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Miocene thermal history of the southwestern margin of the Styrian Basin: vitrinite reflectance and fission-track data from the Pohorje/Kozjak area (Slovenia)

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Abstract

The Kozjak (Possruck) and Pohorje mountains form the southwestern basement rim of the Neogene Styrian Basin. This region was affected by two Tertiary magmatic events: the emplacement of the Oligocene Pohorje tonalite, and of Early/Middle Miocene dacites in the western Pohorje.

Vitrinite reflectance and fission-track data are used to reconstruct the thermal history and to constrain the exhumation of the Pohorje/Kozjak area. Early Miocene sediments lacking a thermal overprint contain apatite grains of Eggenburgian (~19 Ma) cooling age, only 1–2 Ma older than the time of deposition. The cooling rate of the mainly Austroalpine source units was very fast, denoting tectonic denudation. It means that in the Eastern Alps during Early/Middle Miocene time the Pohorje/Kozjak region in addition to the Tauern and Rechnitz windows was supplying sediment into the surrounding basins with nearly syn-sedimentary apatite cooling ages.

Vitrinite reflectance anomalies in Early Miocene sediments in the Ribnica–Selnica trough, located between the Kozjak and Pohorje mountains, and at the eastern margin of the Kozjak mountains give evidence for a strong post-depositional thermal overprint. Thermal models based on nearby wells suggest that Miocene temperatures were as high as 220ºC. Apatite fission-track ages indicate that the thermal overprint had terminated by middle Badenian (14.4 ± 2.3 Ma) time.

Vitrinite reflectance anomalies in the Ribnica–Selnica trough are a result of Early/Middle Miocene volcanic activity. Another vitrinite reflectance anomaly, situated at the eastern margin of the Kozjak mountains, extends eastward into the Somat–Radkersburg area. The heat source in this region is not obvious. Possible heat sources are: (1) a shallow pluton beneath this area, which easily can explain the reconstructed Early/Middle Miocene heat flow of more than 250 mW/m^2; and (2) advective heat transport due to rapid exhumation of hot metamorphic rocks in the Pohorje/Kozjak region. Rapid exhumation is proven by fission-track dating. It would explain the appearance of the nearly syn-sedimentary detrital apatite FT ages in the sediments and the post-depositional heating.

Keywords: Slovenia; Pannonian; thermal history; magmatism; rapid exhumation

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1. Introduction

The border region between the Eastern Alps and the Pannonian realm is characterized by extreme Early/Middle Miocene extension. Tari (1994) introduced the term "Rába River Extensional Corridor" for this area comprising the Styrian Basin, the Rechnitz Window area and the southern Danube Basin (Fig. 1a). This major extensional phase facilitated the Early/Middle Miocene (∼14–17 Ma; for reviews of K/Ar age data see Balogh et al., 1994; Ebner and Sachsenhofer, 1995) ascent of latitic magmas in the Styrian Basin and resulted in rapid vertical movements. Early Miocene subsidence rates were especially high in the Styrian Basin (more than 1000 m/Ma; Sachsenhofer et al., 1997). At the same time the Rechnitz metamorphic core complex was rapidly exhumed by tectonic denudation (Dunkl and Demény, 1997).

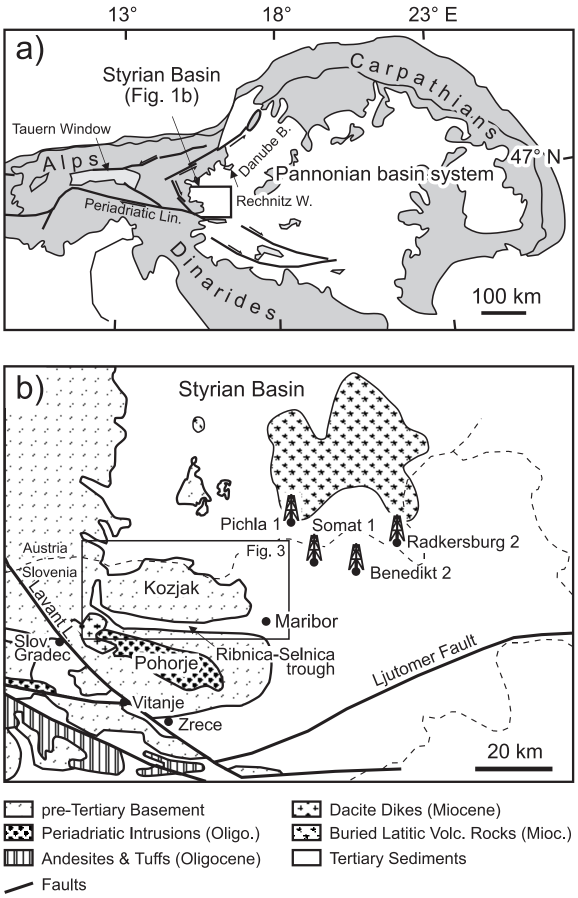

Fig. 1. (a) Location map showing position of the study area within the Alpine–Carpathian–Pannonian realm. (b) Sketch map of the study area.

Both magmatic activity and rapid uplift of basement rocks resulted in very high Early/Middle Miocene heat flows. Probably as a result of shallow secondary magma chambers, heat flow in close vicinity to volcanic centers reached more than 300 mW/m^2 (e.g. Eastern Styrian Basin, Sachsenhofer, 1994, Ebner and Sachsenhofer, 1995). The exhumation and tectonic denudation of the Rechnitz metamorphic core complex also resulted in significantly increased heat flows (e.g. Rechnitz area, Dunkl et al., 1998).

In the present paper, we investigate the thermal regime along the southern margin of the Rába River Extensional Corridor. This is the Pohorje and Kozjak (Possruck) area, which is located in eastern Slovenia close to the Austrian border (Fig. 1b). Fission-track (FT) data from basement rocks and from sediments are used to constrain exhumation within the Pohorje/Kozjak area.

2. Geological setting

The pre-Tertiary basement in the Pohorje and Kozjak area is formed by unmetamorphosed Mesozoic carbonates and low- to high-grade metamorphic rocks (Mioc, 1977). In the Pohorje massif Middle Austroalpine crystalline rocks were intruded by tonalites during Oligocene times (Faninger, 1970). The Pohorje tonalite is genetically related to a continuous belt of calc-alkaline plutons, which occur along the Periadriatic Lineament (Exner, 1976; Laubscher, 1983; von Blankenburg and Davies, 1995) and to Oligocene (∼25 Ma) andesites and tuffs southwest of Vitanje (Odin et al., 1994; Fig. 1b). Paleogene sediments are restricted to a small area near Zrece at the southern margin of the Pohorje.

Neogene sedimentation started during Early Miocene (Ottnangian/Karpatian: ∼17–18 Ma) times (Jelen et al., 1992; see Fig. 2 for a correlation of Central Paratethyan stages to the standard time-scale according to Rögl, 1996). The Early Miocene sediments lie transgressively on the pre-Tertiary basement. They are represented by basal conglomerates,

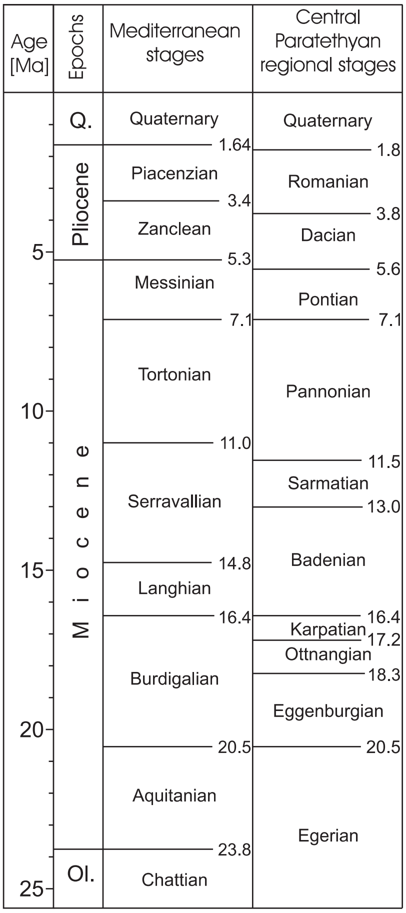

Fig. 2. Correlation chart for Mediterranean and Central Paratethyan biostratigraphic stages (modified after Rögl, 1996).

and marine sandstones, siltstones and marls. Bituminous marls occur in the lower part, thick pelitic tuffs and tuffites occur in the upper part of the Early Miocene sequence. The total thickness of Ottnangian and Karpatian sediments reaches 1000 m (Mioc, 1977; Znidarcic and Mioc, 1988). Tonalite pebbles in Karpatian sediments give evidence of Early Miocene erosion of the Pohorje pluton. Karpatian sediments are unconformably overlain by Middle Miocene (Badenian) conglomerates, sands, silts, marls and algal reef limestones.

The center of an Early/Middle Miocene dacitic volcanic activity was in the western Pohorje area (Fig. 1b), where numerous dikes, stocks and sills of a deeply eroded volcanic root zone occur within locally contact-metamorphosed Paleozoic and Cretaceous sediments. The northernmost occurrence of dacitic dikes is near Vuzenica (GP-34 in Fig. 3). Large buried volcanic cones of the same age occur in the internal part of the Styrian Basin (Fig. 1b). Up to 100 m thick horizons with (usually non-welded) tuff, but no nearby magma source are known from the eastern margin of the Kozjak.

Early Miocene sediments are exposed along the deeply eroded northern and eastern rim of the Kozjak and in the fault bounded Ribnica–Selnica trough, which separates the Kozjak and Pohorje massifs. Towards the east and northeast, Early Miocene sediments were encountered in drillholes beneath Middle Miocene strata in the Pichla 1, Somat 1, Benedikt 2 and Radkersburg 2 wells (see Fig. 1b for location of wells). The top of the 500 m (Benedikt 2, Radkersburg 2) to 1500 m thick (Pichla 1) Early Miocene was reached in depths between 25 m (Somat 1) and 1230 m (Radkersburg 2).

The southwestern margin of the Pohorje is formed by the Lavant Line, a dextral strike-slip fault, which displaced the Periadriatic Lineament in post-Pannonian time (Kázmér et al., 1996). Early Miocene sediments occur west of the Lavant Line between Slovenj Gradec and Vitanje. These deposits are separated from small remains of Early Miocene sediments east of the Lavant Line near Zrece. The latter unconformably overlie coal-bearing Upper Cretaceous to Eocene strata (Hamrla, 1987). Along the eastern and southeastern margin of the Pohorje the Austroalpine crystalline rocks are covered by Plio-/Pleistocene sediments.

3. Samples and methods

More than 100 fine-grained and/or coaly samples, most of them with an Early Miocene age, were collected from outcrops. Vitrinite reflectance of these sediments was measured following established procedures (Stach et al., 1982). Results are presented as mean random reflectance values (R_r). In order to avoid subjective conceptual models, a kriging approach (e.g. Davis, 1986) was used to draw the vitrinite reflectance isoline-map shown in Fig. 3.

PDI-1D software of IES, Jülich (Wygrala, 1988) was used in modeling the thermal histories of Somat 1 and Radkersburg 2 wells. Information on subsi-

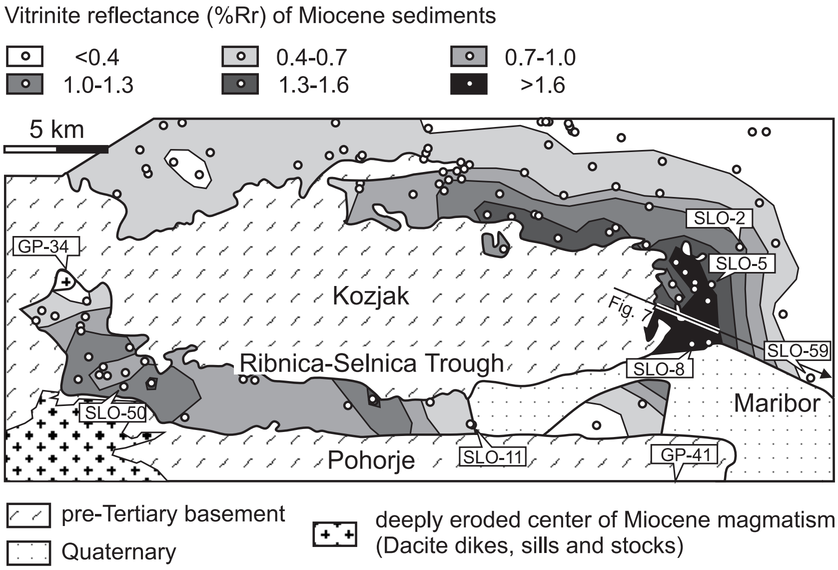

Fig. 3. Vitrinite reflectance map of early Miocene sediments around the pre-Tertiary Kozjak area (see Fig. 1b for location of map). Locations of fission-track samples are indicated. Arrow marks position of cross-section (Fig. 7).

dence of the Somat 1 well was provided by Geoplin d.o.o. (Ljubljana). Vitrinite reflectance data are from Rainer (1998). Information on subsidence and vitrinite reflectance from the Radkersburg 2 well were taken from Ebner and Sachsenhofer (1991).

Based on their different thermal overprint (reflectance values), Early Miocene sandstones from six sample sites were selected for apatite fission track dating. Four localities (SLO-2, -5, -8, -59) are situated east of the Kozjak, another two are located within the Ribnica–Selnica trough (SLO-11, -50). For comparison, a dacite from the western Ribnica–Selnica trough (Vuzenica; GP-34) and a (Middle Austroalpine) gneiss sample from the eastern Pohorje mountain (GP-41) were also investigated (see Fig. 3 for sample locations).

The fission-track samples were treated by the common heavy liquid and magnetic separation processes. For apatite 1% nitric acid was used with 2.5–3 min etching time (Burchart, 1972). Neutron irradiations were made at the RISØ reactor (Denmark). The external detector method was used (Gleadow, 1981), after irradiation the induced fission-tracks in the mica detectors were etched by 40% HF for 40 min. Track counts and length measurements were made with a Zeiss Axioskop microscope, computer-controlled stage system (Dumitru, 1993), with magnification of $\times 1000$. 25–30 crystals were dated in the thermally overprinted samples, 60 crystals in the samples without overprint. Several apatite mounts per sample were prepared in order to obtain a statistically relevant number of track length measurements, in spite of low track densitites (see Table 1).

The FT ages were determined by the zeta method (Hurford and Green, 1983) using apatite from Durango and Fish Canyon Tuff. Reference ages of 27.9 ± 0.7 Ma for the Fish Canyon Tuff and 31.4 ± 0.5 Ma for Durango apatite have been adopted according to Hurford and Green (1983) and Green (1985). FT ages of thermally non-overprinted sediments were calculated according to Green (1981). The error was calculated by using the classical procedure, i.e., by the double Poisson dispersion (Green, 1981).

4. Results

4.1. Vitrinite reflectance pattern

A detailed vitrinite reflectance map of the Kozjak area is presented in Fig. 3. It is characterized by extremely high vitrinite reflectance values in the central and western Ribnica–Selnica trough and along the eastern margin of the Kozjak. All vitrinite reflectance

Table 1
Fission-track results obtained on samples from the surroundings of the Kozjak mountains

Code	Locality	Lithology	R_r	cryst.	P_s (Ns)	P_i (Ni)	P_d (Nd)	$P(\chi^2)$ [%]	FT age [Ma ± 2s]	Track length (*n*) [μm]	Uranium [ppm, V.C.]
Sediments											
SLO-59	Maribor	sandstone	0.36	60	2.36 (1016)	10.4 (4650)	4.66 (9076)	<1	22.3±1.8	14.2±1.2 (50)	32(0.70)
SLO-11	Railway tunnel	sandstone	0.46	60	2.60 (1383)	11.3 (6279)	4.66 (9076)	<1	19.5±1.4	14.1±1.5 (76)	35 (0.75)
Overprinted sediments											
SLO-2	Gradiska	sandstone	1.15	30	2.06 (433)	11.9 (2501)	4.48 (10915)	14	14.5±1.6	14.4±1.3 (40)	38 (0.43)
SLO-5	Sv. Urban	sandstone	1.55	25	2.51 (538)	17.7 (3734)	4.66 (9076)	50	12.5±1.3	14.2±1.2 (40)	54 (0.75)
SLO-8	Kamnica	sandstone	2.51	27	2.50 (464)	12.2 (2202)	4.48 (10915)	36	17.6±1.9	14.4±1.0 (30)	38 (0.51)
SLO-50	Kovac	sandstone	1.20	25	0.08 (246)	0.54 (1674)	4.66 (9076)	84	12.8±1.8		1.7 (0.74)
Basement and subvolcanic dike											
GP-34	Vuzenica	dacite		25	0.16 (352)	0.96 (2139)	4.66 (9076)	52	14.6±1.8	14.8±1.0 (31)	2.9 (0.39)
GP-41	G. Veronika	gneiss		25	0.15 (218)	1.26 (1849)	4.66 (9076)	35	10.2±1.5	14.7±1.4 (50)	3.9 (0.49)

P = Track densities ($\times$ 10^5 tr/cm^2); (N) =number of tracks counted; $P(\chi^2)$ = probability of obtaining χ^2 value for n degree of freedom (where n = no. crystals $-$ 1); FT = apatite ages calculated using dosimeter glass CN 5 with zeta = 373.3 ± 7.1; V.C.: variation coefficient of the uranium content.

maxima are confined to Early Miocene sediments. The vitrinite reflectance maximum in the western Ribnica–Selnica trough with reflectance values up to 1.35%R_r is located north of the center of dacitic volcanism in the western Pohorje area. Vitrinite reflectance in this part of the Ribnica–Selnica trough shows a general decrease to the north. Vitrinite reflectance of a sample close to the Vuzenica dacite is only about 0.4%R_r. The anomaly in the western Ribnica–Selnica trough is separated by a broad area with reflectance values below 1.0%R_r from a small anomaly in the central Ribnica–Selnica trough (up to 1.45%R_r). The eastern border of the latter is sharp. Vitrinite reflectance in the eastern Ribnica–Selnica trough is in the range of 0.35 to 0.7%R_r.

The highest reflectance values (up to 2.5%R_r) occur northwest of Maribor at the eastern margin of the Kozjak. Towards the east, vitrinite reflectance of outcrop samples decreases rapidly to values below 0.4%R_r. Because of a Quaternary cover and poor exposures, the southern end of the vitrinite reflectance anomaly (and its continuation into the eastern Ribnica–Selnica trough) cannot be defined.

Vitrinite reflectance of Early Miocene coals near Zrece and Slovenj Gradec is about 0.4%R_r (Hamrla, 1985/86). Samples northwest of Vitanje are characterized by slightly higher values (0.5–0.8%R_r). In the Zrece area a vitrinite reflectance break exists between the Early Miocene sediments (0.4%R_r) and underlying upper Cretaceous to Eocene coal-bearing sequences (0.7 to 0.8%R_r; Hamrla, 1987).

Vitrinite reflectance of post-Early Miocene sediments is always significantly below 0.4%R_r. The Early/Middle Miocene boundary is located close to the northeastern corner of Fig. 3 and is characterized by about 0.3%R_r.

4.2. Fission-track results and evaluation

4.2.1. Provenance of apatite and zircon in studied fission-track samples

In the case of sedimentary samples the composition and the origin of the detritus have specific importance for the interpretation of FT data. The studied syn-rift sandstones were deposited in Early Miocene times. The sedimentation rate of the coarse deposits was very high (in the order of 1000 m/Ma). The heavy mineral compositions of the samples reflect several local provenance areas. Although, the sample sites are situated rather close, the characteristic heavy minerals are different. The sediment was derived from different paleo-valleys with minor mixing from various sources. The presence (and predominance in sample SLO-2) of euhedral apatite grains with many tiny zircon inclusions, and exclusively euhedral, colorless zircon crystals indi-

Table 2
Provenance relevant features of the heavy mineral fraction of sandstones from the surroundings of the Kozjak mountains

	Apatite	Zircon	Rutile	Kyanite	Typical inclusion in apatite	Main lithology of the of the source area
SLO-2	♦♦♦ big, clear ○	♦ colorless	++		zi. ≫ ilm.	Tonalite ≫ AA
SLO-5	♦ ○	♦ mainly colorless ○	+		ilmenite	AA > Tonalite
SLO-8	♦♦ ○○	♦♦ colorless ○○ mainly reddish	+			AA ∼ Tonalite
SLO-11	♦ ○○	♦ red		++	(zi.)	AA ∼ Tonalite
SLO-50	○○○	○○				AA
SLO-59	○○○	○		+	ilmenite	AA

Number of symbols are proportional to the amount. Garnet, turmaline and some epidote are the predominant minerals with similar amount in the samples. ♦ = Euhedral; ○ = anhedral; AA = Austroalpine nappe pile of gneiss–micaschist composition.

cates that the Periadriatic tonalite intrusions were the source for the sandstone (Table 2). The low variation coefficient (V.C.) of the uranium content of SLO-2 apatites denotes also a single source — the V.C. in case of tonalite samples from the Pohorje and other Periadriatic localities ranges between 0.22 and 0.4 (unpublished results). We can exclude the dacite body as a source of the euhedral apatite prisms, as the uranium content of the apatite in the dacite is less by more than an order of magnitude, than the uranium content of the euhedral apatite crystals in the SLO-2 sample (Table 1).

The apatite crystals of the GP-34 Austroalpine gneiss sample contain numerous euhedral, lamellic ilmenite inclusions, which are also present in samples SLO-5 and -59, suggesting an Austroalpine source for these sandstones.

4.2.2. Sediment samples without total resetting or with insignificant thermal overprint

The fission-track results are listed in Table 1. The pooled FT ages of the samples with low vitrinite reflectance (SLO-59 and 11) are averages of different provenance ages. The chi-square tests were failed proving the heterogeneous origin, while all the overprinted samples passed the test. The age-spectra and the column diagram of the individual grain ages give graphical aid for the proper evaluation of these samples (see Fig. 4).

The low vitrinite reflectance of samples SLO-59 and SLO-11 (R_r = 0.36 and 0.46%) predicts a thermal overprint of the sediment of maximum 70ºC, which can produce only minor reduction in the apatite FT ages. Thus, the observed single-grain ages can be interpreted as cooling ages of the source areas of the sandstones. The grain-age distribution of the samples shows two overlapping age clusters (Fig. 4), which cannot be separated accurately. An age cluster has always some asymmetry towards the old ages; in our case the young group extends until around 40 Ma. Thus, its separation from the old one and the calculation of the mean is a bit biased, but the range of uncertainty is ∼0.1 Ma, having no effect on the geological interpretation.

The averages of these young groups are only 1–2 million years older than the age of sedimentation (19.3–18.2 Ma and 17.7–16.4 Ma respectively). In case of rapid cooling the apatite closure temperature is around 130ºC (see Baldwin et al., 1993),

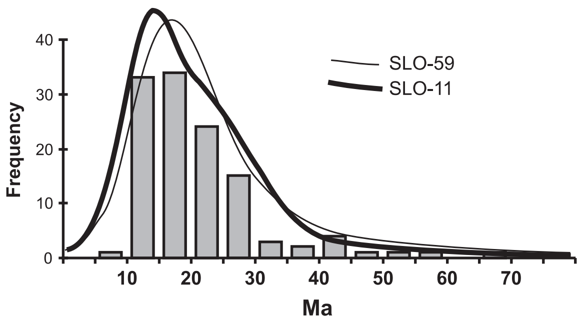

Fig. 4. Age spectra of non-overprinted sandstone samples (calculated by the method of Hurford and Green, 1983). The column-diagram combines all the 120 crystals of the two samples.

thus we can estimate a cooling rate of between 50–120ºC/Ma for the source area of the sandstone. The heavy mineral characteristics show a predominantly Austroalpine source region, with secondary contribution of Periadriatic tonalites. Stingl (1994) studied Ottnangian boulder beds with megaclasts up to several meters in size (Radl Formation) from the northern margin of the Kozjak and emphasized that their source is situated in the Pohorje mountains. This is evidence for a high relief in the Pohorje/Kozjak area and supports the above interpretation. The presence of such young cooling ages on the surface in the close neighborhood of the deposition area means very rapid, syn-sedimentary exhumation of the deep level of the Austroalpine crystalline in the Kozjak–Pohorje region.

Apatite grains of an older group (ranging between ~35 and 70 Ma) derived from now eroded upper levels of the Austroalpine crystalline basement. Its last metamorphism of greenschist–amphibolite facies grade has terminated at around 80 Ma. The oldest apatite FT cooling ages of the eastern Eastern Alps are between 70 and 50 Ma expressing the late cooling stage of the Cretaceous metamorphism (Dunkl, 1992; Hejl, 1997).

Single-grain-ages and track lengths measured in the dated grains show a weak negative correlation (the tracks in the older grains are slightly shorter, see Fig. 5). This proves also that the older grains have suffered more thermal overprint during the Paleogene cooling period, than the rapidly cooled grains of the young age cluster.

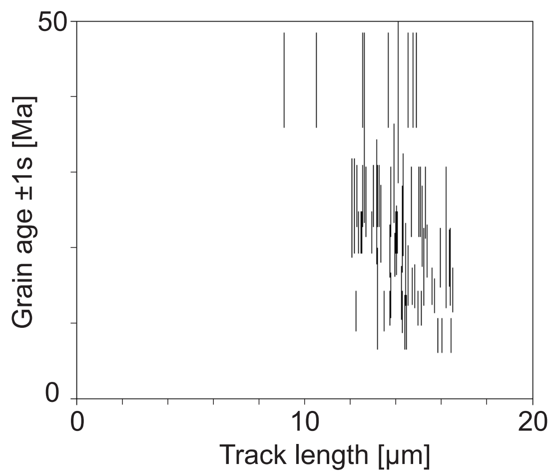

Fig. 5. Plot of the individual grain ages (±1 *s* error) versus track lengths measured in the dated grains (SLO-59 and -11 together).

4.2.3. Overprinted sediment samples

The apatite FT ages of samples SLO-2, -5, -8 and -50 are younger than the age of sedimentation (Table 1). The high coal rank (1.15–2.51%R_r) explains the total resetting of detrital apatite ages by a post-depositional heating. These samples passed the chi-square tests, indicating total annealing of the spontaneous fission-tracks. The samples usually contain few confined tracks; in case of sample SLO-50 the measurement was not possible due to the low uranium content. The averages of the confined track lengths (Fig. 6) are practically identical, verifying the similar thermal history. The mean of the ages is 14.4 ± 2.3 Ma (middle Badenian). This age dates the end of the thermal overprint.

4.2.4. Basement and dike samples

The dacite dike of Vuzenica (GP-34, see Fig. 3) belongs to the root of a volcano of Early/Middle Miocene age. The apatite FT age (14.6 ± 1.8 Ma) and the very minor shortening of the tracks prove that the depth of emplacement was shallow or the exhumation of the dated dike took place soon after the volcanic activity. Therefore, the FT age is probably close to the age of emplacement. K/Ar biotite ages of the — thermally overprinted — basement in the Pohorje mountains range from 16.9 to 18.7 Ma (Dolenec, 1994).

The gneiss sample from the eastern slope of the Pohorje mountains (GP-41) gave the youngest apparent age. It can be an end value of the group of Neogene ages, but it may also indicate the difference of the exhumation history of the crystalline basement of the Pohorje and Kozjak mountains. Perhaps, uplift in the eastern Pohorje continued into the Upper Miocene.

5. Discussion of paleogeothermics

Oligocene magmatism along the Periadriatic Lineament predates the deposition of the Ottnangian/Karpatian sediments and, therefore, did not influence their vitrinite reflectance. However, according to Hamrla (1987) high vitrinite reflectance

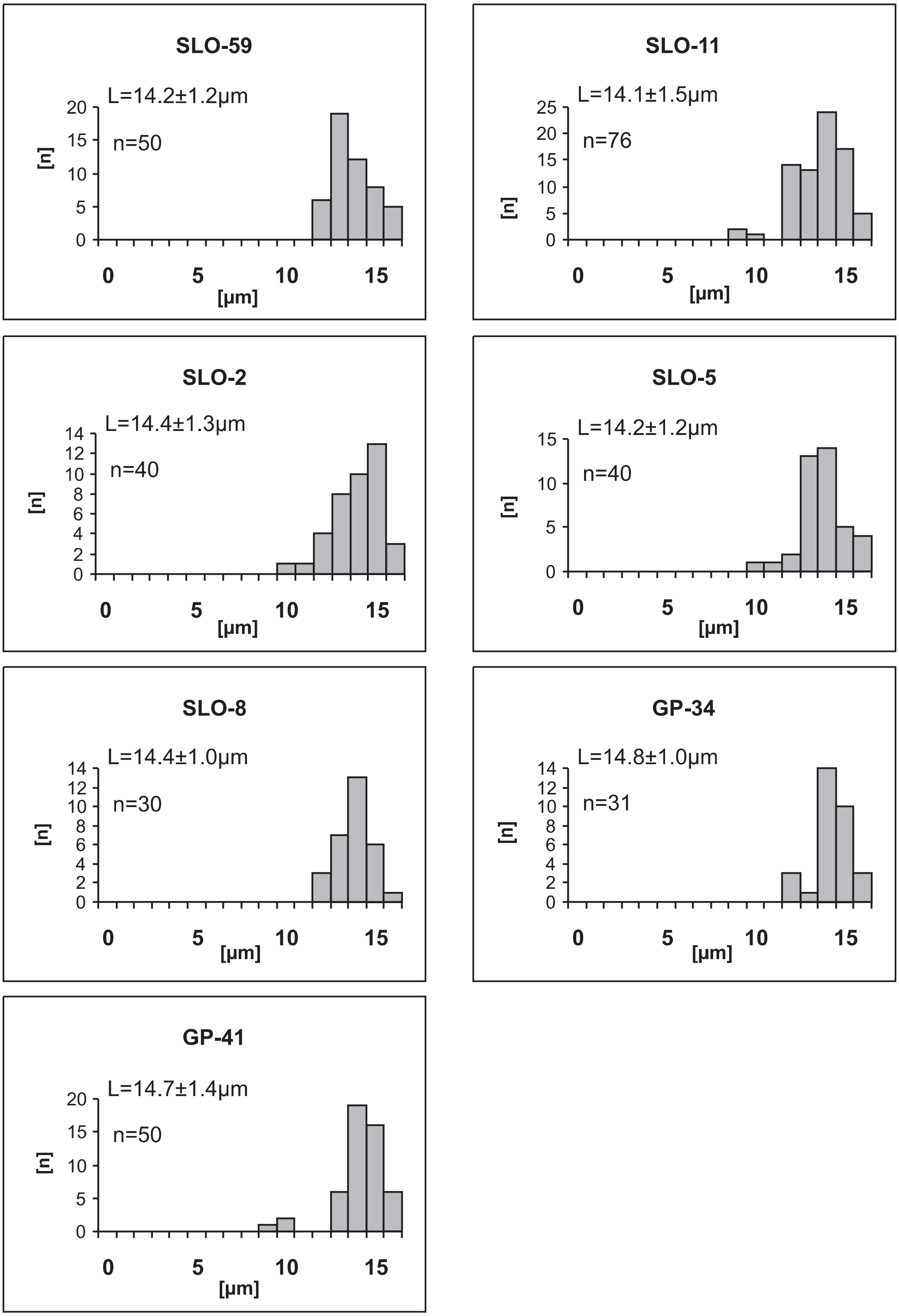

Fig. 6. Confined track length distributions of the apatite samples.

of Cretaceous to Eocene coals (which contrasts with relatively low reflectance in Early Miocene sediments) are a consequence of this magmatic event.

There is a clear spatial relationship between the position of the root of the dacite volcano and the vitrinite reflectance anomaly in the western Ribnica–Selnica trough. The dike emplacement postdates Early Miocene sedimentation, thus we consider the volcanic activity as the main reason for this local maturation maximum. According to the geological map (Znidarcic and Mioc, 1988) and field observations, the dacite occurrence at Vuzenica (GP-34 sample) is a small, isolated body. That is why it has not any observable effect on the coal rank pattern (Fig. 3). Elevated vitrinite reflectance values occur not only in the Ribnica–Selnica trough, but also along the western–southwestern margin of the Pohorje Mountain between Slovenj Gradec and Vitanje (see Fig. 1; up to 0.8%R_r).

The vitrinite reflectance maximum at the eastern rim of the Kozjak (NW Maribor) is located in the deepest part of the (~1000 m thick) Early Miocene sequence (Znidarcic and Mioc, 1988; Fig. 7). Basement rocks and Early Miocene sediments are downthrown along normal faults west of Maribor (see also Fodor et al., in press). This, and a general (shallow) eastward dip of the sediments result in the outcropping of a higher part of the Early Miocene sediments in the Maribor area. Their low reflectance values (0.29 to 0.36%R_r; Fig. 7) occur a few hundred meters below the (now eroded) Karpatian/Badenian boundary. This indicates a relatively small reflectance gradient in the upper part of the Early Miocene section, which contrasts with a significantly higher gradient in its lower part.

The vitrinite reflectance maximum is not restricted to the eastern rim of the Kozjak, but continues in the subsurface far to the northeast and east. This is proven by Early Miocene sediments with high vitrinite reflectance in the Somat 1 (up to 2.5%R_r), Pichla 1 (2.5%R_r), Benedikt 2 (2.7%R_r) and Radkersburg 2 (1.1%R_r) wells (Jelen, 1985/86; Ebner and Sachsenhofer, 1991; Rainer, 1998; see Fig. 1b for position of wells). The results of numeric heat flow models for the Somat 1 and Radkersburg 2 wells were calibrated with vitrinite reflectance data and formation temperatures and are presented together with their vitrinite reflectance data in Fig. 8. These models suggest Karpatian heat flow maxima in the order of 375 to 400 mW/m^2. A lower — but still extremely elevated — Karpatian heat flow (about 250 mW/m^2) was reconstructed for the Pichla 1 well (Sachsenhofer, 1994).

The observed reflectance interval and the thickness of the Karpatian sediments in the Somat 1 well are similar to those in the Maribor area, indicating similar heat flow histories. The low vitrinite reflectance at the Karpatian/Badenian boundary and the relatively low vitrinite reflectance gradient in the upper part of the Early Miocene section suggest that the heat flow also decreased in the Maribor area after the Karpatian time. However, it cannot be excluded that elevated heat flows continued into early Badenian times.

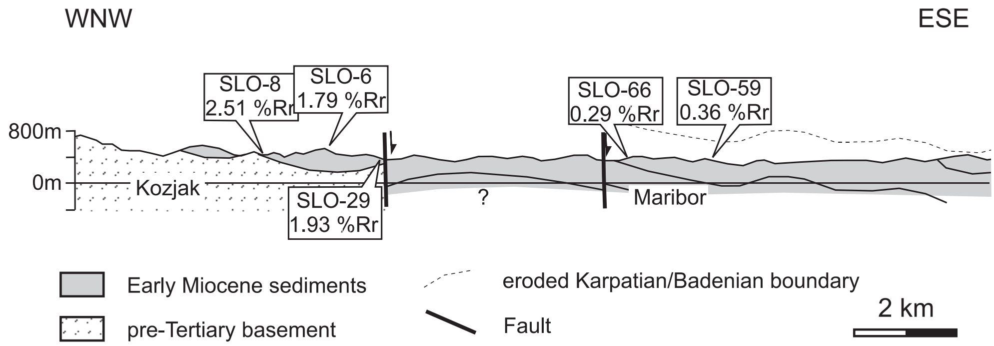

Fig. 7. Simplified geological cross-section through the eastern margin of the Kozjak–Maribor area (see Fig. 3 for location of section). Reflectance values of samples from the neighborhood of the cross-section are indicated. The reconstructed position of the Karpatian/Badenian boundary is shown by dashed line for the eastern part of the cross-section. Thin continuous lines indicate bedding of early Miocene sediments. (Geology and position of faults according to Znidarcic and Mioc, 1988.) The depth of the pre-Tertiary basement in the Maribor area is unknown.

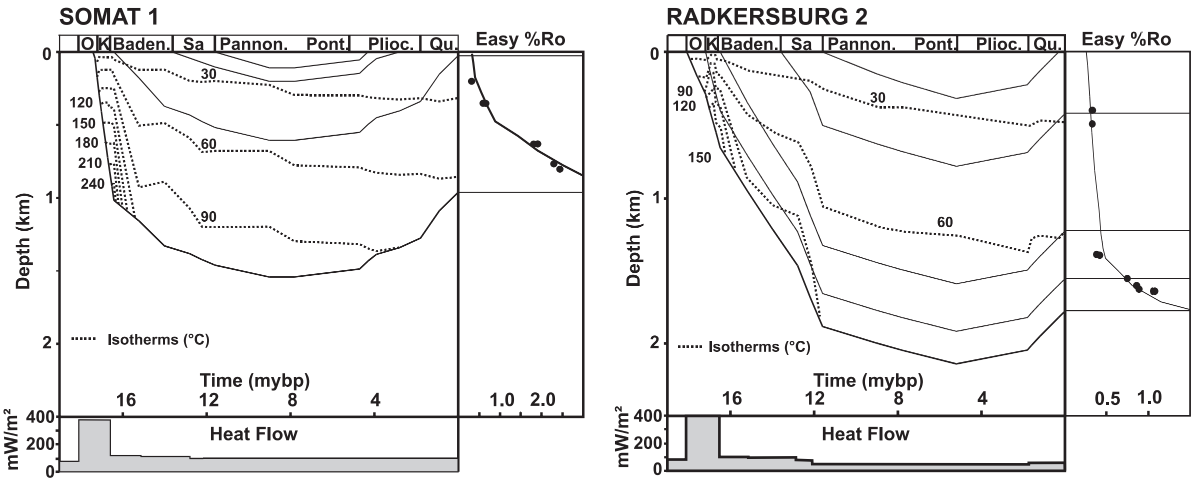

Fig. 8. Burial history, temperature history, and heat flow model of the Somat 1 and Radkersburg 2 wells. In the right part of the figures measured (dots) and calculated vitrinite reflectance values (solid line) are plotted vs. depth.

Vitrinite reflectance values are a result of time and temperature. Therefore, vitrinite reflectance values cannot be directly converted to paleotemperatures. However, because the effective heating time is similar, the temperature reconstructions for the Somat 1 and Radkersburg 2 wells (Fig. 8) can be used to estimate the paleotemperatures in the Maribor area. Probably the 0.4%R_r isoreflectivity line of Fig. 3 corresponds to a paleoisotherm of 60 to 65ºC. Reflectance values of 0.7, 1.0, 1.3 and 1.6%R_r correspond to 125, 155, 175 and 190ºC (±5%), respectively. The highest vitrinite reflectance data in the western Ribnica–Selnica trough suggest paleotemperatures of 180ºC, those northwest of Maribor (2.5%R_r) of 220ºC.

The heat source for the vitrinite reflectance anomaly in the Maribor area is not as obvious as in the Ribnica–Selnica trough. There are two possibilities to explain this important phenomenon.

(1) As mentioned above, Miocene volcanic dikes are known only from the western Pohorje mountains and Miocene volcanoes occur in the Styrian Basin north of Pichla (Fig. 1b). As one working hypothesis, we can postulate a large shallow Early/Middle Miocene pluton (magma chamber) beneath the vitrinite reflectance anomaly, whose magma did not reach the surface. This supposed pluton could easily explain the observed extremely high Miocene heat flow.

(2) The Pohorje and Kozjak mountains form the crystalline margin of the Pannonian basin system that was formed during Miocene extension. At the northeastern rim of the Styrian Basin the core-complex style of extension produced the Rechnitz Window (Tari, 1994; Fig. 1a). If the Kozjak/Pohorje region is also a part of a metamorphic core complex, we have to consider the effect of the advective heat transport due to the subvertical displacement of hot rock bodies (Dunkl et al., 1998). This scenario gives also an explanation for the very young FT ages of detrital apatite grains. In this case both the appearance of the ‘freshly cooled’ apatite grains in the sediment, and the post-depositional overprint of the syn-rift sediments (at Maribor) would be the consequence of the rapid uplift of the metamorphic rocks.

We prefer the first explanation, although the postulated magma chamber was not yet identified by geophysical methods.

As mentioned above, the vitrinite reflectance anomaly near Maribor extends to the Benedikt–Radkersburg area. The distribution of a maximum in the present-day heat flow (up to 120 mW/m^2; Ravnik et al., 1995) is in rather good coincidence with this high maturity zone. However, the recent heat flow anomaly cannot be related to the Miocene thermal event. Perhaps, it is the consequence of the late Neogene exhumation of the deeper Miocene sequence. These late Pliocene compressional tectonics (the latest inversion period in the evolution of the Pannonian Basin; Horváth, 1995) are responsible for the exhumation and denudation of an up to 2 km thick sediment layer at the northern marginal zone of the Pannonian Basin (Árkai et al., 1995). Such magnitude of uplift during the last 2–4 Ma may have produced heat flow anomalies.

6. Conclusions

The following conclusions are drawn.

– The Early Miocene clastic sediments were derived from distinct, local sources. According to the facies, the variable heavy mineral composition and the simultaneous extensional tectonics the source region was a scarp-dominated, mountainous landscape.

– In the surroundings of the Kozjak mountains the Ottnangian–Karpatian sediments contain apatite grains of late Eggenburgian cooling age, only 1–2 Ma older than the time of deposition. The cooling rate of the mainly Austroalpine source units was very fast, denoting tectonic denudation. It means that in the Eastern Alps during Early/Middle Miocene time not only the Tauern and Rechnitz windows (Fig. 1a), but also the Pohorje/Kozjak region was supplying sediment into the surrounding Tertiary basins with nearly syn-sedimentary apatite cooling ages.

– Vitrinite reflectance anomalies in Early Miocene sediments in the Ribnica–Selnica trough and at the eastern margin of the Kozjak mountains are evidence for a strong post-depositional thermal overprint. The vitrinite reflectance patterns suggest that maximum heating at the eastern end of the Kozjak (with temperatures up to 220°C) ended at the Karpatian/Badenian boundary (16.4 Ma) or during the early Badenian (16.4–15 Ma). Apatite fission-track ages indicate that the thermal overprint had ended in middle Badenian (14.4 ± 2.3 Ma) time. The difference between these ages represents the short time interval during which the sediments cooled from maximum temperatures to approximately 100°C.

– The vitrinite reflectance anomaly in the western Ribnica–Selnica trough is located in the immediate vicinity of the dacite body in western Pohorje mountains. In this case the thermal overprint can be attributed to the volcanic activity.

– Vitrinite reflectance of Early Miocene sediments is also elevated in the Vitanje area at the southwestern margin of the Pohorje mountain. It can be interpreted also as the consequence of high Early/Middle Miocene heat flows in the Pohorje region.

– For the heat source of the Maribor–Benedikt–Radkersburg area we consider the following possible explanations:

(1) The heat flow maxima with more than 250 mW/m^2 can be best explained by magmatic events. We therefore postulate the existence of shallow Karpatian/early Badenian plutons (magma chambers) below this area. These supposed bodies would be situated between the western Pohorje dacites and the Miocene volcanoes in the Styrian Basin.

(2) If the magnitude and style of extension in the Kozjak/Pohorje region was similar to the Neogene core complex-style extension at the northeastern end of Styrian Basin, the advective heat transport would increase the geothermal gradient and would result in high organic maturation and apatite FT resetting. In this case the rapid uplift of the metamorphic rocks (Miocene apatite FT cooling ages in the sediment) and the ongoing effect of the 'thermal dome' on the syn-rift sediment would be interdependent. This scenario gives also an explanation for the very young FT ages of detritic apatite grains.

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