Sedimenti vsebujejo tudi nevulkanogeno primes, ki najverjetneje izvira iz zgornjeoligocenskih meljevcev.

Sklep

Zgornjeoligocenski vulkanizem na Slovenskem je zapustil sledove svojega delovanja tudi na smrekovškem podgorju. Vulkanizem je deloval v morskem okolju, kjer je nastal vulkanski masiv z enim ali več stratovulkanov in izrazitim pozitivnim reliefom. Sestava magme se je zaradi frakcijske kristalizacije bazaltne taline s časom spreminjala od bazaltne prek bazaltne andezitne in kisle andezitne do dacitne in tako ustvarila vulkanski diferenciacijski niz. Tako so se v zgodnjem obdobju vulkanskega delovanja izlili na morsko dno bazalti in bazaltni andeziti. V poznem obdobju vulkanskega delovanja so prevladovali kisli andeziti in daciti, ki so se izlili kot lava ali pa so intrudirali v še nekonsolidirane vulkanoklastične sedimente; pojavljale so se tudi vulkanske eksplozije magmatskega ali mešanega magmatsko-hidrovulkanskega značaja. Robovi plitvih intruzivov in lave so se avtobrečirali in mešali z okolnim sedimentom, zaradi česar je nastal niz avtoklastičnih in mešanih avtoklastičnih-vulkanoklastičnih kamnin. Vulkanski kompleks je bil podvržen nenehni eroziji in presedimentaciji že med samim vulkanskim delovanjem. Kasnejša erozija in živahno tektonsko delovanje sta oblikovala njegovo današnjo podobo.

Zahvala

Zahvaljujem se Inštitutu za geologijo, geotehniko in geofiziko, ki mi je omogočil delo pri reševanju te problematike. Raziskave je financiralo Ministrstvo Republike Slovenije za znanost in tehnologijo.

Prisrčna zahvala velja prof. dr. Josipu Tišljarju iz Univerze v Zagrebu za recenzijo rokopisa in številne koristne nasvete.

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Plate 1 – Tabla 1

Fig. 1. Autobrecciated lava flow; SW of Komen

Sl. 1. Avtobrečirani lavini tok; jugozahodno pobočje Komna

Fig. 2. Hyaloclastite breccia; southern slopes of Krnes

Sl. 2. Hialoklastična breča; južno pobočje Krnesa

Fig. 3. Peperitic breccia; southern slopes of Krnes, westwards of the farmhouse Kugovnik

Sl. 3. Peperitna breča; južno pobočje Krnesa, zahodno od kmetije Kugovnik

Plate 2 – Tabla 2

Fig. 1. Angular hyaloclasts in a hyaloclastite from southern slopes of Krnes. Plane polarised light, magnification 14.5 ×

Sl. 1. Oglati hialoklasti v hialoklastitu z južnega pobočja Krnesa. Presevna polarizirana svetloba, povečava 14.5 ×

Fig. 2. Peperitic breccia; southern slopes of Krnes, W of the farmhouse Kugovnik. Angular, locally resorbed and flow-foliated andesite clasts in fine-grained matrix. Plane polarised light, magnification 14.5 ×

Sl. 2. Peperitna breča; južno pobočje Krnesa, zahodno od kmetije Kugovnik. Oglati, sem in tja resorbirani in zaradi tečenja poviti klasti andezita v drobnozrnati osnovi. Presevna polarizirana svetloba, povečava 14.5 ×

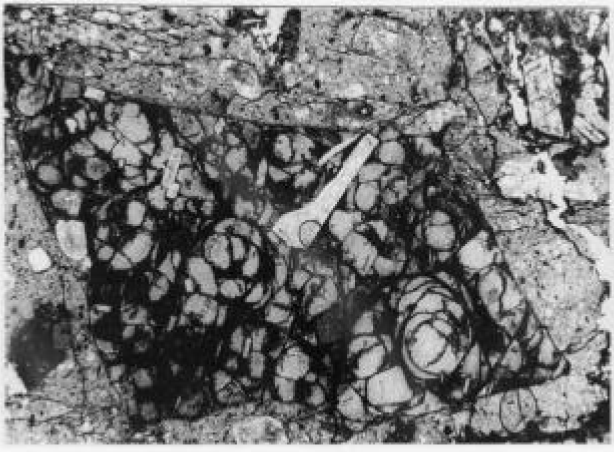

Fig. 3. Peperitic breccia; southern slopes of Krnes, near the farmhouse Atelšek. An angular clast of acid andesite composition with perlitic texture. Plane polarised light, magnification 14.5 ×

Sl. 3. Peperitna breča z južnega pobočja Krnesa, blizu kmetije Atelšek. Oglat klast kislega andezita kaže perlitsko strukturo. Presevna polarizirana svetloba, povečava 14.5 ×

Plate 3 – Tabla 3

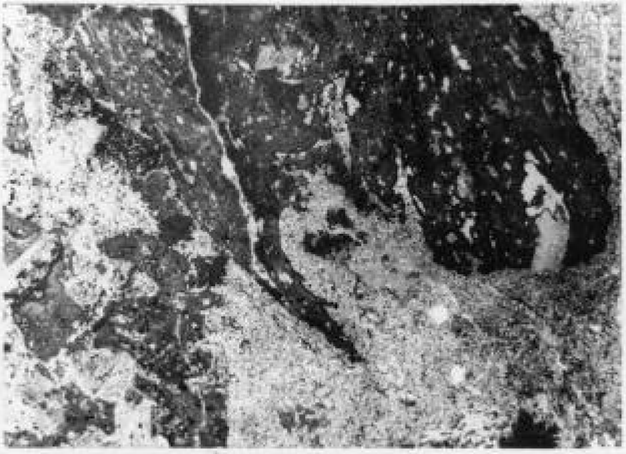

Fig. 1. Hyaloclasts of acid andesite (dark-coloured areas) set in a fine-grained matrix. Peperite; southern slopes of Krnes, westwards of the farmhouse Kugovnik. Plane polarised light, magnification 14.5 ×

Sl. 1. Hialoklasti kislega andezita (temnejši deli) v drobnozrnati osnovi. Peperit z južnega pobočja Krnesa, zahodno od kmetije Kugovnik. Presevna polarizirana svetloba, povečava 14.5 ×

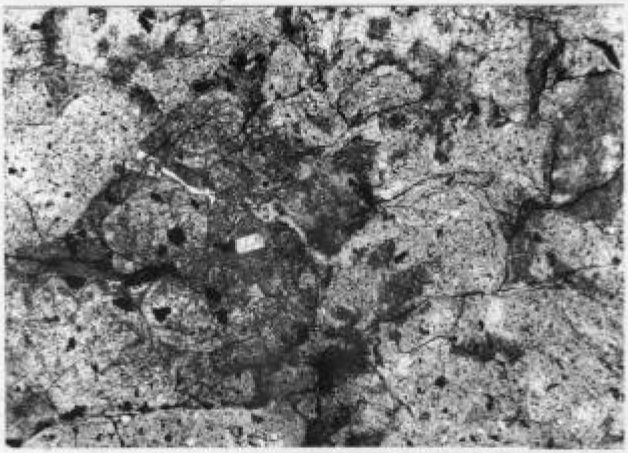

Fig. 2. Irregularly shaped hyaloclasts of an acid andesite (darker areas) set in a fine-grained matrix. Peperite; southern slopes of Krnes, westwards of the farmhouse Kugovnik. Plane polarised light, magnification 14.5 ×

Sl. 2. Nepravilne oblike hialoklastov kislega andezita v drobnozrnati osnovi. Peperit z južnega pobočja Krnesa, zahodno od kmetije Kugovnik. Presevna polarizirana svetloba, povečava 14.5 ×

Fig. 3. Resedimented(?) pumice-rich tuff; southern slopes of Krnes. Volcanic glass of a tube pumice is replaced by heulandite, quartz and smectite. Plane polarised light, magnification 14.5 ×

Sl. 3. Presedimentirani plovčev tuf z južnega pobočja Krnesa. Vulkansko steklo cevastega plovca je nadomeščeno s heulanditom, kremenom in montmorillonitom. Presevna polarizirana svetloba, povečava 14.5 ×