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ORIGINAL PAPER

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Permian volcanism in the Central Western Carpathians (Slovakia): Basin-and-Range type rifting in the southern Laurussian margin

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Abstract The 1,500- to 2,000-m-thick Permian volcano-sedimentary Malužiná Formation of the uppermost nappe of the Central Western Carpathians (a segment of the Alpine-Carpathian orogenic belt) occurs in several fault blocks distributed across Slovakia. This unit is a part of a post-Variscan overstep suite that followed accretion of the Gothic terranes to Laurussia. It consists of three upward-fining megacycles of semi-arid/arid, fluvial-lacustrine clastic redbeds and local dolomites and evaporites. Abundant intercalated volcanic rocks are predominantly mafic lava flows; volcaniclastic rocks and dykes are subordinate. Felsic rocks are represented by rare volcaniclastics and dykes. Compositionally, the mafic rocks are rift-related continental tholeiites with enriched light REE patterns having $(La/Yb)_n$ ratios between 2 and 5.5 and with mantle-normalized patterns characterized by negative Nb-Ta anomalies. The rocks were derived from subcontinental lithospheric mantle and were affected by crustal contamination. It is inferred that the volcanism of the Malužiná Formation formed in a Basin and Range tectonic setting in which rifting followed collision of the Palaeo-Tethys ridge with the trench bordering southern Laurussia. This model can be applied to other Permian volcanic suites of rift basins in the Eastern Alps and Carpathians over a strike-length of about 1,000 km, which indicates the width of the slab window.

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Introduction

The Western Carpathians is an easterly continuation of the Penninic Austro-Alpine domain of the Alps and is a part of the Alpine-Carpathian orogenic belt (Fig. 1). This mountain range extends across Slovakia and is bounded on the south by the extensive lowlands of the Pannonian basin, and on the north by the thrust boundary between the nappes and the Bohemian Massif or North European Platform. The western geographic border of the Western Carpathians is in the Danube River valley (near Bratislava) and the eastern border is

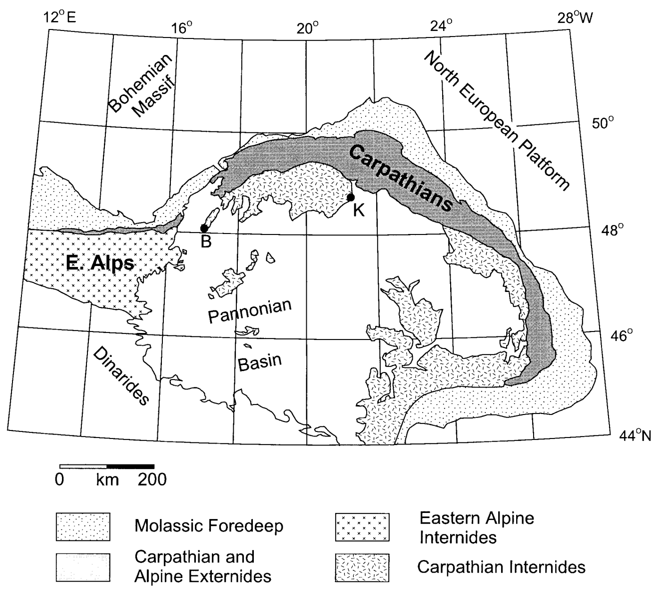

Fig. 1 A simplified tectonic map of the Alpine-Carpathians-Pannonian area (modified from Kovac et al. 1997) showing the major subdivisions of the Carpathians and Eastern Alps as well as location of Bratislava (*B*) and Kosice (*K*)

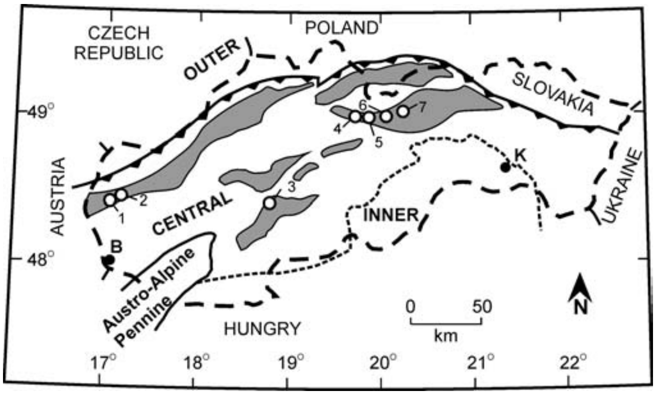

Fig. 2 Geological subdivisions of the Western Carpathians in Slovakia (the Outer, Central and Inner zones) showing the distribution of the Hronicum nappe in the Central zone (*shaded area*) and the extension of Austro-Alpine Pennine to Slovakia (modified from Vozárová and Vozár 1996). The boundary between the Outer and Central zones is a thrust. Bratislava (*B*) and Kosice (*K*). Sample locations (*empty circles*; Table 1): *site 1*: sample C-28; *2*: sample C-27; *3*: sample T-2; *4*: sample NT-5; *5*: sample C-13; *6*: samples C-15, C-18 and C-20; *7*: samples C-3, C-4 and C-7

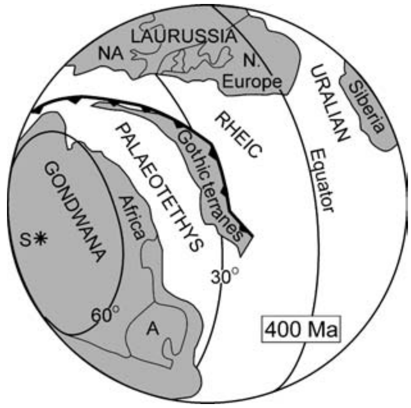

Fig. 3 Tectonic reconstruction for the Early Devonian (after Stampfli et al. 2001a, 2001b) showing the location of the Laurussia, Gondwana, Gothic terranes and Palaeo-Tethys, Rheic and Uralian Oceans. North America (*NA*), northern Europe (*N. Europe*), Arabia (*A*) and South Pole (*S*). The Gothic terranes were a part of the Gondwana, which subsequently separated opening up the Palaeo-Tethys Ocean. Collision of the Gothic terranes with southern Laurussia closed the Rheic Ocean. The projection is centred on present-day latitude 10°N and 20°E

the Uh River (near Kosice). Geologically, the Western Carpathians has been subdivided into three zones (from north to south): the Outer, Central and Inner zones, which represent a series of north-vergent Alpine nappes (Fig. 2). The Outer zone (Flysch zone) is a part of the Carpathian and Alpine Externides while the Central and Inner zones form the Carpathian Internides of Slovakia, which are correlated with the Eastern Alpine Internides (Kovac et al. 1997, Fig. 1). The Central zone or the Central Western Carpathians is a belt that runs across Slovakia and plunges at both ends under Neogene sediments of the Pannonian basin. A part of the Central zone and most of the Inner zone is covered by Tertiary sequences related to the Pannonian basin.

The Permian volcano-sedimentary rocks (Malužiná Formation) discussed in this paper make up most of the uppermost Hronicum nappe of the Central zone (Fig. 2). The volcanic rocks are distributed in several fault blocks that extend over an area 450×70 km. Together with the underlying Carboniferous continental sedimentary rocks they constitute the Late Palaeozoic Ipoltica Group, which reaches a maximum thickness of ~2,500 m (Vozárová and Vozár 1981, 1988). This group forms a part of a post-Variscan overstep sequence that followed accretion of the Gothic terranes to Laurussia (Fig. 3).

The Gothic terranes, which include Armorica and correlatives, are inferred to have been rifted off the northern Gondwanan margin in Late Silurian leading to the development of the Palaeo-Tethys Ocean in their wake (Fig. 3; Tait et al. 2000; Stampfli et al. 2001a, 2001b, 2003). Subduction of the Rheic Ocean beneath the leading edge of the Gothic terranes eventually led to collision with the southern margin of Laurussia in Late Devonian to Early Carboniferous (~380–340 Ma; Stampfli et al. 2003). This was followed in the Carboniferous and Permian by subduction of Palaeo-Tethys beneath the southern margin of the accreted Gothic terranes and dextral transpressional and transtensional displacement of terranes. Triassic roll-back of the trench converted some of these rift basins into oceanic back-arc basins.

The purpose of this paper is to present data on the stratigraphy of the Ipoltica Group, volcanology and geochemistry of the volcanic rocks from the Permian Malužiná Formation of the Central Western Carpathians and to constrain a rifting process associated with their origin. It is suggested that these mafic volcanic rocks, as well as the other Permian volcanic suites of post-orogenic rift-basins in the Carpathians and the Eastern Alps, are associated with Basin and Range rifting, which followed subduction of the Palaeo-Tethys ridge beneath southern Laurussia.

Geological setting

The Ipoltica Group has been subdivided into two formations: the Stephanian Nižná Boca and the Permian Malužiná Formations (Vozárová 1981; Vozárová and Vozár 1981, 1988). The Nižná Boca Formation consists of upward coarsening, fluvial-deltaic-lacustrine, turbiditic clastic rocks interbedded with thin felsic to intermediate volcaniclastic rocks (Fig. 4). The upward coarsening suggests it represents a clastic wedge deposited during the last stage of the Variscan orogenesis. Stephanian B-D (~303–290 Ma; according to Gradstein and Ogg 1996; Okulitch 1999; Haq and van Eysinga 1998) macroflora, microflora and palynomorphs have been reported from the upper part of the Nižná Boca Formation (Ilavská 1964; Planderová 1973, 1979; Sitár and Vozár 1973).

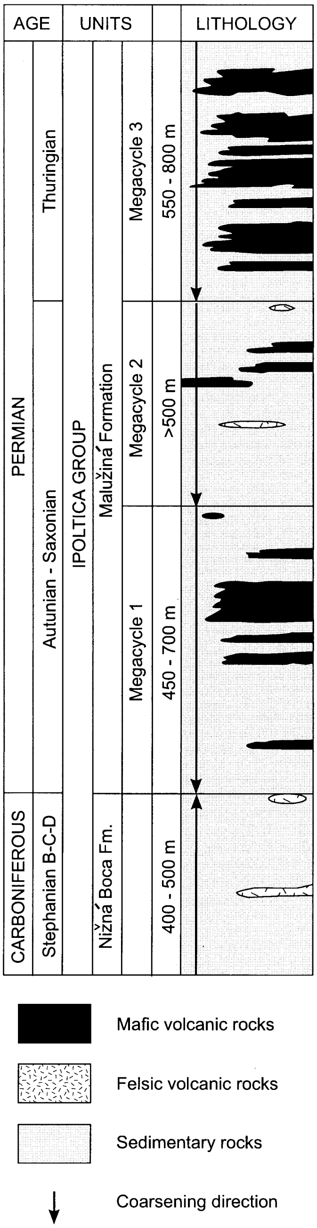

Fig. 4 Stratigraphic column of the Ipoltica Group from the Hronicum nappe highlighting the distribution of the volcanic rocks (modified from Vozárová and Vozár 1988)

The Nižná Boca Formation is a regressive clastic sequence with numerous cycles evolving from medium- to fine-grained sandstones to siltstones and claystones, which are frequent in the lower part of the sequence. In the upper part, the cycle commences at the base with coarse-grained sandstones (even conglomerates in some places) and passes gradually through medium- and fine-grained sandstones to siltstones and claystones. Sandstones show graded bedding and horizontal parallel lamination. The latter is also typical of finer-grained sediments (mudstones and claystones). Abundant graded-bedded sandstones with minor intercalations of muddy siltstones as well as layers with oriented plant detritus indicate fluvial-delta association. Alternation of fine-grained sandstones, siltstones and mudstones of grey to black colour in the Nižná Boca Formation is typical of lacustrine depositional environment. Felsic subaerial volcanism in the Nižná Boca Formation is represented by volcanogenic material frequently mixed with non-volcanic detritus and rare, thin felsic flows.

The Malužiná Formation, which conformably overlies the Nižná Boca Formation, is made up of three upward-fining megacycles of semi-arid/arid, fluvial-lacustrine clastic redbeds and local dolomites and evaporites (Fig. 4). Thin interbedded mafic lavas are common in megacycles 1 and 3. Microfloral assemblages recovered from the Malužiná Formation range from Lower to Upper Permian in age (Planderová 1973; Planderová and Vozárová 1982). In particular, the basal part of the Malužiná Formation is Lower Permian (Autunian; 290–271 Ma according to Gradstein and Ogg 1996; Haq and van Eysinga 1998; Okulitch 1999) whereas the middle and upper parts are Saxonian and Thuringian in age (Upper Permian; 271–248 Ma; according to Gradstein and Ogg 1996; Haq and van Eysinga 1998; Okulitch 1999). Uranium mineralization occurring in the upper part of megacycle 2 yielded ages of 263 and 274 Ma using the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ method (Novotný and Badár 1971; Novotný and Rojkovic 1981; Vozár 1997). The Malužiná Formation is conformably overlain by Lower Triassic clastic sediments.

The Malužiná Formation comprises a thick succession of red beds, which consist of alternating conglomerates, sandstones and shales. Locally, there occur layers of dolomites, gypsum and caliche. The strata represent various stages of a fluvial environment. A full sequence starts with conglomerates, or conglomeratic, coarse-grained sandstones. The upper part of a sequence is characterized by silty or shaly overbank deposits with intercalations of thick cross-bedded sandstones (crevasse deposits). The uppermost part of megacycles is composed of monotonous red shales and muddy siltstones with varying admixtures of sandstones. Upward fining cycles in the order of 10–15 m occur within the three megacycles. Sediments of the Malužiná Formation were formed in fluvial and fluvial-lacustrine environments in semiarid/arid climate. Bases of the three megacycles consist of channel-lag and point-bar deposits, laterally associated with a flood plain. Upper parts of megacycles also contain playa association, scarce inland sabkha and fluvial-lacustrine association.

Clastic sediments from both formations contain clasts of rocks derived from (1) granitoids and/or high-grade gneisses and migmatites, (2) synsedimentary volcanics, and (3) rare low-grade metamorphic rocks. The rocks of the Ipoltica Group were affected by the regional burial metamorphism characterized by the pumpellyite-prehnite-quartz association.

Volcanology and petrography

The volcanic rocks constitute a major part of the Malužiná Formation (Fig. 4). Compositionally, the vol-

Table 1 Representative analyses of rocks of the Malužiná Formation. *Mg#* 100xMgO/MgO+FeO* in mol%; *LOI* loss on ignition; *Fe_2O_3** total Fe as Fe_2O_3. Flows:*C-3*, *C-4*, *C-7* Kvetnice, Poprad (site 7 in Fig. 2); *C-13* II eruptive phase, Malužiná, Nizke Tatry Mts (site 5); *C-15* I eruptive phase; Ipoltica, Nizke Tatry Mts (site 6); *C-18*, *C-20* II eruptive phase, Ipoltica, Nizke Tatry Mts (site 6); *C-27* Losonec, Male Karpaty Mts (site 2); *C-28* Solosnica, Male Karpaty Mts (site 1). Dykes: *NT-5* (feeder dyke) Nižná Boca, Nizke Tatry Mts (site 4); *T-2* Tribec (site 3)

Sample	NT-5	C-3	C-4	C-7	C-13	C-15	C-18	C-20	C-27	C-28	T-2
SiO_2 (wt%)	49.46	50.46	50.03	52.20	50.94	52.69	51.12	52.45	51.19	48.66	73.3
TiO_2	1.50	1.58	2.03	1.49	2.16	1.87	1.57	1.14	1.62	1.29	0.27
Al_2O_3	15.87	18.08	18.04	16.81	15.38	16.43	16.21	16.43	16.98	15.89	14.62
Fe_2O_3*	9.74	7.21	10.05	8.72	9.62	11.21	9.04	7.61	8.35	7.99	2.44
MnO	0.13	0.39	0.26	0.16	0.26	0.27	0.17	0.19	0.17	0.14	0.02
MgO	8.31	5.33	6.57	6.16	4.68	3.04	5.05	7.20	7.29	6.62	0.81
CaO	6.48	8.94	3.32	8.12	8.30	5.42	8.28	5.74	5.46	8.18	0.87
Na_2O	4.00	3.38	5.06	3.26	3.81	4.98	3.90	4.35	4.02	2.93	3.66
K_2O	0.42	0.37	0.77	0.46	0.36	1.27	1.48	1.44	1.26	1.35	2.18
P_2O_5	0.26	0.22	0.29	0.20	0.23	0.54	0.24	0.22	0.26	0.19	0.07
LOI	3.84	4.23	3.67	2.49	4.33	2.33	2.99	3.29	3.43	6.86	1.81
Total	100.02	100.19	100.09	100.06	100.07	100.05	100.05	100.07	100.03	100.10	100.05
Mg#	62.80	59.40	56.40	58.30	49.10	34.90	52.50	65.20	63.40	62.10	39.7
Cr (ppm)	193	127	81	92	26	145	27	157	125	154	58
Ni	143	65	44	56	1	49	5	121	56	84	21
Co	42	33	31	31	31	30	6	30	31	32	8
V	132	175	233	165	249	193	15	132	183	166	26
Cu	22	15	12	19	25	25	6	26	20	15	5
Pb	7	24	19	13	15	10	4	48	19	9	9
Zn	111	78	178	76	334	88	111	151	290	170	30
Rb	22	10	22	15	12	15	55	40	45	75	79
Sr	288	277	393	267	262	381	138	538	352	272	288
Ga	17	19	18	18	17	17	23	19	19	17	24
Ta	0.71	0.58	0.65	0.41	0.35	0.72	0.59	0.74	0.81	0.65	
Nb	14.94	9.95	11.23	9.06	9.60	12.58	13.18	14.71	14.47	11.51	16
Hf	5.27	4.80	5.46	4.39	4.72	7.19	5.00	5.21	5.15	3.94	
Zr	219.5	197.0	244.2	184.9	202.2	329.8	214.7	228.9	224.6	162.2	185
Y	30.63	30.26	37.03	27.81	31.71	53.54	31.21	25.41	29.92	22.37	41
Th	3.80	2.93	3.85	2.74	3.29	3.73	4.69	7.20	4.76	4.00	13
La	19.95	13.66	19.08	12.87	14.20	21.43	21.29	22.90	20.51	19.63	
Ce	43.52	31.92	44.36	29.80	33.40	52.76	46.89	49.97	46.99	42.67	
Pr	5.64	4.31	5.96	4.02	4.54	7.48	6.02	6.12	6.09	5.46	
Nd	23.52	19.13	25.86	17.48	20.35	34.65	25.68	24.31	26.29	22.28	
Sm	5.58	4.99	6.26	4.58	5.40	8.91	5.95	5.12	6.01	4.90	
Eu	1.51	1.53	1.90	1.39	1.67	2.54	1.55	1.18	1.61	1.32	
Gd	5.82	5.51	6.84	5.10	5.98	9.87	6.08	4.95	5.86	4.63	
Tb	0.91	0.88	1.09	0.82	0.96	1.57	0.94	0.74	0.90	0.68	
Dy	5.77	5.54	6.86	5.16	5.95	9.85	5.89	4.70	5.54	4.24	
Ho	1.16	1.17	1.39	1.07	1.20	2.04	1.18	0.97	1.15	0.89	
Er	3.41	3.46	4.06	3.09	3.49	5.90	3.47	2.80	3.35	2.48	
Tm	0.49	0.47	0.58	0.44	0.49	0.84	0.48	0.41	0.48	0.35	
Yb	3.17	3.18	3.78	2.90	3.13	5.45	3.14	2.59	3.00	2.28	
Lu	0.48	0.47	0.56	0.42	0.46	0.83	0.47	0.38	0.46	0.34	

canic rocks are bimodal with a strong predominance of mafic types, which occur as lava flows and subordinate volcaniclastic rocks and dykes. The felsic types occur mainly as volcaniclastics and dykes. The volcanic rocks form two distinct eruption phases (I and II) in megacycles 1 and 3, respectively. These basaltic rocks occur as numerous 0.5- to 2.5-m-thick lava flows that can be followed for a distance of tens to hundreds of metres. Volcanic successions where flows repeat one above the other are typically several tens of metres thick. The rocks are porous, frequently amygdaloidal and locally brecciated. The lavas of the upper part of the eruptive phases II show structures resembling pahoehoe lavas. The lava flows are intercalated with thin (5–20 cm thick) layers of sedimentary and volcaniclastic rocks. Volcaniclastic rocks are rare, occurring typically as ashes, sands and lapilli and are indicative of quiet eruptions into shallow water, or into a subaerial environment. They occur particularly in the eruption phase I and at the beginning of the second phase where they were deposited in subaqueous environment. The volcaniclastic rocks show fine horizontal lamination or even cross lamination of ash tuffs, and graded bedding in small cycles (5–15 cm). The sediments and volcaniclastic rocks in contact with lavas show thermal metamorphism (5–20 cm rims).

The mafic lavas are comprised predominantly of clinopyroxene, plagioclase and Fe-Ti oxides. They are medium grained with an ophitic to subophitic or porphyritic texture. Plagioclase is the most abundant mineral present. It forms either euhedral phenocryst laths or interstitial anhedral crystals. All plagioclase crystals show signs of gradual alteration to saussurite. Pleochroic clinopyroxene occurs either as phenocrysts or small crystals in the groundmass. It corresponds to augite ($Wo_{41–43}$ $En_{43–48}$ $Fs_{9–15}$; mineral analyses performed by electron microprobe at Comenius University, Bratislava) with compositional characteristics of clinopyroxene from within-plate tholeiitic basalts (cf. Letterier et al. 1982). The Fe-Ti oxides typically form microphenocrysts in the groundmass. Felsic rocks contain variable but usually low amounts of phenocrysts of feldspar and quartz set in a fine-grained groundmass. Both rock types, mafic and felsic, are extensively altered and the primary minerals are only rarely preserved. The low-grade metamorphism that affects the Permian volcanic rocks is probably of Alpine origin, and none of the high temperature – low pressure metamorphism in the Carpathians has been dated as Permian, probably also due to Alpine overprinting.

Analytical methods and alteration

Thirty-sixty representative samples were selected from a suite of about 100 samples collected during the mapping of the Late Palaeozoic basins of the Hronicum and the surrounding areas (Vozárová and Vozár 1981, 1988). Major elements were analysed at the laboratories of the Slovak Geological Survey, Bratislava (Slovakia) whereas several trace (Rb, Sr, Zr, Nb, Y, Th, Cr, Ni, Co, V, Cu, Pb, Ga and Zn) elements in these samples were analysed by X-ray fluorescence at the Regional Geochemical Centre at Saint Mary's University, Halifax, Canada. Analytical precision as determined on replicate analyses is generally better than 5% for the major oxides and between 5–10% for minor and trace elements (Dostal et al. 1986). Additional trace elements (the rare-earth elements, Hf, Zr, Nb, Ta, Y and Th) were analysed in ten samples (Table 1) by inductively coupled plasma-mass spectrometry (ICP-MS) at the Geoscience Laboratories of the Ontario Geological Survey, Sudbury, Canada. The precision and accuracy of the method were given by Ayer and Davis (1997) and are generally within a 5% limit.

Secondary processes, which affected the rocks including pervasive low grade metamorphism, were accompanied by selective chemical modifications such as elevated LOI values. Many rocks are amygdaloidal and it is possible that some small quartz-filled amygdules were not removed during the sample preparation. To minimize the effects of alteration on rock composition, the evaluation of the petrogenesis and tectonic setting of the rocks is based mainly on trace elements [e.g. high-field-strength elements (HFSE) and REE] considered to be relatively 'immobile' in hydrothermal fluids (Winchester and Floyd 1977; Goddard and Evans 1995; Zulauf et al. 1999). Extensively altered samples were omitted from most of these evaluations.

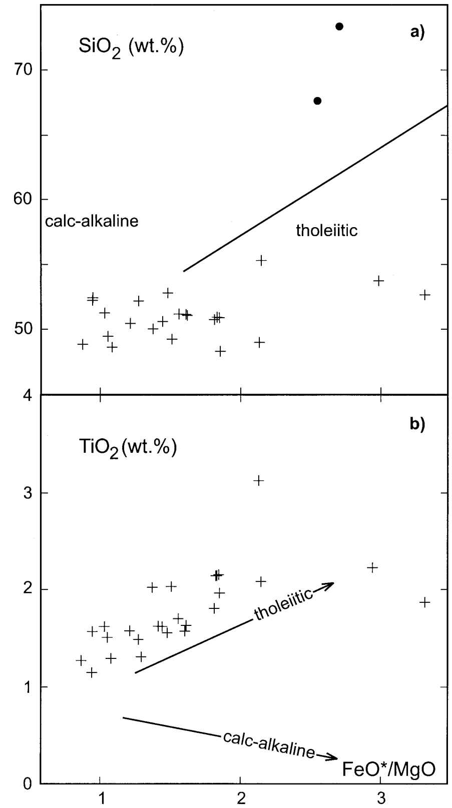

Fig. 5 **a** SiO_2 (wt%) versus FeO*/MgO and **b** TiO_2 (wt%) versus FeO*/MgO diagrams for the volcanic and subvolcanic rocks of the Malužiná Formation. The *line* separating the calc-alkaline and tholeiitic fields in **a** is after Miyashiro (1974). Vectors for tholeiitic and calc-alkaline trends in **b** are also after Miyashiro (1974). Mafic rocks (*crosses*), felsic rocks (*solid circles*; shown only in **a**)

Geochemistry

The Malužiná volcanic suite is bimodal and includes mafic and subordinate felsic (with >65 wt% SiO_2) types (Fig. 5). The mafic rocks have usually SiO_2 in a narrow range of 47.5 to 52.5 wt% (Fig. 5). They have Mg# [=100x(MgO/MgO+FeO*) in mol%] values typically between 70 and 45 and display tholeiitic Ti-enrichment trends with increasing differentiation, although in the most fractionated rocks, Ti decreases (Fig. 5).

Compared with island-arc tholeiites (e.g. BVTP 1981), the Malužiná mafic rocks have higher abundances of Ti and other HFSE. Their TiO_2 contents range between 1 and 2 wt% (Fig. 5). However, relative to alkali basaltic rocks (e.g. BVTP 1981; Wedepohl 1985), they have low abundances of P_2O_5 (0.2–0.6 wt%) and TiO_2. Compositionally, the rocks resemble tholeiites from continental flood basalt provinces and rift-related continental tholeiites (BVTP 1981; Rollinson 1996).

Concentrations of transition elements in the basalts and subvolcanic rocks (Table 1) are low (e.g. Cr <200 ppm) confirming that these rocks underwent significant fractional crystallization. Despite some scatter, the rocks exhibit decreasing Mg, Ni, Cr and Al/Ca with increasing

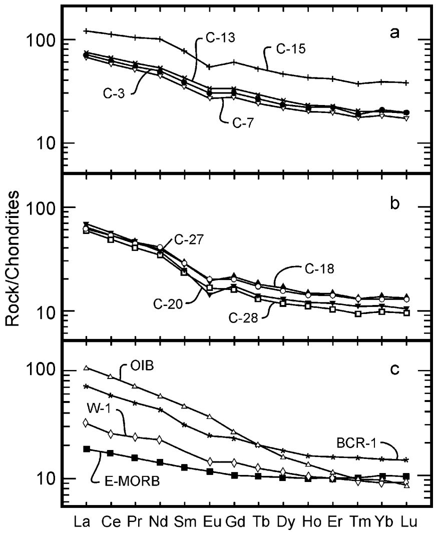

Fig. 6 a, b Chondrite-normalized REE patterns of the mafic rocks of the Malužiná Formation. The USGS standard rocks BCR-1 (Columbia River plateau basalt, Govindaraju 1994) and W-1 (Mesozoic Eastern North America continental tholeiitic basalt, Govindaraju 1994) as well as E-type MORB and oceanic island basalts (OIB; Sun and McDonough 1989) are shown for a comparison (**c**). Normalizing values after Sun and McDonough (1989)

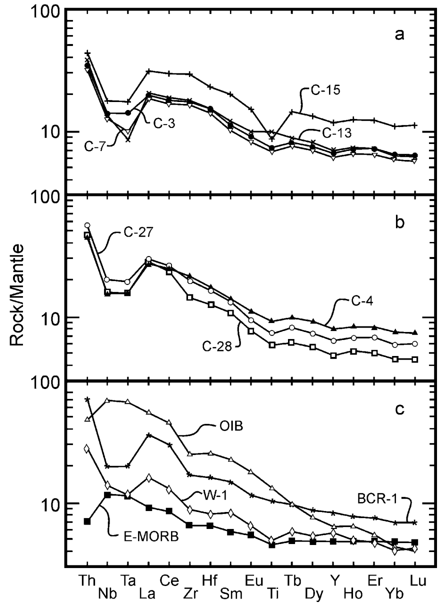

Fig. 7 a, b Mantle-normalized trace element abundances of the mafic rocks of the Malužiná Formation. The USGS standard rocks BCR-1 (Columbia River plateau basalt, Govindaraju 1994) and W-1 (Mesozoic Eastern North America continental tholeiitic basalt, Govindaraju 1994) as well as E-type MORB and OIB (Sun and McDonough 1989) are shown for a comparison (**c**). Normalizing values after Sun and McDonough (1989)

differentiation at almost constant Si, Al, Sr and Ti/Zr, but increasing TiO_2 (Fig. 5) and P_2O_5. This trend is consistent with the fractionation of plagioclase, clinopyroxene and olivine and rules out significant titanomagnetite fractionation. TheTi/V ratios in the rocks are high (>40) within the range of typical continental tholeiites (Shervais 1982).

Chondrite-normalized REE abundances in the tholeiitic basalts (Fig. 6) are enriched in light REE (LREE) and have relatively unfractionated heavy REE (HREE) with $(La/Yb)_n$ between 2 and 5.5 and $(La/Sm)_n$ between 1.2 and 2.5. The small negative Eu anomaly in the patterns of some samples is indicative of extensive fractional crystallization involving plagioclase. The REE patterns resemble many continental tholeiites as well as back-arc basalts (Rollinson 1996). Their mantle-normalized plots of incompatible trace elements (Fig. 7) display a gradual increase from Lu towards large-ion-lithophile elements (LILE) accompanied by a relative depletion in Nb-Ta and Ti with respect to the LILE and LREE. There appears to be some regional variations in composition. The basaltic rocks from the Male Karpaty Mts and those of the II eruptive phase from the Nizke Tatry Mts usually have a higher $(La/Yb)_n$ ratio (4–5.5), and have higher K, Rb and Th abundances.

The felsic rocks (e.g. sample T-2 in Table 1) have typically high contents of Al_2O_3 (>14 wt%) and high and variable incompatible trace elements. Compositionally, they do not appear to be directly related to the mafic rocks, although they show a spatial and temporal association with those rocks. They probably represent crustal melts where melting was triggered by an elevated temperature gradient caused by ascending basaltic magma.

Petrogenesis

As a whole, the Western Carpathians Permian basalts, like typical continental tholeiites, are enriched in LREE and Th relative to mid-ocean ridge basalt (MORB) (Fig. 7). To account for this enrichment, which is accompanied by depletion of Nb and Ta relative to LREE, two different mechanisms have been invoked for continental tholeiites (Hooper and Hawkesworth 1993): (1) crustal contamination of mantle melt and (2) derivation from an enriched mantle source.

1. Crustal contamination. The fact that the rocks were erupted through continental crust raises the possibility that crustal contamination produced some of their compositional characteristics. Indeed, the Permian volcanic rocks exhibit features, which can be attributed to such a process. They have low Nb/La (e.g. mafic rocks ~0.55–0.75 vs mantle ~1.0) and high Th/La (0.17–0.30 vs mantle ~0.12; Sun and McDonough 1989) ratios. However, a simple model in which the Permian basaltic magma was generated by AFC (assimilation and fractional crystallization; DePaolo 1981) from a MORB-type magma is not readily consistent with the lack of correlation of major elements and indexes of differentiation such as Mg# with incompatible trace elements and their ratios. Thus, although the rocks were probably modified by crustal contamination, this process was not the main cause of their compositional characteristics.

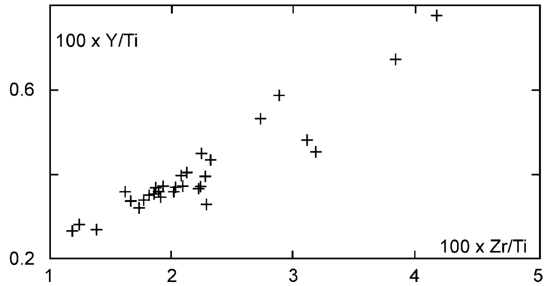

Fig. 8 Variations of Zr/Ti versus Y/Ti for the mafic rocks of the Malužiná Formation

2. Source enrichment. Elongated trends on graphs of ratios of incompatible elements such as Zr/Ti versus Y/Ti (Fig. 8) and Zr/Y versus Nb/Y cannot be generated by variable degrees of melting or fractional crystallization (considering similar major element compositions), but imply source heterogeneity or source mixing. The incompatible trace element patterns of the Permian basaltic rocks (Fig. 7) are dissimilar to the patterns of the oceanic basalts and plume-related basalts implying different mantle sources; the Malužiná basalts are likely related to a lithospheric mantle source. These patterns are typical of subduction-related rocks as well as of some continental volcanic rocks (including continental tholeiites), which are not associated with contemporary subduction processes. In fact, the patterns resemble low-Ti basalts from the continental flood basalt provinces such as Parana, Madagascar, Columbia River plateau, Eastern North America (Piccirillo et al. 1988; Dostal and Greenough 1992; Dostal et al. 1992; Hooper and Hawkesworth 1993) as well as rift-related back-arc basalts (Munoz and Stern 1989). This shape of the patterns of the within-plate basalts, probably reflects older, possibly subduction-related processes that modified the lithospheric mantle, which then became the source (Hooper and Hawkesworth 1993). Parental magma for the Permian basaltic rocks from Slovakia is inferred to be generated from such an enriched heterogeneous source in the subcontinental lithospheric mantle. However, the relatively high Th/La (a sensitive indicator of crustal contamination; Taylor and McLennan 1985) ratios of these rocks suggest that they might also have been contaminated with crustal material prior to emplacement. Subtle differences in the trace elements, including $(La/Yb)_n$ and $(La/Sm)_n$ ratios can be attributed to heterogeneities of the subcontinental lithospheric mantle.

Tectonic setting

Geochemical characteristics of the mafic rocks of the Permian Malužiná Formation suggest that the rocks were derived from subcontinental lithospheric mantle during a rifting process. Unfortunately, the Permian volcanic rocks are preserved in an Alpine thrust sheet, and associated deformation as well as post-Alpine faulting has obscured the nature of any faults contemporaneous with extrusion of the volcanic rocks. However, rapid changes in thickness of the Permian rocks may indicate syndepositional faulting. Rifting can take place in several different tectonic contexts, such as intra-continental rifting, back-arc rifting, ridge-trench interactions and post-orogenic gravitational collapse. In general, geochemical data alone cannot allow discrimination between these different tectonic settings, and consideration of the tectonic context is necessary.

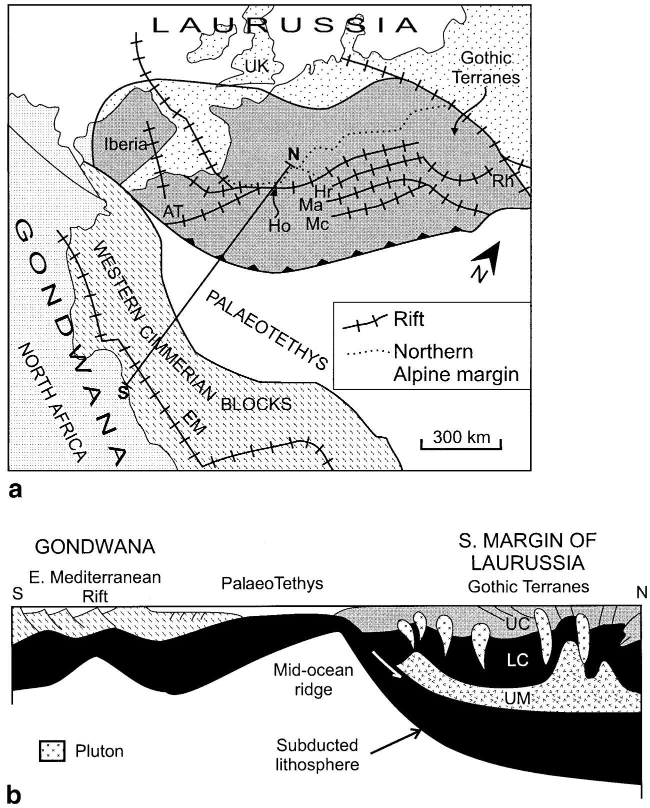

Fig. 9 **a** Early Permian reconstruction of the western Tethyan realm modified from Stampfli et al. (2001a, 2001b). Rift zones: *AT* Alpine-Tethys; *Ho* Houillere; *EM* Eastern Mediterranean; *Hr* Hronicum; *Ma* Meliata-Hallstatt; *Mc* Maliac; *Rh* Rhodope/Pindos. Land areas of Laurussia (*dotted field*); accreted Gothic terranes (*shaded field*). Gondwana includes North Africa and the Western Cimmerian (or the Early Alpine) blocks. **b** Lithospheric cross section across the western part of the Palaeo-Tethys (see N-S line in **a** for location) showing collision of the Palaeo-Tethys mid-ocean ridge with the trench bordering the southern margin of Laurussia. *UC* Upper continental crust; *LC* lower continental crust; *UM* upper mantle wedge

The Permian extensional volcanism took place following the Variscan orogeny. West of Iberia, the Variscan (= Alleghanian) orogeny involved collision between eastern Laurentia and Gondwana. East of Iberia, the Variscan orogeny was the product of a Mid-Late Devonian collision between the Gothic terranes and southern Laurussia with an eastward-widening Palaeo-Tethys Ocean developing between the Gothic terranes and North Africa (Tait et al. 2000; Stampfli et al. 2001a, 2001b; Fig. 3). In the Carboniferous, N-dipping subduction along the northern Palaeo-Tethys margin led to further consolidation of the Variscan orogen (Fig. 9). In the Permian, this convergent deformation was replaced by transtensional deformation (Stampfli et al. 2001a, 2001b), which produced pull-apart rift basins (Fig. 9). In the Triassic, renewed N-dipping subduction of the Palaeo-Tethys beneath southern Laurussia led to some of these rift basins developing into small back-arc basins (Meliata-Hallstatt, Maliac, Rhodope/Pindos; DeBono 1998; Stampfli et al. 2001a, 2001b; Vavassis 2001).

The Carboniferous-Permian switch from convergence to extension has been attributed by Stampfli et al. (2001a, 2001b, 2003) to collision of the Palaeo-Tethys mid-ocean ridge with the trench. Such a tectonic setting is analogous to the Tertiary impingement of the East Pacific Rise with the Middle America Trench. The consequences of this impingement have been described by Dickinson and Snyder (1979), Thorkelson and Taylor (1989) and Stock and Hodges (1989). Subduction of progressively younger oceanic lithosphere led to flattening of the subduction zone producing landward migration of the arc and shortening due to coupling between subducting and overriding slabs. This was followed by impingement of the East Pacific Rise and Mendocino transform fault, which produced R-T-F (ridge-trench-fault) and F-F-T (fault-fault-trench) triple points that migrated away from one another, and led to lengthening of the transform fault that developed along the former trench. The irregularity of the continental margin produced local zones of extension and compression, which led to the separation (and rotation) of blocks (e.g. Humboldt, Salinian and Baja California). The lengthening of the transform margin led to a growing slab window that gave rise to a switch from arc to rift magmatism above the slab window. The rift magmatism resulted from mantle upwelling and diapirism leading to increased heat flow, melting of lithospheric and asthenospheric mantle, thinning of the crust, uplift of the Colorado Plateau and extension. The extension above the slab window produced the Basin and Range province (~1,500 km in strike-length), an extensive area of block faulting in which horsts are separated by graben filled with continental sediments and rift volcanic rocks.

The analogous tectonic setting of the Permian Ipoltica basin and the Tertiary Basin and Range suggests that similar ridge-trench interactions took place. Other contemporaneous rifts in the Alps are the Salvan-Dorénaz graben in the Helvetic domain (Capuzzo and Bussy 2000) and the Zone Houillère rift in the Penninic domain (Cortesogno et al. 1993). This indicates the regional extent of the slab window (Fig. 9). In the Permian case, impingement of the Palaeo-Tethys ridge with the trench along the southern margin of Laurussia is inferred to have taken place. Thus, the volcanism of the Malužiná Formation as well as other Permian volcanic sequences of the Carpathians and Eastern Alps are inferred to be related to Basin and Range rifting following collision of the Palaeo-Tethys ridge with the trench. This extends over a strike-length of about 1,000 km (from Rhodope to Houillère) and indicates the width of the slab window, i.e. about two-thirds of the size of the Basin and Range province in the south-western USA.

Conclusions

The Permian (Autunian-Thuringian) volcano-sedimentary Malužiná Formation, which occurs in the Hronicum nappe of the Central Western Carpathians, is part of a post-Variscan overstep sequence that was formed after accretion of the Gothic terranes to Laurussia. It made up of interbedded volcanic rocks and redbeds, consisting mainly of alternating conglomerates, sandstone and shales deposited in a fluvial and fluvial-lacustrine environment in semiarid/arid climate. Although the volcanic rocks are bimodal, mafic types predominate and are continental tholeiites derived from the subcontinental lithospheric mantle during rifting. These data are consistent with the tectonic model proposed by Stampfli et al. (2001a, 2001b) in which Basin and Range type extension took place in the southern margin of Laurussia due to the collision of the mid-Palaeo-Tethys ridge with the trench bordering Laurussia. The model can be extended to Permian volcanism of the Western Carpathians and probably also to the Eastern Alps.

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