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Mesozoic Volcanic Activity of the Western Carpathian Segment of the Tethyan Belt: Diversities in Space and Time

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With 9 Text-Figures and 3 Tables

Slowakische Republik
Karpaten
Tethys
Vulkanismus
Petrologie
Geochemie

Contents

Mesozoischer Vulkanismus im westkarpatischen Abschnitt der Tethys: Unterschiede in Raum und Zeit

Zusammenfassung

In einem NW–SE-Querschnitt durch die westlichen Karpaten wird in verschiedenen mesozoischen tektonischen Einheiten vulkanische Aktivität in Abhängigkeit vom unterschiedlichen geodynamischen Umfeld beobachtet. Das Alter des Magmatismus erstreckt sich von der oberen Trias zur mittleren Kreide. Vulkanische Produkte beinhalten Gesteine alkalischer, tholeiitischer und kalk-alkalischer Affinität. Prozesse von kontinentalem Rifting, Zusammensetzung und Mächtigkeit der Kruste und Subduktionsprozesse bedingten die Verschiedenheiten der vulkanischen Produkte.

Abstract

In a NW–SE cross-section through the Western Carpathians, volcanic activity related to different geodynamic setting can be observed in the various Mesozoic tectonic units. The age of magmatism varies from Upper Triassic to Middle Cretaceous. Volcanic products include rocks of alkaline, tholeiitic and calc-alkaline affinity. The processes of continent rifting, as well as the composition and thickness of the crust and subduction processes caused the diversity of the volcanic products.

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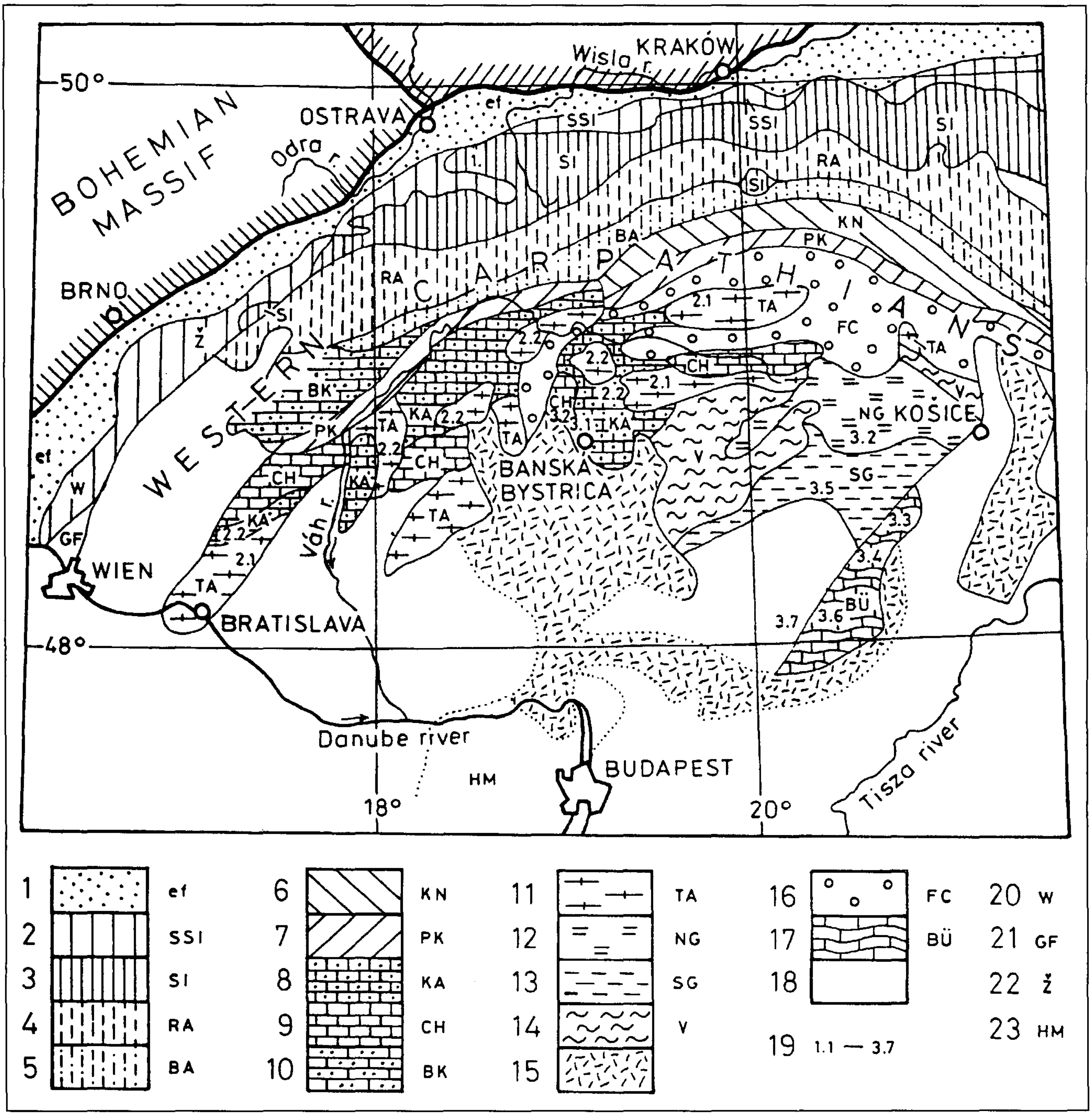
1. Introduction

In a NW–SE cross-section through the Western Carpathians of Poland, Czech Republic, Slovak Republic and Hungary a wide range of volcanic rock types outcrops in various Mesozoic units (Text-Fig. 1).

The main geological processes which caused the diversity of sedimentation in the areas under consideration are those created by the relative movements of the Apulian promontory of the African plate and the European platform on one side, and the existence of oceanic domains of various dimensions, developed in various times during the Mesozoic, on the other side. These have been discussed recently by RAKÚS et al. (1990) and DERCOURT et al. (1990).

In the following summary we adapt the generally accepted division of the Western Carpathians (in a cross-



Text-Fig. 1.
Simplified tectonic scheme of the Western Carpathians (MAHEL, 1973, adapted).
1 = Foredeep; 2 = Subsilesian and Ždanice nappes; 3 = Silesian nappe; 4 = Rača nappe; 5 = Bystrica nappe; 6 = Krynica nappe (1–6 = outer Western Carpathians); 7 = Pieniny Klippen belt; 8 = Krížna nappe; 9 = Choč nappe; 10 = Biele Karpaty nappe; 11 = Tatricum (Proterozoic (?) = Cenomanian); (7–11 = central Western Carpathians); 12 = North Gemericum; 13 = South Gemericum (12–13 = inner Estern Carpathians); 14 = Veporicum; 15 = Late Cenozoic volcanics; 16 = central Carpathians flysh; 17 = Bükk Mts.; 18 = Tertiary filling of basins; 19 = volcanics of individual tectonic units; 20 = Waschberg zone; 21 = Greifenstein zone; 22 = Ždánice unit; 23 = Hungarian Midmountains.
ef = External zone of the foredeep; ssi = Subsilesian nappe; si = Silesian nappe; RA- Rača nappe; BA = Bystrica nappe; KN = Krynica nappe; PK = Pieniny Klippen belt; KA = Krížna nappe; BK = Biele Karpaty nappe; TA = Tatrides; NG = North Gemeride nappe; SG = South Gemeride nappe; V = Vepor nappe; FC = Central Carpathian Flysh basins; BU = Bükk Mts. unit; 1.1–3.7 = Geological units (see text) with Mesozoic volcanics; W = Waschberg zone; GF = Greifenstein nappe; Ž = Ždánice unit; HM = Hungarian massif.

section perpendicular to the mountain chain) into three main tectonic zones: the outer, central and inner zones. Descriptions of the general characteristics of these zones can be found elsewhere (ANDRUSOV, 1968; BUDAY et al., 1968; SĂNDULESCU, 1975).

2. The Outer Western Carpathians

The huge allochthonous Cretaceous–Palaeogene complexes which form the backbone of the outer Western Carpathian zone contain, in addition to the predominant sedimentary flysch-type sequences, the products of volcanic activity of Hauterivian–Aptian age. The volcanics form the "teschenite-picrite" province. Together with teschenites and picrites, various types of alkaline basalts, monchiquites, ouachitites, ankaratrites, pyroxenites and others are also known from several hundreds of occurrences in the Czech Republic and in Poland.

The rock association of the Beskydy Mts. (1. on Text-Fig. 1) affected the attention of numerous authors as early as in the 19th century. HOHENEGGER (1861) introduced the name "teschenite" (Těšín: town on the Czech/Polish border; Polish: Cieszyn; German: Teschen) and TSCHERMAK (1866) introduced the name "picrite". Both names are still in use. Later on PACÁK (1926) and SMULIKOWSKI (1930) described the wide spectrum of rock types in the province.

During recent decades the teschenite-picrite association has been studied by numerous authors (ŠMÍD, 1962; MAHMOOD, 1973; GUCWA & WIESER, 1985; KUDĚLÁSKOVÁ, 1987; HOVORKA & SPIŠIAK, 1988; NARĘBSKI, 1990).

The majority of outcrops are sills: lava flows, hyaloclastites and tuffitic material are less widely distributed. Geological criteria (deformation of magmatic bodies together with surrounding sediments, absence of magmatic bodies in the main tectonic lineaments, presence of conform hyaloclastite as well as tuffite bodies etc.) allow us to consider them to be the product of synsedimentary volcanic activity in the sedimentary basin of the Silesian unit.

Volcanic activity took place within the Hauterivian and Aptian. This time span is roughly identical to the time span of volcanic activity in several Mesozoic tectonic units within the central Western Carpathian zone. Corresponding eruptives are of similar character – even though they are described under various names.

The volcanic activity of Hauterivian–Aptian age within the Silesian unit of the outer Western Carpathians took place in a within-plate environment (HOVORKA & SPIŠIAK, 1988; NARĘBSKI, 1990). The activity was synchronous with deposition of the sedimentary sequence of the Silesian unit (basin), which was situated southeast of its present-

Table 1.
Chemical composition of the main rock types from different Western Carpathian Mesozoic units.
1: Picrite (Hončova hůrka), 2: monchiquite (Kojetín), 3: fourchite (Frenštát pod Radhoštem), 4: teschenitic clinopyroxenite (Staříč) (1–4: outer Western Carpathians, [KUDĚLÁSKOVÁ, 1987]), 5: alkaline hyalobasalt (Suchá dolina, the Tatry Mts.), 6: hyalobasalt (Dumbier, the Nízke Tatry Mts.), 7: basanite (Višňové, the Malá Fatra Mts.) (5–7: HOVORKA & SPIŠIAK [1988]), 8: alkaline basalt (Rúbane, the Veľká Fatra Mts.: HOVORKA & SÝKORA, [1979]), 9: picrite (Poniky, HOVORKA & SPIŠIAK [1988]) (5–9: central Western Carpathians), 10: rhyolite (the Drienok nappe, SLAVKAY [1965]), 11: andesite (the Drienok nappe, SLAVKAY [1965]), 12: tholeiitic basalt (Jaklovce, the Meliata unit, HOVORKA & SPIŠIAK [1988]), 13: tholeiitic basalt (Szarvaskö, the Bükk Mts., BALLA et al. [1983]) (10–13: inner Western Carpathians)
The analyzed rock samples were affected by weathering processes (but all analyzed silicates were fresh). High values of loss of ignition are influenced by the presence of carbonate amygdales and carbonate xenoliths/ocelli. After the recalculation of analytical data to 100 percent volatile free, no substantial changes of the original distribution of the oxids occur. This has been proved by the "homogeneous" character of selected trace elements in discriminant diagrams in Text-Fig. 8. High loss of ignition in the rocks of this type has been documented within the whole Alpine-Carpathian belt (TROMMSDORF et al., 1990).

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	37.10	39.30	32.80	38.56	40.84	40.61	38.70	36.66	34.06	77.23	59.60	49.00	49.47
TiO_2	2.15	2.95	3.85	2.30	3.65	2.62	2.92	2.54	1.34	0.16	0.83	1.37	1.86
Al_2O_3	11.60	13.50	11.15	14.90	11.99	12.15	11.62	10.22	5.72	12.02	15.16	15.50	15.05
Fe_2O_3	6.05	4.95	11.34	7.95	8.57	3.91	6.51	1.81	6.75	1.46	5.73	2.28	3.70
FeO	5.03	5.75	6.61	6.02	6.31	6.48	7.04	7.25	3.93	0.09	2.69	6.35	7.60
MnO	0.18	0.17	0.31	0.18	0.18	0.16	0.16	0.14	0.12	0.41	0.09	0.17	0.19
MgO	17.20	7.80	6.70	6.08	10.25	10.51	7.81	9.50	22.26	0.41	0.28	7.05	5.98
CaO	12.20	11.20	13.45	13.32	11.07	11.04	14.72	14.90	9.05	0.48	4.09	8.90	8.43
Na_2O	0.75	2.15	2.30	1.90	2.10	1.58	2.13	2.25	0.41	0.96	2.62	4.15	4.28
K_2O	0.55	2.05	1.80	2.33	0.36	1.16	1.43	0.59	0.92	4.92	2.30	0.54	0.10
P_2O_5	0.65	0.70	2.85	0.43	0.22	0.59	0.94	0.76	0.74	0.03	0.24	0.18	0.22
LOI	6.50	9.00	6.45	5.90	3.96	8.76	5.96	12.82	13.94	1.57	6.04	3.10	6.85
Ba	-	1350	700	800	185	910	660	450	980			63	50
Sr	-	950	1250	-	370	219	450	320	680			159	160
Sc	-	18.7	11.8	12.9	24	42	10	23	20			30	44
Hf	-	7.5	8.9	-	-		-	-	-			-	4.2
V	80.0	15	75	65	126	126	107	101	-			330	316
Cr	752	193	29	95	200	550	162	288	680			239	380
Co	70	38	34	32	41	50	32	30	96			42	47
Ni	550	102	37	120	182	170	98	170	780			145	234
La	50	82	105	53	49	32	39	30	54			4.2	4.6
Ce	102	160	222	134	135	78	100	78	101			16.7	19
Nd	43	78	144	60	-	-	-	-	46			13.2	10.5
Sm	7.3	13	24	9.9	9.6	5.4	7.0	5.6	10.3			4.1	4.0
Eu	2.6	4.4	6.9	3.7	3.2	2.5	3.0	2.5	2.6			1.6	1.91
Tb	0.92	1.58	2.25	1.1	2.1	0.92	1.6	1.2	-			1.4	1.1
Ho	0.95	1.80	2.80	1.4	-	-	-	-	-			1.30	-
Tm	1	1	1	5.0	4.8	2.5	4.6	3.6	-			0.64	0.85
Yb	2.10	2.10	2.80	2.10	2.2	2.0	2.2	1.9	1.3			5.0	3.8
Lu	0.31	0.35	0.30	1	0.28	-	0.22	0.22	0.18			0.92	0.71
Gd	-	10.6	15.5	8.9	-	-	-	-	6.82				

day position. The volcanic bodies underwent tectonic transport together with neighbouring sediments of psammite-pelite flysh character.

The primary geotectonic process which caused this volcanic activity was short-term rifting of the continental crust (GUCWA & WIESER, 1985; HOVORKA & SPIŠIAK, 1988; NARĘBSKI, 1990).

Opinions as to the character of the parental magma to the teschenite-picrite suite differ. NARĘBSKI (1990) came to the conclusion that two independent parental magmas existed:

a) tholeiitic (subalkaline) and
b) teschenitic.

This was based mainly on geochemical arguments. Evidence for the intensive and widespread assimilation of carbonate rock in the petrogenesis of the magmas has been evaluated recently by the authors (HOVORKA & SPIŠIAK, 1988). Partial melting of the upper mantle took place under Pt conditions of spinel peridotite stability. Based on the degree of partial melting and amount of subsequent fractional crystallization, two main magma types can be distinguished: alkaline olivine basalts s.l. and picrites (HOVORKA & SPIŠIAK, 1988).

Fractional crystallization within secondary magma chambers located in the continental crust strongly modified the composition of rising magmas.

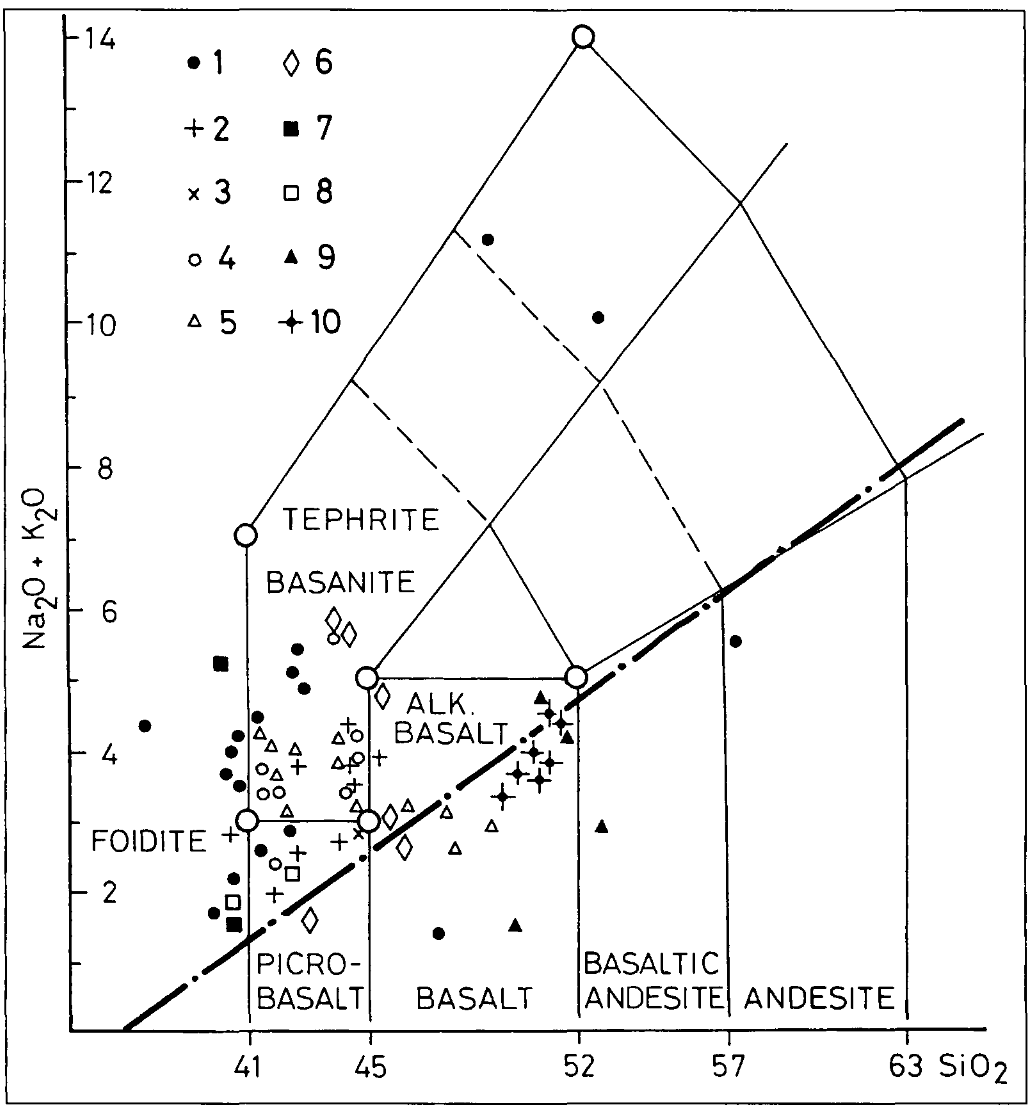
In contrast to NARĘBSKI (1990) we demonstrated the pronounced alkaline character of the whole-rock association. This statement is based on:

a) the REE patterns of the main rock types (Text-Fig. 9),
b) the composition of pyroxenes (Text-Fig. 4) is characteristic for the rocks of alkaline suites,
c) the presence of nepheline and sometime also analcime in the groundmass of some rock types allows their classification as an undersaturated rock sequence,
d) all analytical data (rock and mineral composition, Table 2) together with the results of numerous thin-section studies enable the authors to identify processes of assimilation (of carbonate rocks) as one of the processes leading to the origin of a varied spectrum of volcanic/subvolcanic rock types.

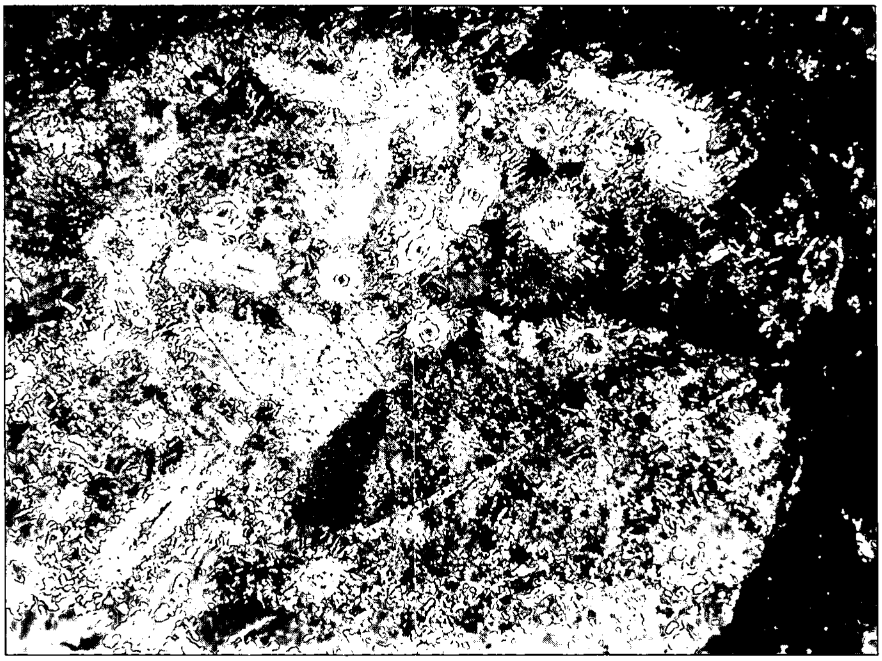
In modern petrological studies carbonate aggregates of a few millimeters diameter in basic volcanic rocks are described to be carbonate ocelli formed by liquid immiscibility, which process is characteristic for alkaline magmas.

The solution of the problem needs specialized studies. So at the time being we conclude that most probably both processes, e.g. processes of liquid immiscibility together with processes of assimilation (mostly carbonate rocks) influenced the magmas of the given province.

The supposed processes of assimilation can also be deduced from results of the whole-rock analyses of main rock types taken into consideration a deficiency of SiO_2 is typical (a range of 38–43 % SiO_2 is most common). In these analysed samples, an anomalously high CaO (as a result of a high amount of carbonate xenoliths/amygdales) and low level of alkaline oxides are characteristic. Analysed samples (even they have fresh appearance) are



Text-Fig. 2.
TAS diagram of volcanic rocks (LE MAITRE, 1984).
The broken line separates the field of tholeiitic (below) and alkaline rock suites (above); MACDONALD & KATSURA (1964).
Outer Western Carpathians: 1 = volcanics of the teschenite-picrite association.
Envelope units: 2 = Tatry Mts; 3 = Nízke Tatry Mts.
Krížna nappe; 4 = Malé Karpaty Mts.; 5 = Malá Fatra Mts.; 6 = Nízke Tatry Mts.; 7 = volcanics of the picrite suite (the Krížna nappe); 8 = volcanics of the picrite suite (the Choč nappe).
Inner Western Carpathians: 9 = Meliata unit; 10 = Szarvaskö complex.
Analytical data presented in HOVORKA & SPIŠIAK (1988).



Text-Fig. 3.
Xenolith of organic-detritic limestone (Liassic?) in alkaline basalt.
Nízke Tatry Mts.
Enlargement 95×.

altered/carbonated. Mineralogical signs of alteration, e.g. altered plagioclases, olivines and groundmass are also documented. These observations influence the projection of analysed rock samples in the TAS diagram (Text-Fig. 2).

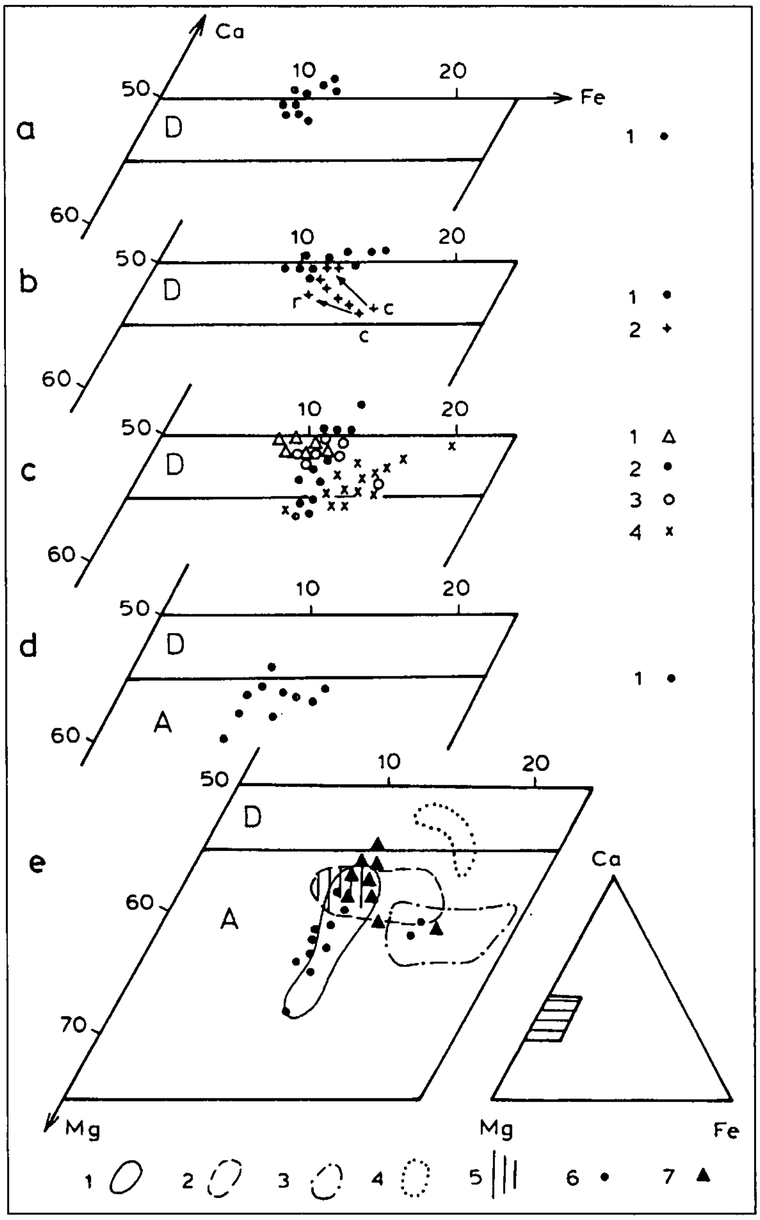
3. The Central Western Carpathians

From the geological point of view the very complicated Western Carpathian central zone, which comprises mountain chains situated between the Pieniny Klippen belt and the Margecany – L'ubeník lineament, contains several volcanic associations.

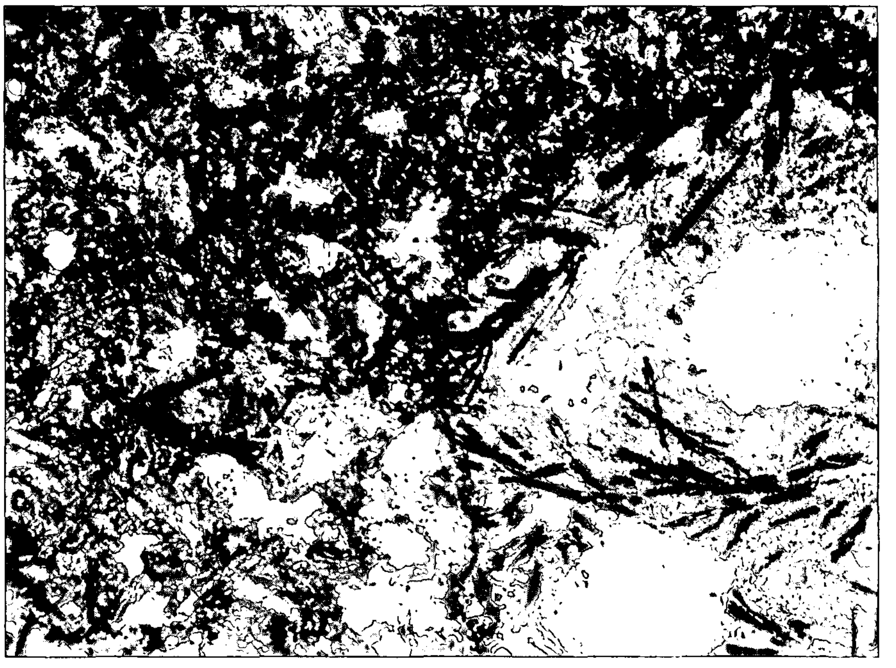
3.1. Alkaline Basalts of the Tatric Units

Some of the Mesozoic sequences of the central zone are generally considered to be in an autochthonous/subautochthonous position (Tatric/envelope units) on Palaeozoic (or older) complexes of "core" mountains and the Slovenské Rudohorie Mts.

In the Malé Karpaty Mts. Tatric (envelope) unit, alkaline basalts/hyalobasalts, most probably of Aptian age, are present in the form of hyaloclastites. Analysed clinopyroxenes (HOVORKA & SPIŠIAK, 1988) allow a comparison of the above mentioned occurrences with those of other Tatric units (Text-Fig. 1).



Text-Fig. 4.
Analyzed clinopyroxenes
a) Effusives of teschenite-picrite association.
A = augite, D = diopside, (MORIMOTO, 1988).
b) Envelope unit volcanics.
1 = Malé Karpaty Mts.; 2 = Malá Fatra Mts.; 3 = c = core, r = rim.
c) Krížna nappe volcanics.
1 = Strážovská hornatina Mts.; 2 = Malá Fatra Mts.; 3 = Vel'ká Fatra Mts.; 4 = Nízke Tatry Mts..
d) Choč nappe volcanics = 1 = Banská Bystrica region.
e) Meliata Group and Szarvaskö complex volcanics.
1 = field of 1st crystallization stage clinopyroxenes; 2 = field of 2nd crystallization stage clinopyroxenes; 3 = Szarvaskö complex peridotites and gabbros clinopyrocenes; 4 = clinopyroxenes of Upper Mantle xenoliths and kimberlites; 5 = cores of clinopyroxene protocrystals (1–5 = BALLA & DOBRETSOV, 1984); 6 = Opátka; 7 = Jaklovce (6–7 Meliata group, HOVORKA & SPIŠIAK [988]).
All clinopyroxene analyses plotted on Text-Fig. 2a–2d are listed in HOVORKA & SPIŠIAK (1988).



Text-Fig. 5.
Partly recrystallized xenolith (?) with dark micas in alkaline basalt.
Nízke Tatry Mts.
Enlargement 30×.

Only one occurrence of alkaline basalt in the Nízke Tatry Mts. is presently known. A range of massive alkaline basalts form a dyke cutting the Middle Triassic limestones. By analogy with other alkaline basalt occurrences within the Tatric units we suppose this body to be of Cretaceous age.

In the central part of the Nízke Tatry Mts. no Liassic sediments are known. However carbonate rock xenoliths in alkaline basalt with well-preserved paleontological remnants (Text-Fig. 5 suggest a Liassic age for the xenoliths), provide evidence for the very complicated geological structure of this mountain range (HOVORKA & SPIŠIAK, 1988).

In the Osobitá peak region of the westernmost Tatry Mts. occurrences of glassy volcanics were described originally as diabases and later as limburgites and limburgite tuffs (KREUTZ, 1913). These volcanics have been studied successively by several authors (RAKOWSKI, 1930; ZORKOVSKÝ, 1949; KOTANSKI & RADVANSKI, 1959). The hyaloclastite character of subaqueously disintegrated lava flows was demonstrated by HOVORKA & SPIŠIAK (1981). Besides hyaloclastites both massive and amygdaloidal types of lava flows are known.

From the above discussion the following conclusions can be drawn:

a) Volcanic rocks present in all known occurrences in the above tectonic units are very similar (the composition of clinopyroxenes [Table 2] supports such a statement [Text-Fig. 4]). The only magma-types are alkaline basalts in various textural developments (holocrystalline, glassy, amygdaloidal, massive).
b) In several occurrences xenoliths of carbonate rocks (Text-Fig. 5) have been described (HOVORKA & SPIŠIAK, 1981; HOVORKA et al., 1982).
c) Alkaline basalt magmas penetrate carbonate complexes, though at present they are deposited directly on granodiorite massifs. Thus, the supposed autochthonous/subautochthonous position of the Tatric/envelope Mesozoic units is very unlikely.
d) The uniform character of the products of volcanic activity located in the various mountain chains allows us to suppose that magmatism took place in the Lower Cretaceous within a single basin. In this basin short-term extension (embryonic spreading) processes took place.

3.2. Alkaline Basalts of the Krížna Nappe

The Krížna nappe represents the most typical allochthonous Mesozoic tectonic unit of the central Western Carpathian zone. The remnants of Krížna nappe rock sequences are found in the central zone, mostly located on the Tatric Mesozoic units. The Krížna nappe rock sequences with volcanics present are known from the following mountain chains: the Malé Karpaty Mts., the Považský Inovec Mts., the Strážovská hornatina Upland, the Malá Fatra Mts., the Vel'ká Fatra Mts. and the Nízke Tatry Mts. The lithological character of the Triassic sedimentary members of the above mentioned tectonic unit is more or

Text-Fig. 6.
Plastic deformation of not yet lithified carbonate mud by moving basaltic magma. Epigenic cracks are filled up by calcite.
Vel'ká Fatra Mts.
Polished surface. Enlargement 1,5×.

Table 2.
Composition of Clinopyroxenes.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	49,79	39,84	43,05	40,86	45,07	48,70	44,01	45,07	50,27	49,89	49,51
TiO_2	1,65	5,01	4,07	5,30	4,70	3,69	4,66	4,70	1,06	1,26	1,53
Al_2O_3	6,95	10,39	8,25	10,17	9,65	5,91	8,38	9,65	2,89	4,65	4,72
Cr_2O_3	-	-	-	0,10	-	-	-	-	0,21	-	-
FeO^{+}	5,43	7,52	6,38	7,71	8,61	7,15	7,03	8,61	7,52	7,36	-
MnO	0,12	0,16	0,14	0,06	0,14	0,13	0,12	0,14	0,18	0,13	7,03
MgO	12,88	12,32	12,41	11,68	11,48	14,32	11,47	11,48	17,00	16,96	16,64
CaO	21,82	23,97	24,72	23,12	19,89	19,78	23,55	19,89	20,87	18,87	19,56
Na_2O	0,06	0,57	0,54	0,37	0,38	0,44	0,61	0,38	0,27	0,30	0,29
K_2O	0,03	0,21	0,42	-	-	-	-	-	-	-	0,04
Total	98,73	99,99	99,98	99,37	99,92	100,12	99,83	99,92	100,35	99,42	99,52
Formula based on 6 oxygens											
Si^{IV}	1,85	1,53	1,63	1,56	1,69	1,80	1,66	1,69	1,86	1,85	1,84
Al^{IV}	0,15	0,47	0,37	0,44	0,31	0,20	0,34	0,31	0,13	0,15	0,16
Al^{VI}	0,15	-	0,00	0,02	0,11	0,06	0,04	0,11	-	0,05	0,04
Ti	0,05	0,14	0,12	0,15	0,13	0,10	0,13	0,13	0,03	0,04	0,04
Cr	-	-	-	0,00	-	-	-	-	0,01	-	-
Fe^{+3}	-	0,00	0,00	-	0,00	0,00	0,00	0,00	0,00	0,00	-
Fe^{+2}	0,17	0,24	0,20	0,25	0,27	0,22	0,22	0,27	0,23	0,23	0,22
Mn^{+2}	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,01
Mg	0,71	0,70	0,70	0,67	0,64	0,79	0,65	0,64	0,94	0,94	0,92
Ca	0,87	0,98	1,01	0,95	0,80	0,78	0,95	0,80	0,83	0,75	0,78
Na	0,00	0,04	0,04	0,03	0,03	0,03	0,04	0,03	0,02	0,02	0,02
K	0,00	0,01	0,02	-	-	-	-	-	-	-	0,00

FeO^{+}= total Fe as FeO, 1-3 = clinopyroxene from picrites (1) and basanites (2-3) - the outer Western Carpathians; 4-8 = clinopyroxene from basanites - the central Western Carpathians; 9-11 = clinopyroxene from basalts - the inner Western Carpathians; selected data from Hovorka - Spišiak (1988)

Text-Fig. 7.
Contact between carbonate mud (homogeneous) and basaltic magma.
Vel'ká Fatra Mts.
Enlargement 5,5×.

less uniform, whilst during the Jurassic–Lower Cretaceous period a wide range of sedimentation condition was established (MAHEL, 1968 in MAHEL et al., 1968). Volcanic activity within the depositional basin took place in the Barremian–Albian within the so-called "Zliechov development" (MAHEL, 1968 in MAHEL et al., 1968).

The available geochemical data allows us to distinguish, in addition to widespread alkaline olivine basalts, basanites and picrobasalts, and rare picrites and hyaloclastites (HOVORKA & SPIŠIAK, 1988). All analysed clinopyroxenes have the composition (analyses in: HOVORKA & SPIŠIAK, 1988) typical of the alkaline olivine basalts (Tab. 2). The presence of abundant (carbonate) blebs which could may be immiscible ocelli has also been observed for this volcanic province.

Besides volcanic/volcaniclastic rocks, the stratigraphical position of which is generally clear, in this tectonic unit some subvolcanic bodies (dykes) located within the Middle Triassic limestones are known (Text-Figs. 6,7). Based on their identical geochemical characteristics and identical clinopyroxene composition with volcanics of Cretaceous age, we suppose them to be the subvolcanic equivalents of the Cretaceous volcanics.

3.3. Picrites of the Choč Nappe

The only known evidence of Mesozoic volcanic activity in this allochthonous tectonic unit is the presence of volcanics occurring within Middle Triassic limestones in the northern vicinity of Banská Bystrica. These volcanics are picrites, for which partly-preserved olivines and well-preserved clinopyroxenes (Text-Fig. 4), amphiboles and phlogopites are typical.

Based on the identification of picrites occurring both in the Choč and the Krížna nappes in the surroundings of Banská Bystrica (even though the sedimentation areas of these tectonic units were evidently separate), we suppose their penetration in the form of dykes into the above mentioned tectonic units took place after their emplacement to the present day position. These intrusives are most probably of Late Tertiary: the intrusions are located in N–S trending tectonic zone (Zázrivá fault system).

4. The Inner Western Carpathians

Within this tectonically very complicated zone volcanic activity had a diverse character and uneven intensity in several Mesozoic units.

4.1. Rhyolite-Andesite Volcanics of the Drienok Nappe

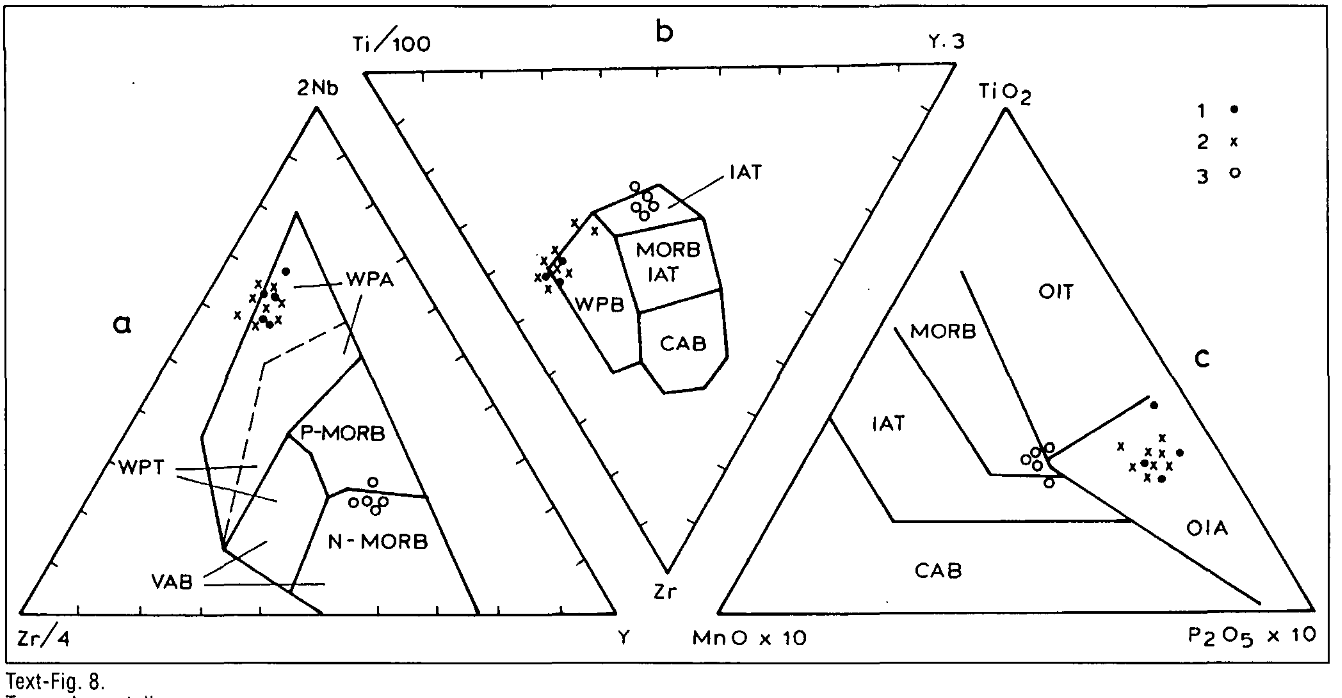
This tectonic unit, according to the lithology of its Triassic sedimentary sequences, belongs to the Inner Carpathian sedimentary area (labile European shelf: RAKÚS et al., 1990; DERCOURT et al., 1990), even though it is placed within the central Western Carpathian zone. Among the tectonic Mesozoic units this unit has one of the uppermost positions. The Drienok nappe Lower Triassic sequences consist of varied sediments characterized by the presence of rhyolite-andesite volcanics. Their occurrences in the Poniky area (the Banská Bystrica district) have the character of brecciated lavas, ignimbrites and products of subaqueous volcanic activity as well. Based on the data available (SLAVKAY, 1965), these volcanics belong to the calc-alkaline series.

4.2. Acid Pyroclastics of the Silica Nappe

Within the basal thrust zone of this undoubtedly tectonically emplaced unit (KOZUR & MOCK, 1973), in addition to bodies of tholeiitic basalts, bodies of intensively tectonized serpentinized spinel peridotites as well as gabbros are also known (HOVORKA et al., 1985; RÉTI, 1985). Together with evaporites they form a tectonic melange, members of which are derived from the underlying Meliata as well as Rudabánya units. In addition, very rare products of volcanic activity occur in the form of fine-grained acid pyroclastic material within Anisian limestones.

4.3. Rhyolite-Andesite Volcanics of the Szentistvan Hills

In the northern part of the Bükk Mts. (Hungary) within the so-called Hámor dolomites (Anisian) a volcanic complex of calc-alkaline character is known. Processes of fractional crystallization formed a subordinate amount of acid as well as intermediate members of the series. The volcanic activity of Anisian–Ladinian age had a subaqueous as well as subareal character. Its fine-grained (ashy) products can be traced in rock sequences of the above-mentioned stratigraphy in several tectonic units in Hungarian and Slovak territories. The whole volcanic-sedimentary sequence has been affected by Alpine metamorphic recrystallization under conditions from anchizone to greenschist facies (ÁRKAI, 1973).



Text-Fig. 8.
Trace-element diagrams.
a) MULLEN (1983), b) PEARCE & CANN (1973), c) MESCHEDE (1986).
1 = outer Western Carpathians; 2 = central Western Carpathians; 3 = inner Western Carpathians.
Selected analyses from HOVORKA & SPIŠIAK (1988) and unpublished analyses (Tab. 1).

4.4. Rhyolite-Andesite Volcanics of the Óhuta Formation

Among the volcanic sequences originated on the labile shelf of the European block (in sense of RAKÚS et al., 1990) one of the most typical is that situated at present on the northeastern slope of the Bükk Mts. The volcanics belong to the subaqueous type and are of Lower to Middle Carnian age (BALLA & PELIKAN, 1983). Volcanic activity had multiphase character. Also, the volcanics of this formation have been recrystallized under conditions from prehnite-pumpellyite to greenschist facies. Based on the calc-alkaline character and on the very similar ages of the volcanics of the associations characterized above, it is possible that they belong to a single volcanic province.

4.5. Incomplete Ophiolites of the Meliata and the Rudabánya Units

Within the Upper Triassic sedimentary sequences of these units fragments of ophiolite complexes (serpentinized peridotites, gabbros, basalts and radiolarites) are known (HOVORKA, 1978; MOCK, 1980; RÉTI, 1985; HOVORKA & SPIŠIAK, 1988). Volcanics of MORB/IAT affinity (Text-Fig. 8) appear as massive lava flows: in some places hyaloclastites are also found. Some of the volcanics together with neighbouring sediments were subjected to high-pressure low-temperature metamorphic recrystallization (blueschists). Subduction of the rock pile of "Meliaticum" (the Meliata unit and comparable sequences deposited within the "Meliata Ocean" – MOCK, 1980) and subsequent tectonic processes gave rise to individual members of the tectonically dismembered ophiolite complex (HOVORKA, 1978).

The most recently published paleogeographical map of the Norian stage (DERCOURT et al., 1990) shows the Meliata Unit sedimented in the NW part of the Transsylvanian Ocean with a typical oceanic crust (see also RAKÚS et al., 1990). It ought to be pointed out that the Meliata sedimentation area was in direct contact with the continental crust (as evidenced by the clastic sediments: such a spatial location of the Meliata basin was favourable for the high-pressure metamorphic recrystallization having been conditioned by subduction processes that followed.

4.6. The Szarvaskö Ophiolite Formation

A complex of pillow lavas, gabbro bodies and dykes, as well as syngenetic ultramafics, occurs near the Szarvaskö village on the southwestern slope of the Bükk Mts. (Hungary). This belongs to the most interesting magmatic Mesozoic complexes within the whole Carpathian belt. They have been studied during the last decade in detail (PELIKAN, 1983; BALLA et al., 1983; BALLA, 1984; BALLA & DOBRETSOV, 1984; KUBOVICS, 1984 & DOWNES et al., 1990).

Fractional crystallization of basaltic magma with tholeiitic geochemical characteristics at hypabyssal (4–6 km) levels resulted in the formation of the minor acid intrusions (plagiogranite), as well as plagioclase peridotite and wehrlite. The parental magma of the complex penetrated through a sequence of turbidite sediments a few kilometers thick: so the processes of fractional crystallization acted in various levels of the crust. Three generations of clinopyroxenes (Text-Fig. 3) are the result of such magma development (BALLA & DOBRETSOV, 1984). The intercalations of deep-water sediments (with stratigraphically important radiolarites and Mn-rich sediments) within pillow lavas of the sequence allow its stratigraphic age to be determined as Dogger (KOZUR, 1984). From the point of view of its stratigraphy the complex has no equivalent among the other Western Carpathian volcanic complexes. Taking into account its diversities, the Szarvaskö basalt-gabbro-peridotite complex can be classified as an ophiolite complex with some peculiar features (BALLA et al., 1983; BALLA & DOBRETSOV, 1984). The most recent petrological and geochemical studies (including REE as well as Sr and Nd isotopes) carried by DOWNES et al. (1990) provided new evidence for a N-MORB-like origin of the magmatic complex. The Szarvaskö complex has been recrystallized under conditions from prehnite-pumpellyite to greenschist facies (newly-formed prehnites and light green amphiboles and others: BALLA et al., 1983; HOVORKA & SPIŠIAK, 1988).

4.7. Tholeiites of the Darnó-Hill

Basaltic volcanics of tholeiitic character occur as massive lava flows (FÖLDESSY, 1975) as well as pillow lavas in a small horst – Darnó-Hill – in northern Hungary. The whole sedimentary-volcanic complex (Tarnakapolna facies: RÉTI [1985]) has the character of a tectonic melange, which can be compared to the Meliaticum (MOCK, 1990 – personal communication). The presence of radiolarite intercalations occurring between the volcanics suggests a Triassic age (DE WEWER, 1984) for the volcanic activity. However available K/Ar data for gabbros (152, 166, 175 my: ÁRVA-SÓS & JÓZSA [1992]) indicate Jurassic age of the Darnó-Hill magmatites. DOWNES et al., (1990) reached the conclusion that Darnó-Hill basalts are much more altered than these of the Szarvaskö complex and do show the same depletion in REE and have lower Nd values. Also their tectonic setting is different – possibly they have been formed on a continental margin or oceanic island.

Available data, at present suggest:

a) the existence of two tectonic units in which volcanic activity took place, situated on both (i.e. the eastern and western) sides of the Darnó tectonic line,
b) Jurassic age of the Szarvaskö ophiolites and coarse-grained gabbros from the Darnó-Hill volcanics was documented by both the geological and geochronological methods (BALLA et al., 1983: ÁRVA-SÓS & JÓZSA, 1992). At the same time, there are disposal evidences for the Triassic age of the Darnó-Hill basaltic effusives (DE WEWER, 1984). These contradictory data reveal that the problem of stratigraphy has hitherto not been solved.
c) that the volcanic complex of Szarvaskö (in comparison with that of Darnó-Hill) is more complex and evidently larger: the volcanic members of both mentioned complexes have different geotectonic setting (DOWNES et al., 1990). In accordance with MOCK (1980), RAKÚS et al. (1990) and DERCOURT et al. (1990), the ideas according to which the Vardar/Transsylvanian/Meliata Ocean penetrated during the Triassic and the Jurassic ages from the south to the Western Carpathians are acceptable from the point of volcanics also (the presence of basalts of the MORB affinity as well as radiolarites of the Upper Triassic age support such reconstruction).

The Meliata Ocean (MOCK, 1980) as well as the whole Vardar/Transylvanian ocean were characterized by their oceanic crusts. So, volcanics described under 3.5.–3.7. are fragments of the above-mentioned oceanic realm.

Table 3.
Survey of the Western Carpathian Mesozoic volcanic activity.

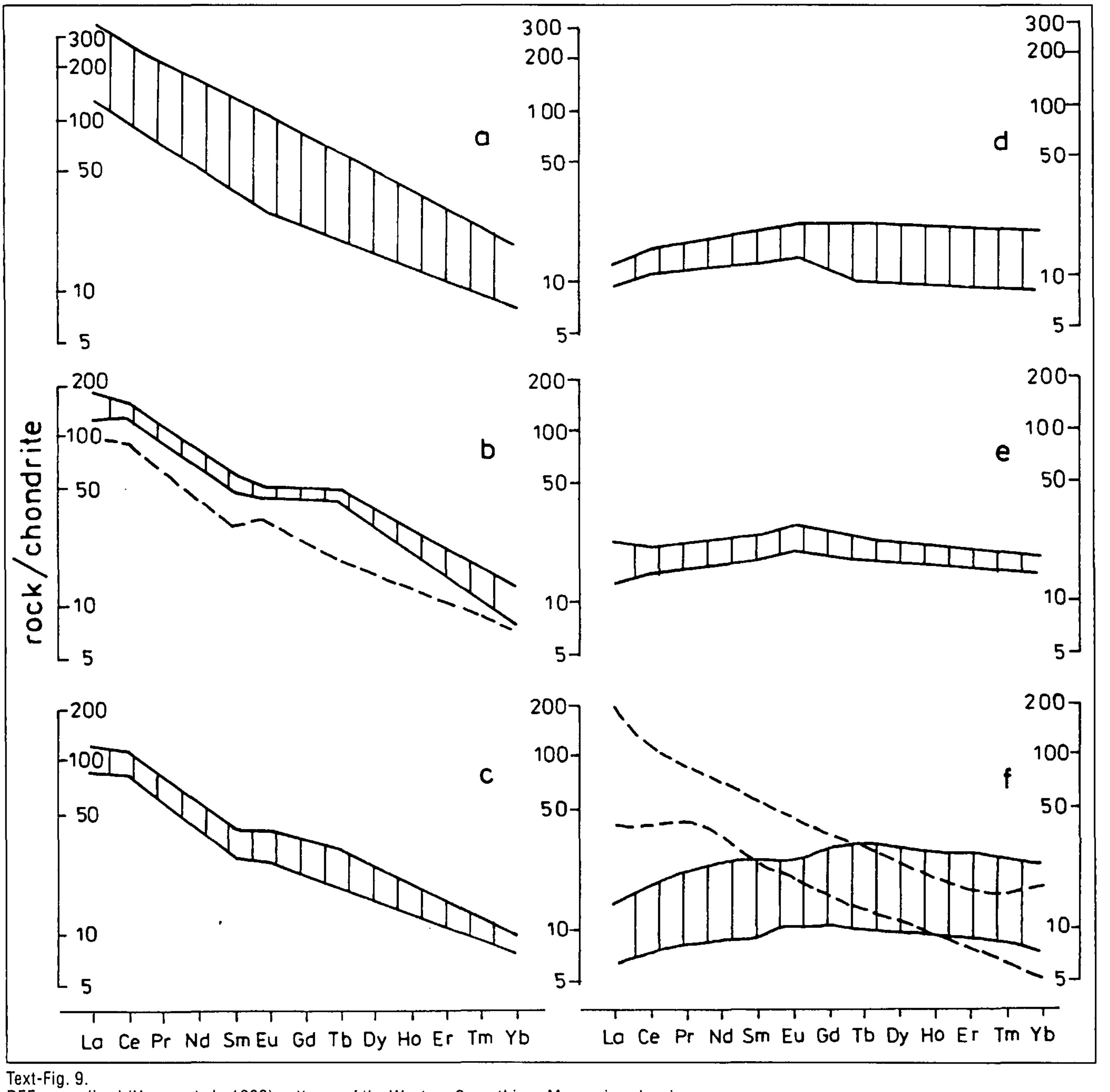
	2 OUTER WESTERN CARPATHIANS	3 CENTRAL WESTERN CARPATHIANS			4 INNER WESTERN CARPATHIANS						
		3.1	3.2	3.3	4.1	4.2	4.3	4.4	4.5	4.6	4.7
Tectonic Unit	Silezic Unit	Tatric "envelope" Units	Krížna Nappe	Choč Nappe	Drienok Nappe	Meliata Unit	Silica Nappe	Szentistván - Hill	Óhuta Formation	Szarvaskö Formation	Darnó-Hill
Assoc.	Teschenite-Picrite Association	Alk. Basalts	Alk. Basalts	Picrites	Rhyolite-Andesite	Dismembered Ophiolite		Rhyolite Andesite	Rhyolite-Andesite	Ophiolite Complex	Basalts
Age	Berriasian-Aptian	Berriasian Aptian		Neogene volcanics within the Mesozoic sequences	Lower Triassic	Upper Triassic	(x)	Anisian-Ladinian	Carnian	Dogger	Triassic
Magma series	Alk	Alk	Alk	CA	CA	TH	CA	CA	CA	TH	TH
Volc. Products	Sills, Lava Flows, Hyaloclastites	Sill, Hyaloclastites, Lava Flows		Sill (?)	Lavas, Ignimbrites, Volcaniclastics	Relics of the Ocean floor of various size		Lavas, Volcaniclastics	Lavas, Volcaniclastics	Pillow Lavas, Sills	Pillow Lavas, Sills
Geotectonic Position	WP	WP	WP	ACM	ACM	OF		ACM	ACM	OF	OF
Lithostr. Unit (x̌)		Vývrat M.; Mlynná Dolina Valley AB; Kamenný Žľab M.	Sasková AB; Beckov Castle Hyaloclastites; Košeca M.; Jedľovina M.; Molčovo M.; Zemianska Dolina Valley M.	Horný Diel Picrites; Stráže Picrites	Skálie M.	Švablica M.; Šugovská Dolina Valley M.	Hosťovce Tuffites				
Remarks						High-pressure met.(blueschists)				TH-basalts of both units have character of OFB	

WP - within plate; OF - ocean floor; ACM - active continental margin; M - member; AB - alkaline basalt; (x) - besides Lower Triassic tuffites also tectonically implaced basite/ultrabasite bodies are known; (x̌) - according to Hovorka & Spišiak (1990)

5. Discussion and Conclusions

❶ From the stratigraphical point of view, the volcanic activity of the Western Carpathian sector of the Tethyan belt took place within a long time period (Triassic–Early Cretaceous). In the innermost tectonic zones it occurred during the Triassic and Jurassic periods (Table 3). In the central as well as the external zones it occurred in the Cretaceous (pre-Cenomanian) period. Thus, volcanic activity took place within the pre-nappe emplacement time-period, with the exception of picrites in the Triassic of the Krížna and Choč nappes. The uniform character of these picrites, and the simultaneous occurrences of the above-mentioned tectonic units just on the N–S oriented Alpine tectonic zone, allow us to suppose the picrites to be post-tectonic (i. e. Late Cenozoic) volcanics. On the other side some basaltic dykes situated within the Variscan granodiorite massif (the Malé Karpaty Mts.) have been geochronologically proven to be Cretaceous in age (HOVORKA et al., 1982).

❷ In the direction more or less perpendicular to the mountain range, a fundamental diversity of magma types (Text-Fig. 1) can be distinguished. Some of the analysed representative rock samples (analyses in HOVORKA's & SPIŠIAK's 1988 monograph) are presented on a total alkali-silica (TAS) diagram (Text-Fig. 2). The plot of analyzed rocks of the teschenite-picrite association within the TAS diagram (Text-Fig. 2) shows widespread distribution. This image is based on the processes (fractional crystallization: assimilation of upper crust material) discussed in previous chapters. Basalts from



Text-Fig. 9.
REE normalized (HASKIN et al., 1968) patterns of the Western Carpathians Mesozoic volcanics.
a = teschenite-picrite association; b = volcanics of the envelope unit: vertically hatched field = Tatry Mts., broken line = Nízke Tatry Mts.; c = Krížna nappe; d = Meliata unit; e = Szarvaskö complex volcanics; f: broken lines = limits of the alkaline volcanic field (GAST, 1968), vertically hatched= field of the MORB (GAST, 1968).

the Western Carpathian zone display genuinely alkaline character, also confirmed by the composition of clinopyroxene phenocrysts (Text-Fig. 4). Picrites from two geological units share striking affinity in the composition, anomalous-low SiO_2 concentration in both is characteristic. Basalts of the inner Western Carpathians are projected within the subalkaline field, they belong to basalt.

Genetically significant trace elements (Text-Fig. 8) evidently discriminate alkaline basalts (in broader sense) from the outer and central Western Carpathian zones from those of the inner one, i. e. from tholeiites of the Meliata unit and Szarvaskö complex as well.

REE pattern of volcanics selected from the outer and central zones of the Western Carpathians (Text-Fig. 9) shows characteristic LREE enrichment. On the other hand, volcanics of the inner Western Carpathians share a flat pattern which is characteristic for the MORB. These patterns (d, e) correspond to the Meliata unit and Szarvaskö complex volcanics. On "f" fields of the MORB as well as that of alkaline basalts are shown for comparison.

Within the sedimentary basins of the Silesian as well as of the Tatric and Krížna nappe units embryonal Early Cretaceous rifting of a within-plate setting took place. Rifting was not followed by sea-floor spreading and the possible formation of ocean crust in these domains has not been proved. As a consequence of embryonic rifting of a more or less contemporary character a small amount (3–5 percent of melting of undepleted Upper Mantle material – SPIŠIAK & HOVORKA, in press) of magma penetrated to the Earth's surface. MICHALIK (1990 in RAKÚS et al., 1990) supposes the subduction of the Penninic ("Vahic") suboceanic lithosphere plate beneath the sialic domain. Melting of the subducting plate caused the intrabasinal volcanism of Barremian, Aptian and early Albian times. The geochemical character (alkaline basalts) of Early Cretaceous volcanics excludes such an interpretation.

From the analyzed clinopyroxenes, as well as from the REE patterns (Text-Fig. 9), magmas of the Silesian, Tatric and the Krížna nappe units in accordance with KUDĚLÁSKOVÁ (1987) and HOVORKA & SPIŠIAK (1988) belong to the alkaline magma series. According to NARĘBSKI (1990) subalkaline/tholeiitic magmas were the sources of the rocks under consideration. The evidence presented excludes the possibility of classifying the above-mentioned Early Cretaceous alkaline volcanics as members of the theoretical ophiolite complex.

The volcanic-sedimentary sequences of the Triassic–Jurassic age which are the integral part of the inner Western Carpathians (units 4.1.–4.7.), in contrast to the previous units contain volcanics of a tholeiitic and in the case of volcanics mentioned under 4.1. also calc-alkaline character. These sequences occur in a geotectonically very complicated zone of tectonic/orogenic activity (island arc : active continental margin) on the one hand, and simultaneously in the domain of the Meliata ocean (MOCK, 1980; DERCOURT et al., 1990) on the other one. The dismembered portions of the oceanic crust are known as incomplete ophiolites (Meliata unit: HOVORKA, 1978; Szarvaskö complex: BALLA et al., 1983; KUBOVICS [1984]; DOWNES et al. [1990]; Darnó-Hill: FÖLDESSY [1975]; Bódva valley ophiolites: RÉTI [1985]).

❸ The diverse character of volcanic rocks in individual tectonic units demonstrates that the processes of spreading as well as compression and subsequent subduction fundamentally influenced the volcanic activity and their products. From this point of view the presence of dismembered ophiolites (Meliata unit: HOVORKA [1978]) and the Szarvaskö complex (BALLA et al., 1983) in the inner zone is characteristic. A completely developed ophiolite assemblage has recently been found as pebbles in the Upper Cretaceous conglomerates in the vicinity of the Dobšiná Ice cave.
The very broad spectrum of volcanics present (Table 3) suggests a complicated geotectonic history for the Western Carpathian sector of the Tethyan belt. At the junction between the central and the inner Western Carpathians, which could also be the collision zone of the Eurasian and African plates, high-pressure recrystallization occurred in the magmatic rocks and the adjacent sediments – resulting in the formation of glaucophane schists in the Meliata unit.

❹ In the rock-types of the teschenite-picrite association of the outer Western Carpathians and in the alkaline basalts of the central zone, numerous carbonate xenoliths (some of which could be immiscible carbonate ocelli have been found. The gradual transition from xenoliths with well-preserved faunal remnants (HOVORKA & SÝKORA, 1979; HOVORKA & SPIŠIAK, 1988) to intensively recrystallized ones, has been described. As a consequence of the substantial amount of xenolithic material in the alkaline volcanics, the whole-rock chemical composition (Table 1) is substantially influenced by the processes of rock assimilation (magma hybridization). In this aspect, taking into account the process of fractional crystallization, too, the great diversity of rock types present in the outer Western Carpathian (1) teschenite-picrite formation can be explained.

❺ The very active "life" of the Tethyan realm between the European continent on the north and the Gondwana shield on the south during the Mesozoic is documented, along with other evidence, by volcanic activity also. The relative motion of the plates, the shortening and spreading of the space between the above mentioned continental megablocks is documented by various types of volcanic activity which took place in different time periods of the Mesozoic. Subsequently Alpine tectonic processes generally reconstructed the architecture of the Mesozoic (but not only Mesozoic) blocks, the volcanic associations present in individual Mesozoic units help to reconstruct the original position of the given units within the framework of the Western Carpathian segment of the Tethys.

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