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K-Ar geochronology and petrography of the Miocene Pohorje Mountains batholith (Slovenia)

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Abstract: A series of K-Ar ages from the Alpine Pohorje Mountains igneous complex is presented. The granodiorite with dacite was emplaced in a dynamic environment in the form of a single major intrusion, between 19–18 Ma (Ottnangian), into metamorphic host rocks. The granodiorite includes an older mafic portion of transitional diorite to pyroxenite composition, cezlakite, yielding an age of ~20 Ma. Granodiorite magmatism was followed by major tectonic activity causing uplift of the Pohorje Mountains complex, and the whole batholith cooled rapidly at rather shallow depths, yielding uniform cooling ages of around 16.7 Ma, at the Karpatian/Badenian boundary. The process was accompanied by the intrusion of minor rhyodacitic dykes in the north-western part of the Pohorje Mountains complex and of thin lamprophyre dykes mostly into the metamorphic rocks on the western margin of the pluton. The pyroclastics within the Miocene sedimentary rocks attest to the latter's young age and subaerial emplacement conditions. In the final stage of the magmatism, aplite-pegmatite melts intruded into the solidified granodiorite. The Pohorje Mountains batholith represents the westernmost intrusion along the extensional structures of the Pannonian Basin. The main magmatic activity could be related to deep transtensional fractures of the Labot fault system north of the Periadriatic zone. The tonalite and granodiorite from the Pohorje Mountains are petrologically different and younger than the Oligocene tonalite from Železna Kapla (Eisenkappel), as well as the tonalites further west, and the tonalites buried in the Zala Basin in Hungary (roughly between 40 to 30 Ma), which belong to Paleogene Periadriatic intrusions.

Key words: Miocene, Pannonian Basin, Periadriatic zone, Pohorje, Labot fault, K-Ar dating, granodiorite batholith.

Introduction

Tertiary calc-alkaline intrusives and volcanics are widespread along the Periadriatic zone (e.g. the Bergell, the Rieserferner, the Adamello, and the Železna Kapla (Eisenkappel, Karawanke) (Fig. 1). The Pohorje Mountains igneous complex (usually abbreviated to PMIC) is situated at the easternmost end of the Periadriatic zone that separates the Eastern Alps from the Southern Alps and the north-westernmost Dinarides. It comprises a pluton and a volcanic stock. They are lithologically subdivided into seven different rock types: tonalite, granodiorite transiting to porphyritic granodiorite, a mafic portion of questionable diorite to pyroxenite composition called cezlakite, dacite, rhyodacite and lamprophyre, locally called malachite. As well as this, aplite-pegmatite veins intersect the plutonic rocks, most frequently in the southern part of the PMIC. Tonalite represents the easternmost part of the pluton close to Slovenska Bistrica, and has a an unclear transitional zone to granodiorite. In the area between Osankarica and Recenjak the latter transits to porphyritic granodiorite that occupies the largest, central area of the PMIC. Near the village of Cezlak a lens of cezlakite is incorporated into the granodiorite. The northeastern part of the PMIC consists of dacite. Its first occurrences can be found on the traverse line from the area of Mala Kopa to Ribnica-on-the-Pohorje. In the same area infrequent dykes of rhyodacite and rare lamprophyre occur (Fig. 2).

During recent decades the PMIC has been the subject of extensive research. This is because the area provides an excellent opportunity to understand the geodynamic significance of this magmatism. Although numerous geological studies (including works which deal with geochemistry, structure, paleomagnetism and stratigraphy) have been performed by many researchers (e.g. Benesch 1918; Dolar-Mantuani 1935, 1938a,b; Faninger 1970, 1973; Mioč & Žnidarčič 1976, 1978; Mioč & Žnidarčič 1983; Dolenec et al. 1987; Činč 1992; Zupančič 1994a,b, 1994/95; Altherr et al. 1995; Sachsenhofer et al. 1998, 2001; Pamić & Palinkaš 2000; Trajanova 2002a; Fodor et al. 2004; Márton et al. 2006), chronological studies have been performed only sporadically, and in limited areas. Because of the overall petrological similarity to the Periadriatic intrusions, the geodynamic framework of the Pohorje Mountains magmatism has been generally attributed to the Periadriatic fault system. This view is further supported by its spatial proximity to the Periadriatic line along which the Upper Oligocene bodies are aligned further west (Fig. 1).

The age of the PMIC igneous rocks has been a subject of vigorous debate over many years. The sequence of eruptions cannot be established by mere observation since there is a general lack of direct stratigraphic relations and intercalations. A meaningful correlation within the relevant time span can, however, usually be obtained by radiometric dating. Recently numerous K-Ar age data have been accumulated for the igne-

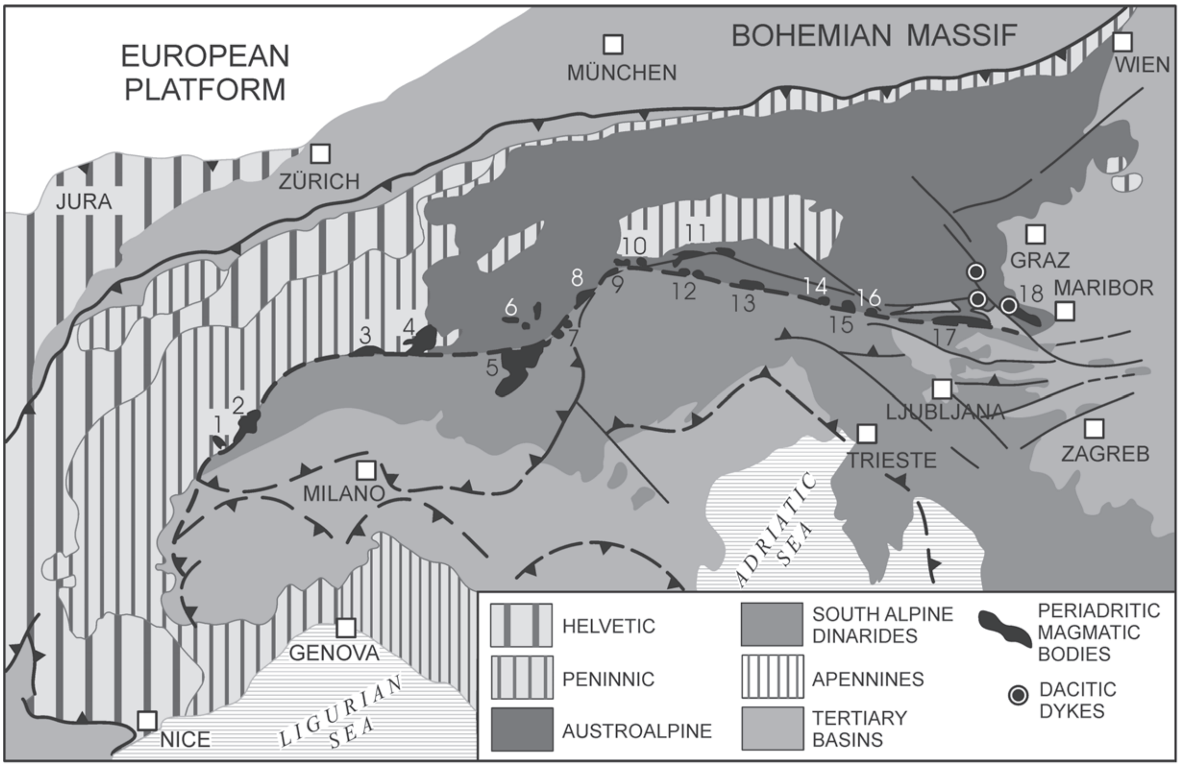

Fig. 1. Position of the Pohorje Mountains igneous complex (18), Železna Kapla (17) and other magmatic bodies (1–16) distributed along the Periadriatic line (Márton et al. 2006).

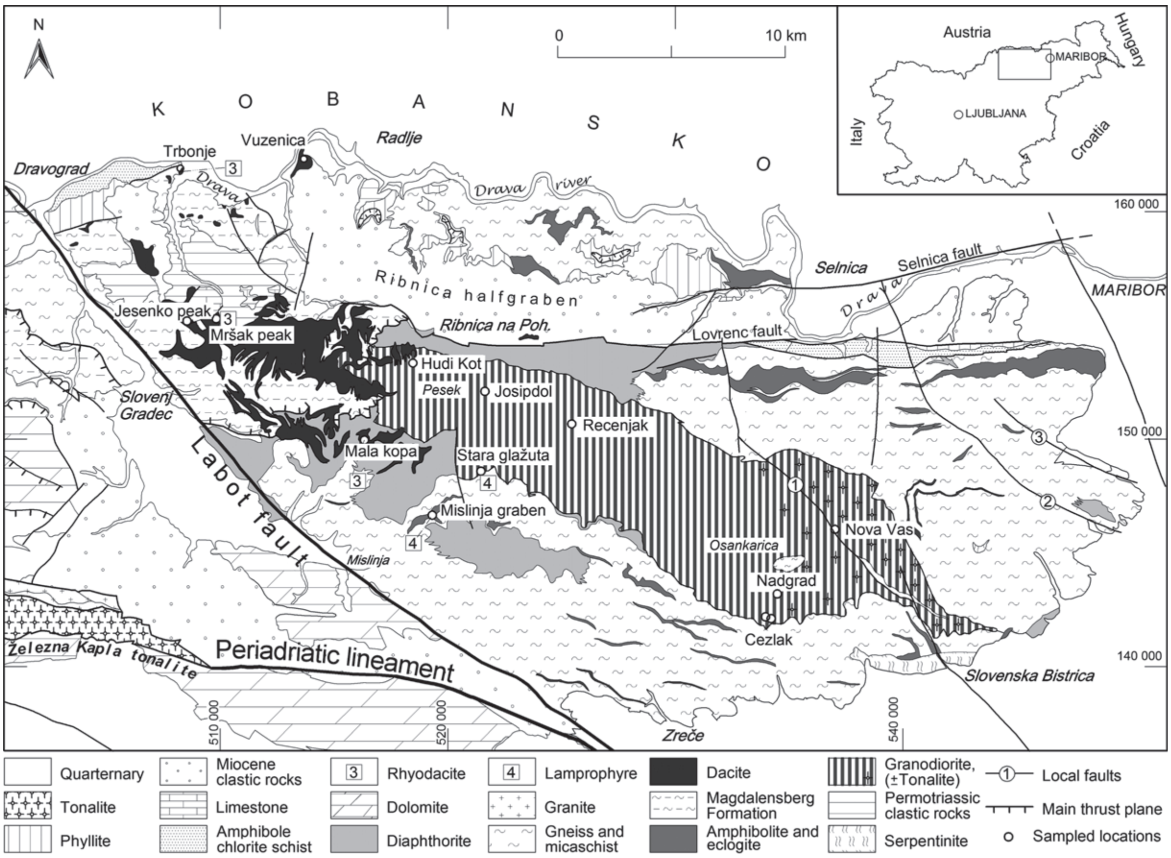

Fig. 2. Simplified geological map of the Pohorje Mts (modified after Mioč & Žnidarčič 1976 and Žnidarčič & Mioč 1988), showing the sampled localities.

ous and metamorphic rocks of this region, making it possible to discuss the sequence of magmatism chronologically.

Here a description of the petrography and geochronology of the studied area is given, as well as of the field relation of the main PMIC rock types. The data thus obtained are then used to propose a model of the volcano-plutonic complex formation, the reconstruction of the bulk shape of the body, and to compare the structural controls on magmatism in the Periadriatic zone and in the Pannonian Basin.

Geological setting

The Pohorje Mountains complex represents the southeastern part of the Eastern Alps. It extends toward the north into the Kobansko region, the Saualpe and the Koralpe (Fig. 1). The Periadriatic dextral strike-slip fault zone represents its southern termination. Toward the west it is bounded by the Karavanke Mountains. The Pohorje Mountains complex and the Karavanke Mountains are separated by the NW-SE-trending Labot (Lavanttal) fault zone. The eastern prolongation of the Pohorje Mountains complex is dismembered and covered by Neogene sediments in the westernmost part of the Pannonian Basin. Along the Labot fault the Pohorje Mountains block was strongly tilted, that is downthrown at its western end and uplifted at its eastern end (Trajanova 2002; Trajanova & Pécskay 2006).

Low to high pressure metamorphic rocks make up the majority of the Pohorje Mountains complex, and their characteristics are described in several works by Hinterlechner-Ravnik (e.g. 1971, 1982, 1988), Hinterlechner-Ravnik & Moine (1977), and Hinterlechner-Ravnik et al. (1991a,b). The deepest sequences are exposed in the southeastern part of the Pohorje Mountains. On the basis of mineralogy UHP metamorphism was observed in eclogites and garnet peridotites near Slovenska Bistrica (Jának et al. 2004, 2006). HP metamorphism was also reported by Sassi et al. (2004) in eclogites.

In the northwestern part of the Pohorje Mountains, the so-called Magdalensberg thrust sheet rests on top of diaphthoresed gneisses and micaschists. It consists of slightly metamorphosed Silurian to Devonian pelagic sediments, with intercalations of volcaniclastic rocks, diabase, limestone and iron dolomite. This series is unconformably overlain by Permian-Triassic and Miocene sediments (Mioč & Žnidarčič 1978 and Žnidarčič & Mioč 1989).

The PMIC intruded into already polymetamorphosed rocks. Except in the case of the contact with the diaphthoresed gneissic sequence, where andalusite schist and gneisses occur, the pluton did not affect the metamorphic rocks significantly (Hinterlechner-Ravnik 1971 and Mioč & Žnidarčič 1978).

The basic interpretation of the tectonic structure of the area was established by Mioč & Žnidarčič (1978) and by Žnidarčič & Mioč (1989). The main tectonic structures are the following: Upper Cretaceous collisional nappes with a phyllonite low angle shear zone, proposed by Trajanova (2002), the Periadriatic zone dislocated along the Labot fault and the Ribnica-Selnica half-graben, passing to a graben east of the village of Selnica.

According to Fodor et al. (2002) the magmatism related to the Neogene basin formation was practically coeval with the cooling of metamorphic rocks in northeast Slovenia. Subsequently it was followed by intensive brittle faulting, yielding the Lovrenc and Selnica faults and local faults crosscutting the Pohorje block mostly in the northwest to southeast direction (Fig. 2). In accordance with these tectonic events, a Miocene clockwise rotation and a subsequent Pliocene counterclockwise rotation occurred in the PMIC (Márton et al. 2006).

Mioč & Žnidarčič (1978) provided structural evidence for the existence of Caledonian and Variscan metamorphism prior to Alpine metamorphism, whereas Hinterlechner-Ravnik et al. (1991b) speculated that metamorphic rocks on the eastern side of the Pohorje Mountains could represent an older tectonic melange, which was reworked during the Variscan and Alpine histories.

Thöni (1999) determined a Sm-Nd age of 93–87 Ma on garnets from metapelites in the southern Pohorje Mountains. Sm-Nd and U-Pb ages of eclogites cluster around 90 Ma (Miller et al. 2005). The conventional K-Ar and zircon and apatite fission-track ages of metapelites scatter between 19 and 10 Ma (Márton et al. 2002, 2004; Fodor et al. 2007). A systematic chronological study of the metamorphic rocks is in progress. Although the polymetamorphic history of the rocks is unquestionable, radiometric dating suggests only Alpine metamorphic events up to now.

Petrography

Based on K_2O versus SiO_2 plots, the main part of the PMIC displays a clear medium to high-K calc-alkaline affinity (Pamić & Palinkaš 2000), while the easternmost part is represented by tonalite, which was also confirmed by various classification criteria (Faninger 1970). This rock is subordinate and generally occurs as isolated outcrops, without a clear relationship with the granodiorite. The structure is massive and medium- to coarse-grained (1 to 5 mm). It consists predominantly of plagioclase, biotite, sparse hornblende, some K-feldspar and quartz. Accessory minerals are allanite, apatite, titanite, zircon and opaque minerals. Traces of micrograins of garnet and pyroxene can be found.

The plagioclase is polysynthetically twinned, and shows numerous deformation effects. In places it is overgrown, corroded and included in younger plagioclases, together with biotite (Fig. 3) and quartz.

The mafic minerals are biotite and sparse hornblende (up to 1 %). Biotite frequently shows undulate extinction, kink bands, and degradational recrystallization, and is extensively corroded by plagioclases, K-feldspar and quartz (Fig. 4). Sometimes it contains inclusions of accessory minerals (allanite, apatite, zircon and opaque minerals). Opaque minerals and sagenite were partly produced by secondary alteration. In such cases the flakes are rimmed or completely replaced by chlorite. Hornblende grains are usually fractured, reaching up to 4 mm in size.

K-feldspar is sparse and can be included in the younger minerals. Grains up to 10 mm in size belong to a subsolidus metasomatic origin. They are often poikilitic with inclusions

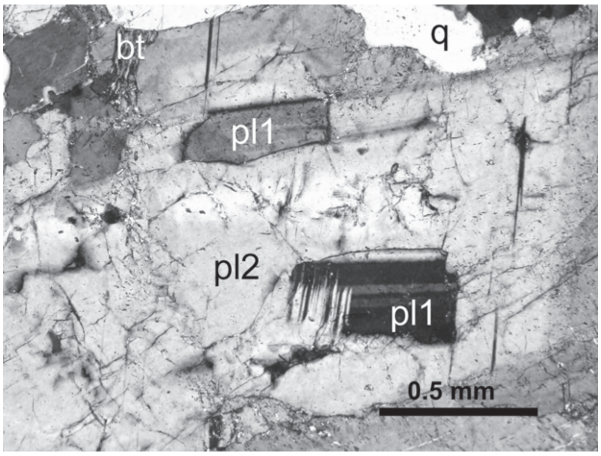

Fig. 3. Polysynthetically twinned plagioclase (**pl1**) overgrown and corroded, together with biotite (**bt**), by younger plagioclase (**pl2**). Tonalite/granodiorite transition. X nicols, Nadgrad.

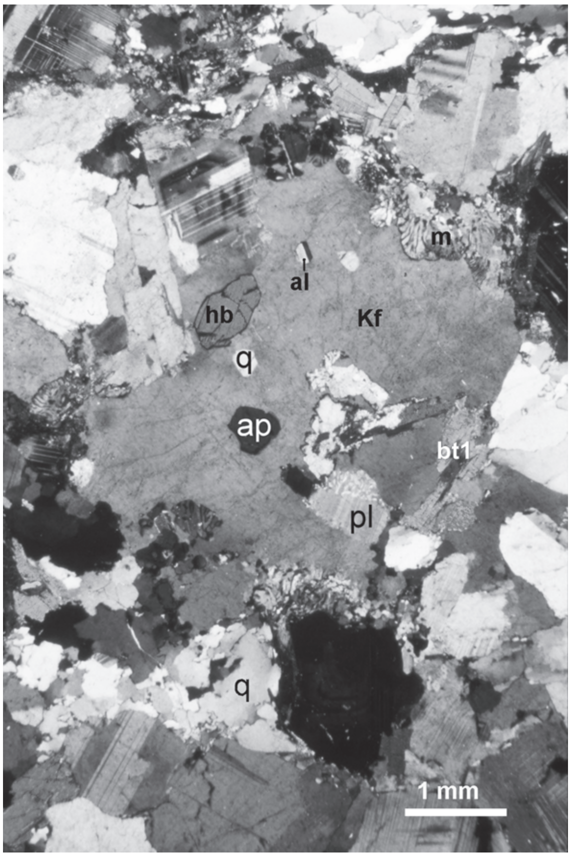

Fig. 4. Subsolidus metasomatic K-feldspar grain with myrmekitic reaction rim toward plagioclases, including plagioclase (**pl**), biotite (**bt**), hornblende (**hb**), apatite (**ap**) and allanite (**al**). The biotite is strongly corroded and slightly chloritized. Tonalite/granodiorite transition, X nicols, Cezlak.

of corroded plagioclases with myrmekitic reaction rims, quartz and biotite (Fig. 4), and are restricted to the transitional zone to granodiorite.

Quartz is squeezed between the grains of plagioclases and of mafic minerals. It exhibits strained and broadly E-W stretched grains with jagged grain boundaries, extremely undulate extinction and strong dynamic degradational recrystallization.

The exact mineralogical composition of the tonalite, and in particular of the quantity of the individual minerals, is greatly obscured by subsequent alteration.

The main body of the PMIC belongs to a medium- to fine-grained *granodiorite*. The structure is massive but the rock displays an oriented fabric developed mostly as a result of external pressure during the magma emplacement, and especially of the dynamic environment during its solidification. Plagioclases, biotite, K-feldspar, and quartz are the main constituents. Hornblende is rarely present. Allanite, some epidote, opaque minerals (mostly magnetite), apatite, zircon and rare titanite occur as accessory minerals.

Plagioclase prevails among feldspars. The coarser grained, polysynthetically twinned plagioclases are older and sparser, and are restricted to the more eastern parts of the pluton (Nova vas and the Nadgrad area), indicating mingling with tonalite. They sporadically include magmatically corroded homogeneous plagioclase grains (noticed also by Zupančič 1994/95) that could belong to xenocrysts. In this transitional area the older plagioclase grains are overgrown and corroded by younger, zoned plagioclase (Fig. 5). The latter show interrupted oscillatory growth with partly resorbed zones, pointing to a dynamic environment of crystallization. They include small flakes of biotite and accessory minerals. In places the outer zone of the plagioclase includes micrograins of optically unaffected quartz (Fig. 5), giving evidence of its epitactic growth and rapid cooling. Their composition ranges from acid to intermediate, with an average An-content of 35 % (Dolar-Mantuani 1938; Faninger 1970 and Činč 1992).

Two generations of biotite occur squeezed between grains of feldspars and of strained quartz. Biotite of the first generation shows larger grains, and is sometimes overgrown by finer, younger biotite. The latter is characterized by minor alteration and a preferred orientation.

According to Dolar-Mantuani (1938) and Faninger (1970), around 5 %, and up to a maximum of 30 %, of the rock is represented by K-feldspar. In deeper parts of the pluton in the area of transition of tonalite to granodiorite two generations can be determined, hence the frequency is higher. The younger K-feldspar includes, assimilates and corrodes the plagioclases, biotite and quartz, forming myrmekitic reaction rims towards the plagioclases (Fig. 4). Zupančič (1994b) proposed that this K-feldspar is a result of an extensive K-metasomatism, which transformed tonalite to granodiorite. However, the newly obtained data support this conclusion only for the transitional area of tonalite to granodiorite and not for the whole granodiorite body.

Quartz represents late crystallization phase of the granodiorite, and is tectonically less affected. It may slightly corrode the plagioclases and biotite.

Hornblende is present subordinately and restricted to the eastern parts of the pluton, closer to the tonalite. Within the rest of the body it is connected to the peripheral parts, and to the more mafic enclaves. In the first case it has xenomorphic fractured grains, similar to xenocrysts that are partly replaced by biotite and corroded by plagioclases. In the peripheral areas the hornblende is hypidiomorphic, and includes biotite flakes.

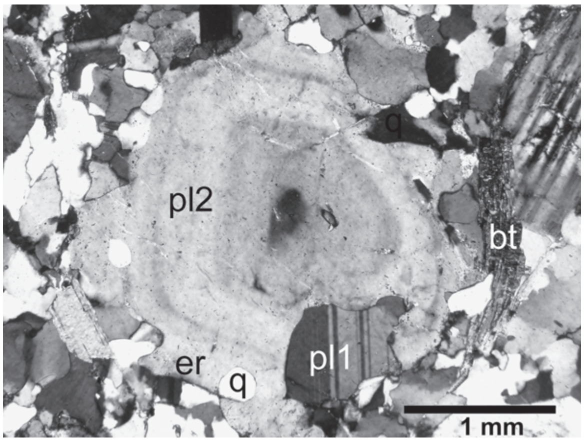

Fig. 5. Zoned plagioclase (**pl2**) overgrowing and corroding older plagioclase (**pl1**). Younger plagioclase includes micrograins of optically unaffected quartz (**q**) in the outer epitaxic rim (**er**). Granodiorite. X nicols, Nadgrad.

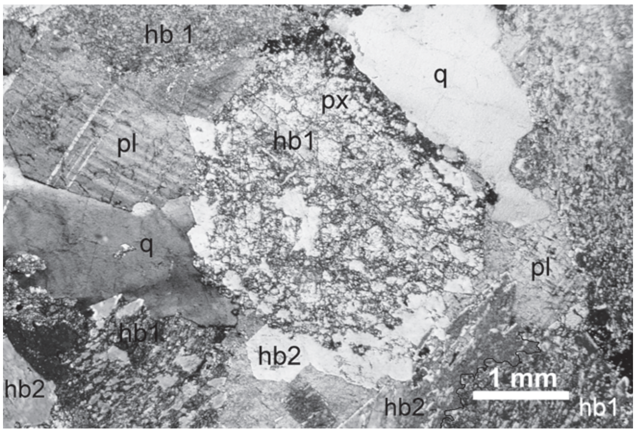

Fig. 7. Relics of pyroxene (**px**) in older hornblende (**hb1**). Euhedral secondary hornblende (**hb2**) grows on older hornblende and pyroxene. Quartz (**q**) replaces plagioclase (**pl**). X nicols, cezlakite from the Cezlak II abandoned quarry.

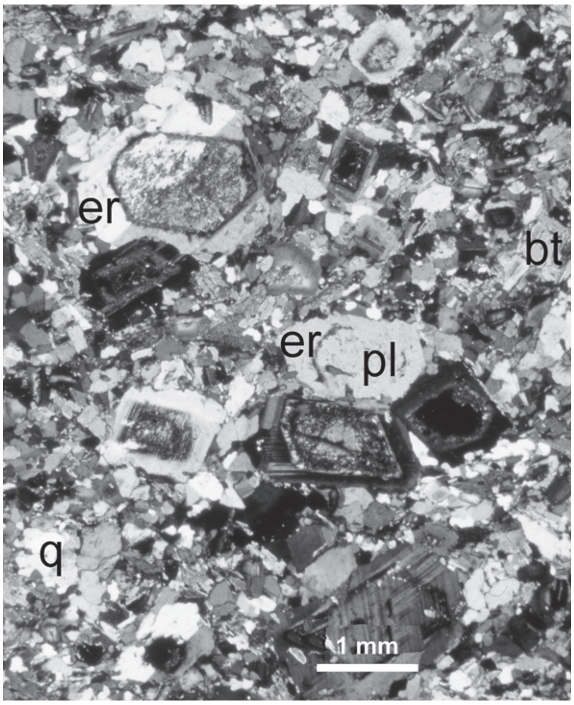

Fig. 6. Porphyritic granodiorite with partly altered cores of zoned plagioclase phenocrysts (**pl**) with epitaxic rims (**er**), biotite (**bt**) and quartz (**q**). X nicols, Hudi Kot.

The granodiorite is crosscut by numerous aplite-pegmatite veins. They have caused alteration of the plagioclases along the fractures indicated by overgrowing sericite and some calcite near the grain boundaries, as well as chloritization of the biotite and crystallization of the K-feldspar micrograins inside the microfractures. At least two generations of the veins can be clearly distinguished. The older veins usually show the same deformation pattern as the surrounding granodiorite.

The composition of the *porphyritic granodiorite* is the same as that of the granodiorite. It is characterized by phenocrysts of plagioclase, which show complex twinning, zoning and pronounced epitactic growth (Fig. 6). The biotite is fine-grained, usually fresh and less corroded than in the granodiorite. The matrix is a fine to micro-grained mixture of plagioclase, K-feldspar and quartz. The latter can be enriched in peripheral areas of the pluton.

Cezlakite, an uncommon transitional rock of diorite to pyroxenite composition, is characterized by a medium to coarse-grained (~4 mm) idiomorphic to xenomorphic texture and a massive structure. Clinopyroxene, hornblende and plagioclase are the main mineral constituents, whereas K-feldspar, biotite and quartz are sparse and together with traces of muscovite are secondary in origin. Titanite, opaque minerals and apatite represent accessory minerals. Chlorite, sparse epidote, calcite, and traces of sericite are products of alteration.

Light-green augitic clinopyroxenes are prevailing constituents of the primary rock. Less altered grains contain numerous patches of hornblende, but usually just represent residual inclusions (Fig. 7). In the peripheral parts pyroxenes have not been preserved, and an oriented structure dominates due to the lineated amphibole grains. Hornblende replaces and assimilates the pyroxene, and includes some accessory minerals. Younger amphibole replaces and overgrows the hornblende and some older plagioclases (Fig. 7), and includes frequent flakes of biotite. The amphiboles show the characteristics of blastic growth, that is of metasomatism in a subsolidus state, when topometasomatic processes usually play a major role (Augustithis 1973). The plagioclases often have crossed lamellas or are polysynthetically twinned. It has been estimated that there is less than about 10 % of them. They are extensively replaced by metasomatic K-feldspar and quartz that occur in interstitial spaces, and usually have slightly undulate extinction (Fig. 7).

Dykes

In the north-western part of the PMIC the groundmass of the rock becomes microcrystalline and gradually transits to a rock with porphyritic texture and holocrystalline groundmass. It has a clear transitional character to porphyritic granodiorite, nevertheless we followed the original terminology keeping the traditional name, *dacite*. Volumetrically, dacite represents only a small portion of the PMIC. The northeasternmost dyke crops out near Vuzenica. It has a grey colour with a greenish tint. Numerous phenocrysts of plagioclase, as well as some biotite, hornblende and quartz, are embedded in a microcrystalline groundmass. In some localities phenocrysts of biotite and plagioclases are slightly altered, sericitized and chloritized. Biotite is usually magmatically corroded and deformed, whereas the younger generation consists of finer flakes which are incorporated in the groundmass, probably demonstrating rapid cooling. Small sills within the metamorphic host rock show oriented structure and partly resorbed phenocrysts of plagioclase and biotite, demonstrating the shear stress effect (Fig. 8). Bigger, older grains of xenomorphic hornblende can be overgrown by biotite, and in some areas they are replaced by secondary minerals (mostly chlorite and calcite). It seems that they belong to xenocrysts. Small idiomorphic phenocrysts of hornblende are frequently skeletal, with salic inclusions in the core, indicating their late and rapid crystallization (Fig. 9). In some peripheral areas (e.g. near Stara Glažuta) and in sills the dacite is significantly enriched with hornblende, yielding lamprophyre-like rock.

Rhyodacite is sparser than dacite, and mostly forms thin dykes. With respect to mineral composition, plagioclase phenocrysts prevail over quartz and biotite, and sporadic K-feldspar also occurs. Hornblende is present rarely. The plagioclases are predominantly zoned and have numerous glassy inclusions (Fig. 10) and/or dark rims. They sometimes contain inclusions of accessory minerals and biotite. Sparse K-feldspar displays idiomorphic phenocrysts overgrowing small grains of biotite and plagioclase. The groundmass is nearly glassy or sub-microscopically crystallized. The shallowest, vesicular dykes of rhyodacite occur at Trbonje. Beside the above-mentioned constituents, the rhyodacite frequently contains xenoliths of slates and sericite-bearing quartz sandstones. Compared to the dacite, hornblende is rarely present or missing, K-feldspar and undeformed quartz phenocrysts are more frequent and often magmatically resorbed (amoeboid, Fig. 11), together outlining one of the most obvious compositional differences.

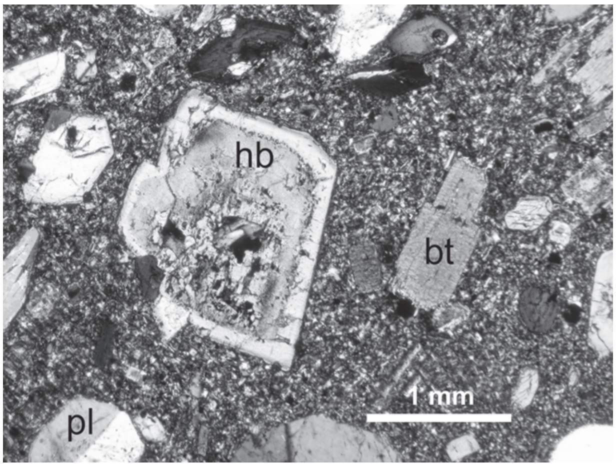

Fig. 9. A skeletal phenocryst of hornblende (hb) with salic inclusions in the core, biotite (**bt**), plagioclase (**pl**); dacite. X nicols, area of the peak Jesenko.

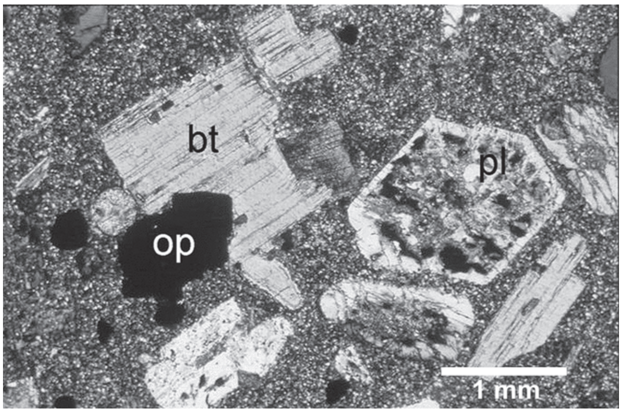

Fig. 10. Fresh, kinked biotite (**bt**) with an opaque grain (**op**) and altered plagioclase phenocrysts (**pl**) including glassy material; rhyodacite. X nicols, peak Mršak.

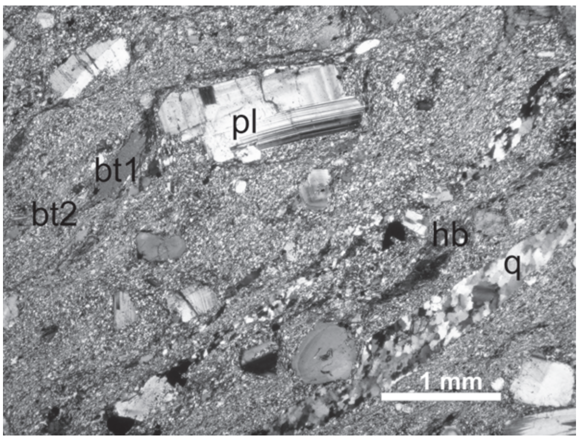

Fig. 8. A sill of dacite with an oriented structure showing the shear stress effect. Brittle deformed phenocrysts of plagioclase, slightly chloritized biotite (**bt1**), sparse hornblende (**hb**) and stretched quartz (**q**) crystallized prior to deformation, while younger biotite (**bt2**) and quartz in the microcrystalline groundmass are syndeformational. X nicols, E of Ribnica-on-the-Pohorje.

Along the western margin of the pluton some small, mafic dykes of *lamprophyre*, variety malchite, occur. The dykes crosscut the foliation planes of the metamorphic host rock at low angles. They consist of phenocrysts of hornblende (often with salic inclusions in the core, as in the dacite) and zoned plagioclase, rarely of biotite, and a micro- to cryptocrystalline groundmass (Fig. 12). The presence of microxenoliths is characteristic, as well as rounded, slightly altered plagioclase and deformed hornblende phenocrysts, probably belonging to xenocrysts. In the core of some xenoliths colourless fibres of older amphibole are found, probably belonging to tremolite or anthophyllite, suggesting the metamorphic origin of the inclusions. They are surrounded by and altered to chlorite and some calcite. The transitional ductile to brittle character of the deformation indicates syntectonic emplacement and subsequent post-cooling deformation of the lamprophyre.

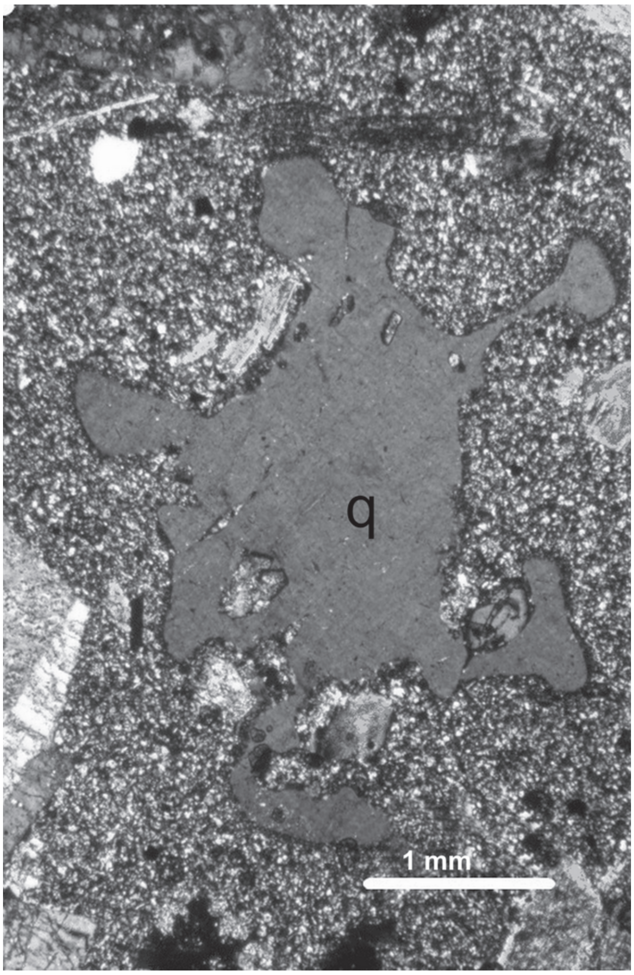

Fig. 11. Magmatically resorbed amoeboid quartz (**q**) phenocrysts in rhyodacite. X nicols, Mala Kopa.

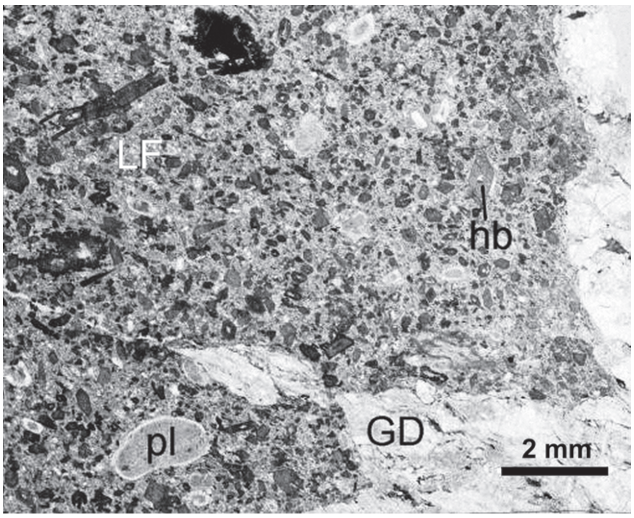

Fig. 12. A lamprophyre (**LF**) dyke intruding the margin of granodiorite (**GD**). Phenocrysts of hornblende (**hb**) often include salic inclusions in the core. The plagioclases (**pl**) are rounded and slightly altered. Stara Glažuta.

Spatial relationships of the rocks

The broad spatial relationship of the rocks of the PMIC can be seen in Fig. 2. The strongest influence of the post-cooling brittle processes is expressed in the tonalite. The latter is intersected by rare, thin veins mostly of aplite and aplitic granodiorite, and is surrounded by high-grade metamorphic rocks. The relatively wide zone of interaction with the granodiorite can be based on petrographic data, reaching the area of Nadgrad and close to Osankarica and Cezlak.

No chilled margins were found along the contact of the granodiorite body towards the host rocks. This could be explained as the effect of a turbulent magma flow during emplacement, which swept away crystallized material (Wilson 1989), or it is possible that the surrounding rocks were still hot enough to prevent chilling. The granodiorite fabric indicates rapid crystallization in a dynamic environment. The marginal parts of the granodiorite body, especially towards the south (e.g. in the Cezlak area), are criss-crossed by numerous aplite-pegmatite veins (Fig. 13). In the area between Osankarica and Recenjak increasing heterogeneity in the grain size of the pluton can be observed, as well as a gradual transition to porphyritic granodiorite. It is difficult to recognize a clear pattern due to the later cleavage following intensive subhorizontal brittle shearing associated with normal faulting, and poor outcrop conditions.

In the southeast, in the area of Cezlak, the cezlakite lens is incorporated in the granodiorite. It is intersected by granodiorite (Fig. 14), as well as by numerous aplite-pegmatite and rare lamprophyre-like veins.

The transition of porphyritic granodiorite to dacite occurs on the transverse line Mala Kopa–Hudi Kot. Dacite forms dykes and smaller sills in the metamorphic host rocks. In the marginal parts of the pluton of this area the dacite changes slowly to more mafic, lamprophyre-like rock. No evidence has been found to show that the dacite intruded into the granodiorite.

In the north-western part of the PMIC (e.g. in the area of Mala Kopa and Trbonje), rhyodacite has intruded mostly as thin, subvertical, undeformed, light grey dykes, with a pronounced discordant relationship to the foliation of the neighbouring metamorphic rocks. Along the contact zones the country rocks are altered into epidote hornfels and skarn. In the area of Mala Kopa minor rhyodacitic dykes have intruded into the pluton, and at one place seem to crosscut the small dacitic sill. The shallowest rhyodacite intrusion was found near Trbonje.

The areas of the Stara Glažuta and Mislinja graben are characterized by the most frequent mafic dykes, lamprophyres, with thicknesses mostly of less than 1 m. These dykes have intruded into the surrounding metamorphic rocks at a low angle to the foliation and sporadically shallowly into the pluton. Within the medium-grade metamorphic rocks they are associated with amphibolite schists and amphibolites (e.g. in the Mislinja graben). Along most of the contacts, extensional displacements can be seen toward the southeast.

Very small aphanitic mafic dykes are included in and also crosscut the aplite-pegmatite veins in the cezlakite, and appear to be the youngest. Their relation to the lamprophyre has not yet been established.

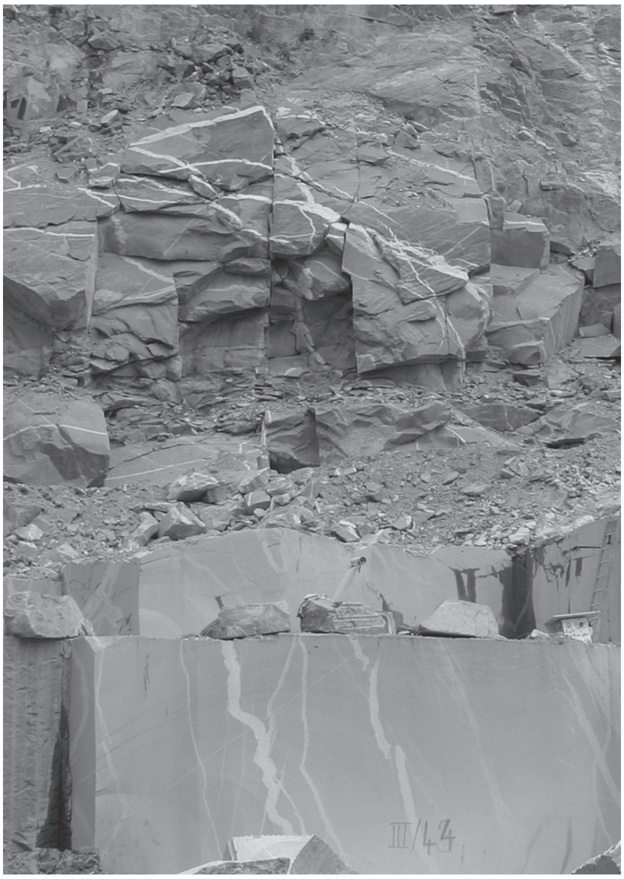

Fig. 13. Aplite-pegmatite veins (white) crosscutting granodiorite. Active granodiorite quarry, Cezlak I.

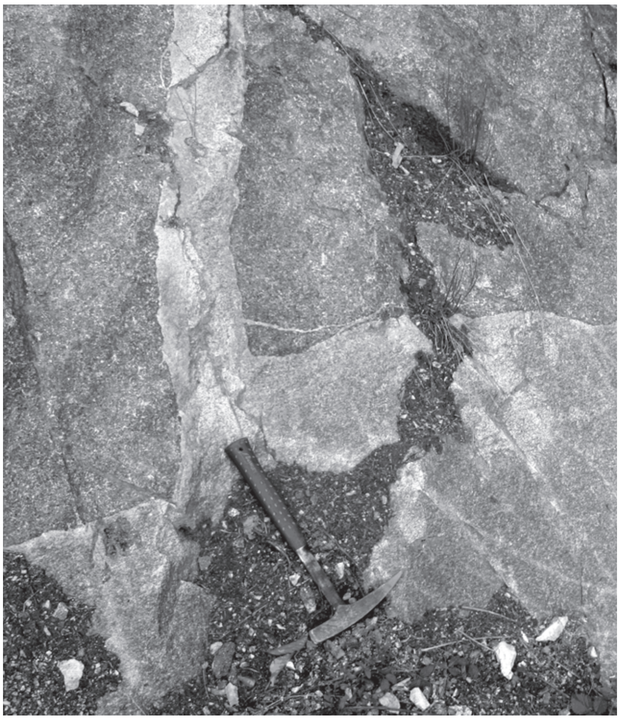

Fig. 14. Granodiorite (light grey) crosscutting cezlakite (dark grey). Abandoned cezlakite quarry, Cezlak II.

Stratigraphy

Sporadic biostratigraphic data are available from the study area. The bulk of the PMIC intrudes into Austroalpine basement rocks. However, in the northwesternmost part, the roof of the body is framed by the nappe of the low-grade metamorphic rocks of the Magdalensberg formation, which are unconformably overlain by Permotriassic clastic rocks and relics of Cretaceous and Tertiary sediments. In the same region dacitic tuffs are interbedded with Miocene sediments. According to Mioč & Žnidarčič (1978) they are mainly Miocene (at that time Helvetian). Paleogene sediments are restricted to a very small area near Zreče, on the southern margin of the Pohorje Mountains. The deposition of Neogene sediments started in the Early Miocene. By means of recent investigations Jelen & Rifelj (2003) have determined a Karpatian age of the sediments north of Maribor, in the area of the southernmost Styrian extensional wedge (Austria). Based on the lateral continuity, these authors have suggested the same age for the Miocene sedimentary rocks of the wider Pohorje area. Numerous dacite and frequent tonalite pebbles occur in the Karpatian (?) unsorted conglomerates. Petrographic and chronological studies of them are in progress.

Earlier chronological data

A first estimate of the radiometric age of the Pohorje Mountains igneous complex was proposed by Žurga in 1926. Based on the relationship to the neighbouring metamorphic and sedimentary rocks, he proposed an Early Miocene age of the pluton. Later, Germovšek (1954) placed the age between the Late Cretaceous and Miocene. The first radiometric age (an Rb-Sr model age of 19.5 ± 5 Ma), determined on tonalites from the Pohorje Mountains, was published by Deleon (1969). According to Faninger (1970), the Austroalpine crystalline rocks of the Pohorje massif were intruded by tonalites during Oligocene times, whereas dacitic volcanism followed in the Early Miocene (Faninger 1973). Based on field relations, the Pohorje pluton was assigned the same age as the Železna Kapla (Eisenkappel) intrusive, for which different authors have determined a Rb-Sr age of 29 to 28 Ma (Mioč & Žnidarčič 1983).

Three K-Ar ages determined on cezlakite and granodiorite (w.r. of cezlakite, 18.7 ± 0.7 Ma; biotite separated from cezlakite, 16.9 ± 0.4 Ma; and biotite separated from granodiorite, 16.4 ± 0.4 Ma) indicate that the emplacement of the pluton occurred in Neogene time (Dolenec 1994).

One dacitic dyke exposed at Vuzenica was dated by the fission-track method. Based on the apatite FT age (14.6 ± 1.8 Ma) Sachsenhofer et al. (1998) concluded that either the depth of the emplacement was shallow or that exhumation of the dated dyke took place soon after the magmatic activity. However, they considered that the tonalite of the Pohorje Mountains is an Oligocene Periadriatic intrusion. Pamić & Palinkaš (2000) assumed that the Pohorje Mountains and the Karavanke plutons are part of a series of mid-Tertiary intrusives which extend along the Periadriatic zone.

Experimental methods

Sampling

Systematic sampling was performed in order to obtain information about the 3-dimensional distribution of isotopic ages in the PMIC. These samples cover an area of the pluton about 10 km wide and 35 km long, with an elevation of nearly 1 km. The samples were collected at several localities along a southeast-northwest oriented section of the PMIC, mostly from quarries and natural outcrops: Nova vas in the Smrečno area (NV), Nadgrad (Ng), quarries Cezlak I and Cezlak II (Cz), Recenjak (Rc), Josipdol (Jd), Hudi Kot (HK), Mislinja graben (MG), Stara Glažuta (SG), Mala Kopa (MK), peak Mršak (pMs), peak Jesenko (pJ), Vuzenica (Vu) and Trbonje (Tb) (Fig. 2). For K-Ar dating 31 representative rock samples were taken, and one sample was taken from Železna Kapla tonalite (Karavanke Mts). A piece with a weight of about 1 kg was broken out of a larger block, free of weathering, xenoliths and joints. The samples chosen for further investigation looked fresh and showed high resistance during the hammering procedure. Final selection of the specimens was performed on the basis of thin section inspection. After this they were crushed and sieved to 200–350 μm. The fine dust was elutriated with distilled water and dried at 110 °C for 24 h.

Based on the mineralogy and the texture of the rock samples, biotite, hornblende and feldspar were separated using conventional techniques (heavy liquids, magnetic separator). The purity of the monomineralic fractions was checked by means of a binocular microscope and improved by hand picking.

Potassium determination

Approximately 0.05 g of each finely ground sample was digested in acids and finally dissolved in 0.2 M HCl. Potassium was determined by flame photometry with a Na buffer and a Li internal standard. The inter-laboratory standards Asia 1/65, LP-6, HD-B1, GL-O were used for checking the results of the measurements.

Argon measurements

Argon was extracted from the samples by RF fusion in Mo crucibles, in a previously baked stainless steel vacuum system. ^{38}Ar spike was added from a gas pipette system and the evolved gases were cleaned using Ti and SAES St707 getters and liquid nitrogen traps, respectively. The purified Ar was transported directly into the mass spectrometer and the Ar isotope ratio was measured in the static mode, using a 15 cm radius magnetic sector type mass spectrometer built in Debrecen.

Details of the instruments, the applied methods and the results of calibration have been described elsewhere (Odin 1982; Balogh 1985).

Age calculations

The atomic constants suggested by Steiger & Jäger (1977) were used for calculating the ages of the samples. All analytical errors are given in terms of ±1σ (i.e. with a 68% analytical confidence level). In order to check the reproducibility and accuracy of the argon and potassium analysis, duplicate measurements were performed on two samples (designated Nos. 5379 and 5272) at Okayama University and at ATOMKI, Debrecen, respectively.

At Okayama University the K-Ar dating was performed using the methods described by Nagao et al. (1984) and Itaya et al. (1991). The analytical errors in Okayama are given in terms of ±2σ.

Results and discussion

The analytical results of the K-Ar dating are summarized in Table 1. Forty-one K-Ar age determinations were carried out on different mineral separates and whole-rock samples from the PMIC and on one biotite separated from the Železna Kapla tonalite. Except for the biotite separate No. 5694 from the Železna Kapla tonalite that gave an age of 32.4 ± 1.2 Ma (Oligocene), all the other ages from the PMIC range between 20.3 and 14.9 Ma (Miocene). No significant gaps were observed in the K-Ar ages of the different rock types (Figs. 15 and 16). Due to the analytical errors the ages generally overlap and reflect their transitional character. However, there is geological proof that this magmatism was episodic.

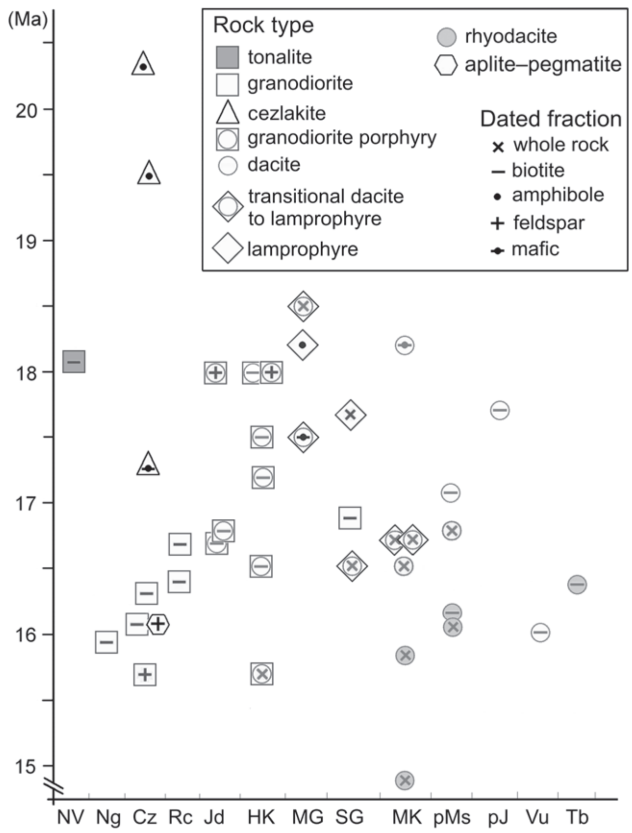

Fig. 15. Distribution of the K-Ar ages for the rocks of the PMIC. The abbreviations of the localities are given in the text, and their succession is shown in Table 1.

Table 1: The K-Ar data obtained on the Miocene igneous rocks of the Pohorje Mts. Abbreviations: gd — granodiorite, lamproph — lamprophyre, met — metamorphic rocks, amph — amphibole, w.r. — whole rock.

Lab. No.	Sample No.	Locality	Rock type	Dated fraction	K (%)	^{40}Ar rad (ccSTP/g)	^{40}Ar rad (%)	K-Ar age (Ma)
5380	NV-1	Nova Vas (Smrečno)	tonalite	biotite	4.29	3.034×10^{-6}	56.9	18.1 ± 0.7
6852	NgTP-1c	Nadgrad	granodiorite (gd)	biotite	5.79	3.583×10^{-6}	62.0	15.9 ± 0.5
5387/A	CZ-II-2A	Cezlak quarry II	cezlakite	amph±px	0.73	5.576×10^{-7}	47.9	19.5 ± 0.8
				mafic (bt)	1.63	1.099×10^{-6}	53.9	17.3 ± 0.7
5387/B	CZ-II-2B			amph±px	0.60	4.751×10^{-7}	29.3	20.3 ± 1.1
5386	CZ-I-1	Cezlak quarry I	granodiorite	feldspar	1.36	8.343×10^{-7}	64.1	15.7±0.6
				biotite	6.46	4.045×10^{-6}	79.4	16.1 ± 0.6
5388	CZ-I-3		granodiorite	biotite	6.03	3.835×10^{-6}	85.1	16.3 ± 0.6
6988	CZ-I aplite		aplite-pegmatite	K–feldspar	8.36	5.244×10^{-6}	76.9	16.1 ± 0.5
5379	RC-1	Recenjak	granodiorite	biotite	6.12	3.918×10^{-6}	61.1	16.4 ± 0.7
				biotite	6.00	3.911×10^{-6}	85.8	16.7 ± 0.4
5383	JD-1	Josipdol	porphyritic gd	biotite	5.87	3.883×10^{-6}	79.0	16.7 ± 0.6
5384	JD-2			biotite	3.32	2.175×10^{-6}	66.2	16.8 ± 0.5
				feldspar	1.34	9.42×10^{-7}	68.8	18.0 ± 0.6
5000	HKM-4	Hudi Kot	porphyritic gd	w.r.	2.66	1.633×10^{-6}	74.3	15.7 ± 0.6
5381	HKTP-1		porphyritic gd	biotite	5.65	3.647×10^{-6}	62.4	16.5 ± 0.7
5130	HKJ-3		porphyritic gd	biotite	7.65	5.144×10^{-6}	78.7	17.2 ± 0.7
6032	HKM-5		porphyritic gd	biotite	4.28	2.931×10^{-6}	60.6	17.5 ± 0.7
				feldspar	2.35	1.656×10^{-6}	65.7	18,0 ± 0.7
5382	HKTP-2		porphyritic gd/dacite	biotite	5.73	4.039×10^{-6}	82.2	18.0 ± 0.7
6014	MGM-4	Mislinja graben	dacite/lamproph	w.r.	1.17	8.468×10^{-7}	63.8	18.5 ± 0.7
			dacite /lamproph	mafic	1.79	1.227×10^{-6}	44.5	17.5 ± 0.7
5653/2	MGM-1B	Mislinja graben	lamproph. in met.	amph.	3.56	2.602×10^{-6}	63.1	18.2 ± 0.7
6034	SgM-3	Stara Glažuta	granodiorite	biotite	4.56	3.053×10^{-6}	68.9	17.2 ± 0.6
			granodiorite	biotite	4.52	2.926×10^{-6}	85.4	16.6 ± 0.4
6030	SgP-1		lamproph. in gd	w.r	1.76	1.214×10^{-6}	78.4	17.7 ± 0.7
6029	SgP-2		dacite /lamproph	w.r.	2.42	1.558×10^{-6}	77.9	16.5 ± 0.6
4998	MKTE-1	Mala Kopa	rhyodacite	w.r.	2.60	1.603×10^{-6}	55.8	15.8 ± 0.7
4999	MKTE-2	Mala Kopa	rhyodacite	w.r.	2.61	1.516×10^{-6}	58.7	14.9 ± 0.6
6012	MKM-3		dacite /lamproph	w.r.	2.55	1.668×10^{-6}	73.7	16.7 ± 0.6
6013	MKM-4		dacite/lamproph	w.r.	2.74	1.790×10^{-6}	71.1	16.7 ± 0.5
6033	MKM-5		dacite	w.r.	2.05	1.323×10^{-6}	74.2	16.5 ± 0.5
				mafic	2.55	1.818×10^{-6}	65.9	18.2 ± 0.7
5385	MSM-1	peak Mršak	rhyodacite	biotite	4.67	2.952×10^{-6}	57.1	16.2 ± 0.7
5272	MSJ-4		dacite	biotite	5.77	3.870×10^{-6}	69.3	17.2 ± 0.6
				biotite	5.94	3.926×10^{-6}	93.1	17.0 ± 0.4
4996b	MSTE-3		dacite	w.r.	2.71	1.781×10^{-6}	61.9	16.8 ± 0.7
4997	MSTE-5	peak Mršak, Primož	rhyodacite	w.r.	3.06	1.948×10^{-6}	66.6	16.1 ± 0.6
5655	JTP-1	peak Jasenko	dacite	biotite	5.54	3.834×10^{-6}	61.9	17.7 ± 0.7
6851	VTP-1b	Vuzenica	dacite	biotite	5.57	3.485×10^{-6}	55.6	16.0 ± 0.6
6854	TTP-1b	Trbonje	rhyodacite	biotite	7.05	4.510×10^{-6}	68.5	16.4 ± 0.5
5694	PKZP-1	**Karavanke – Črna**	**tonalite**	biotite	4.23	5.376×10^{-6}	76.7	**32.4 ± 1.2**

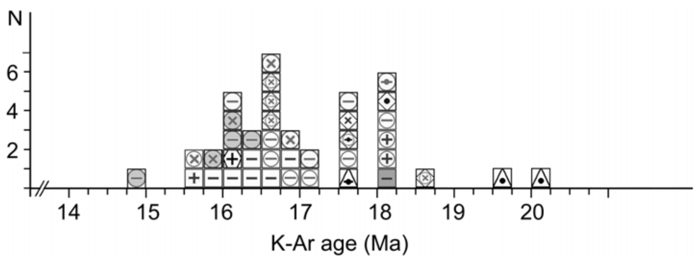

Fig. 16. Histogram of the K-Ar ages for the rocks of the PMIC. No significant gaps can be seen in the K-Ar ages of different rock types. The symbols used are the same as in Fig. 13.

For convenience the results are presented and discussed in terms of the petrographic units of the PMIC.

Tonalite

Only one biotite separate (No. 5380, 18.1 ± 0.7 Ma) from tonalite has been dated. It is considered that this result for the age of the tonalite is just preliminary.

Granodiorite

Four different exposures of granodiorite were sampled, and biotite and feldspar fractions were dated. In order to increase the reliability of the radiometric ages obtained from the granodiorite varieties, the K-Ar ages of a biotite fraction with the same grain size were determined. The reason for this is that the closure temperature, and thus also the time of closure of a mineral, depends on the grain size in the cooling pluton (Hess et al. 1993). In our work, only the 0.200–0.350 mm fraction was used for dating. The ages range between 16.9 Ma and 15.7 Ma (Table 1). Highly consistent ages were obtained on biotite separates (~16.5 Ma) because all the ages were in good accordance within the analytical error. Due to the low K content (3.32 %) of the biotite separate No. 6034, a duplicate analysis was performed in order to check the reliability of the analytical age. Considering that the ages obtained on the same biotite separate were within the limits of the analytical error, a mean age (16.9 ± 0.5 Ma) was accepted. Furthermore, two representative samples (No. 5379 and No. 6034) were analysed at the Geochronological Laboratory of Okayama University: they yielded the same result. The general agreement between the biotite and feldspar age (Separate No. 5386, 15.7 ± 0.6 Ma) suggests that the measured ages may refer to a rapid cooling of the granodiorite. Besides this, the mean age (16.5 Ma) of the biotite fractions provides the best information regarding the cooling history of the pluton.

Porphyritic granodiorite

Samples were taken from two different localities, and nine separates were dated. Slightly different ages were obtained on the biotite (16.5 ± 0.7–17.5 ± 0.7 Ma) and the feldspar separates (18.0 ± 0.6 Ma). The only exceptional older biotite age (No. 5382) was determined on a porphyritic granodiorite, transiting to dacite. Taking into consideration that the biotite ages are generally slightly younger than the feldspar ages, the presence of excess argon in feldspar separates is probable. However, the biotite and feldspar ages overlap, because of the analytical error (Table 1). Therefore the biotite ages can be regarded as the cooling ages of the porphyritic granodiorite.

Cezlakite

Almost identical ages (19.5 ± 0.8 Ma and 20.3 ± 1.1 Ma) were obtained for the amphibole mineral fractions separated from samples Nos. 5387/A and 5387/B. A significant decrease in age (17.3 ± 0.7 Ma, No. 5387/A) was determined on the mafic mineral fraction enriched in biotite. The older amphibole ages (~20 Ma) suggest that this gabbroic body was already formed, when the granodiorite intrusion was emplaced. Yet, based on the analytical data the presence of excess argon in the amphiboles cannot be excluded. This assumption is also supported by the U-Pb zircon age (18.64 ± 0.11 Ma) of the pluton (Fodor et al. 2007). On the contrary, the younger K-Ar age of sample No. 5387/A may reflect the heat effect caused by the intrusion of the granodiorite. This interpretation is also supported by the available geological (e.g. Fig. 14) and petrographical data.

Dacite

The dacitic dykes were sampled at four different localities, and six samples were prepared. The biotite separates (No. 5272 — duplicate analysis, No. 5655 and No. 6851) gave identical ages (~17 Ma) except for one separate (No. 6851, 16.0 ± 0.6 Ma). The whole-rock ages (Nos. 6033 and 4996b, ~16.7 Ma) are slightly lower, but similar. One separate of mafic minerals (intergrowing of biotite and hornblende, No. 6033) yielded the oldest age (18.2 ± 0.7 Ma), which could show some influence of the excess argon and mixed age of the two minerals. The apparent ages obtained on the whole-rock samples can be regarded as the minimum age, and could be slightly younger than the real geological age. On the other hand the whole-rock ages support the reliability of the biotite ages as determined on the same rock sample. According to the petrography, some of the dacite dykes (e.g. Vuzenica) are slightly altered, but since the biotite is mostly fresh it is not supposed that a significant Ar loss could have occurred from the biotite because of this alteration.

Dacite dykes of mafic character (transiting to lamprophyre) were sampled in the areas of the Mislinja graben, Stara Glažuta and Mala Kopa. Because of their fine-grained porphyritic structure and overgrowing, only whole rock (Nos. 6014, 6029, 6012, and 6013) and one mafic separate (No. 6014) were dated. The ages range between 18.5 ± 0.7 and 16.5 ± 0.6 Ma. The older ages are interpreted as being closer to the emplacement age of the dacite, although some excess Ar could be present due to the xenocrysts. The younger ages probably reflect cooling of the dacite.

On the basis of the available radiometric data it is not possible to define a gap between the formation of the granodiorite and the dacite.

Rhyodacite

Taking into account the texture and freshness of the rhyodacite, whole-rock samples and biotite separates (5 measurements) were obtained at three exposures (Trbonje, peak Mršak and Mala Kopa). The whole-rock ages are slightly lower, but consistent with the biotite ages. They range from 16.4 ± 0.5 Ma (No. 6854) to 14.9 ± 0.6 Ma (No. 4999). Two determinations on the biotite separates (Nos. 5385 and 6854) yielded almost identical results (16.2 ± 0.7 and 16.4 ± 0.5 Ma). The results obtained from whole-rock fractions (Nos. 4998, 4999 and 4997) show slight variation, from 16.1 ± 0.6 to 14.9 ± 0.6 Ma. The fresh biotite separate from the shallowest outcrop at Trbonje gives a reliable age (16.4 ± 0.5 Ma). The shallow rhyodacite dykes cooled rapidly, so that the biotite ages, together with field evidence, could reflect the age of their intrusion. The somewhat lower whole-rock ages could be the consequence of the slightly altered glassy groundmass of the rocks, since the glass retentivity of Ar is very poor. The results obtained for the rhyodacite can be used to make comparisons of the isotopic ages with the stratigraphic data of the surrounding sediments. Such comparisons indicate rhyodacite volcanism at the Karpatian/Badenian boundary. These ages could be related to the main tectonic phase which affected the PMIC (Trajanova & Pécskay 2006). This assumption is supported by the available paleomagnetic data (Márton et al. 2006).

Lamprophyre

Samples were taken from the contact between lamprophyre and granodiorite at Stara Glažuta, and from one lamprophyre dyke within metamorphic rocks at the Mislinja graben. Because of the fine-grained porphyritic structure with phenocrysts of hornblende only a whole-rock sample (No. 6030) and an amphibole separate (No. 5653/2) were dated. Both ages (17.7 ± 0.7 and 18.2 ± 0.7 Ma) show higher values than can be supported by the field evidence. It was assumed that one of the reasons for this could be the presence of excess argon in amphiboles, in xenocrysts or in micro-xenoliths. However, the older amphibole ages can be the consequence of its higher closure temperature (500–550 °C K-Ar, 530 ± 40 °C Ar-Ar method, Harland et al. 1990).

Aplite-pegmatite

At the Cezlak granodiorite quarry a single sample from an aplite-pegmatite vein was dated. The K-feldspar separate (No. 6988) yielded an age of 16.1 ± 0.5 Ma. Aplite-pegmatite intruded into already brittle deformed rocks, thus providing geological evidence that it represents the last phase of magmatism. The K-feldspar age can give the uppermost limit of the magmatism termination on the PMIC, and strongly supports the validity of the cooling ages (around 16.7 Ma) obtained from different rocks.

Conclusions

The Pohorje Mountains igneous complex is composed predominantly of granodiorite and dacite. The easternmost part of the pluton is composed of tonalite. Small-sized rhyodacite and lamprophyre dykes represent minor intrusions. No evidence has been found to show that the dacite intruded into the granodiorite. The rocks show a clear gradual transition from plutonic to shallow intrusive rocks.

The results of this systematic geochronological study, as well as the radiometric ages obtained on some of the metamorphic rocks (Fodor et al. 2004), provide strong evidence that the PMIC was formed in the Miocene. The K-Ar ages range between approximately 19.0 Ma and 16.0 Ma. The older ages (19–18 Ma) are close to the emplacement age of the batholith, which is also confirmed by the U-Pb zircon age 18.64 ± 0.11 Ma (Fodor et al. 2007). The age of the transitional diorite to pyroxenite rock named cezlakite is not well constrained, but the radiometric data are supported by field evidence, proving that this small body within the granodiorite is the oldest.

No apparent younging direction has been noticed within the studied area. The K-Ar ages of the granodiorite and dacite generally overlap. The consistent biotite ages indicate that synchronous and rapid cooling of the whole batholith most probably occurred at about 16.7 Ma (Fig. 16), on the Karpatian/Badenian boundary. The pronounced marginal oriented rock structure indicates crystallization in an extensional stress field, and a connection between magmatic and tectonic activity.

At the northwestern part of the PMIC, extensional processes opened pathways for the emplacement of small-sized rhyodacite dykes. The dykes cooled rapidly, so that the biotite ages might reflect the age of their intrusion. Synchronously, thin lamprophyre dykes intruded into the metamorphic rocks along the marginal western part of the pluton, followed by the intrusion of residual aplitic-pegmatitic melts into the already fractured pluton, mostly on its southern part. K-feldspar separated from the aplite-pegmatite is the most suitable tool to determine the age of the last magmatic event in the PMIC, which occurred around 16 Ma.

Tectonic activity characterized by strong tilting of the entire Pohorje Mountains massif continued and rapid unroofing occurred. Extensional processes indicated by post-cooling low angle shearing and brittle faulting is expressed on all rock types. Broadly NW to SE directed thinning formed the thick shear zones within the PMIC.

The magmatic activity in the PMIC is probably connected to the deep transtensional rift zones related to the development of the Labot fault system north of the Periadriatic zone. This magmatism represents the westernmost intrusion along the extensional structures of the Pannonian Basin. In contrast, magmatism along the Periadriatic line was active in the Paleogene. The Pohorje Mountains granodiorite differs petrologically from the Oligocene Železna Kapla tonalite (the Črna tonalite has an age of approximately 32.4 Ma) and is much younger. It is also different from the tonalites which are found further west (marked 1–16 on Fig. 1) and the tonalites buried in the Zala Basin in Hungary (with ages of between 40 and 30 Ma), which, together with the Železna Kapla tonalite, belong to the Periadriatic intrusions.

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References

Altherr R., Lugović B., Meyer H.-P. & Majer V. 1995: Early Miocene post-collisional calc-alkaline magmatism along the easternmost segment of the Periadriatic fault system (Slovenia and Croatia). *Mineral. Petrology* 54, 225–247.

Augustithis S.S. 1973: Atlas of the textural patterns of granites, gneisses and associated rock types. *Elsevier Sci. Publ. Co.*, Amsterdam, 1–378.

Balogh K. 1985: K-Ar dating of Neogene volcanic activity in Hungary: Experimental technique, experiences and methods of chronological studies. *ATOMKI, Report* D/1, 277–288.

Benesch F. 1918: Beiträge zur Gesteinskunde des östlichen Bachergebirges (Südsteiermark). *Mitt. Geol. Ges.* 161–183.

Činč B. 1992: Mineralogical and geochemical characteristics of the aplite and pegmatite veins in the Pohorje tonalite and cezlakite.

M.Sc. Thesis., Faculty of Natural Sciences and Technology, Ljubljana (in Slovenian).

Deleon G. 1969: Overview on the results of the radiometric dating of the granitoid rocks in Yugoslavia. *Radovi Inst. Geol.-Rud. Istraž. Ispit. (Belgrade)* 6, 165–182 (in Serbian).

Dolar-Mantuani L. 1935: Relation between tonalites and aplites of the Pohorje complex. *Geol. An. Balk. Poluost.* XII/2, 1–165 (in Slovenian).

Dolar-Mantuani L. 1938a: Tonalites on Pohorje Mts., the so called Pohorje granites. *Tehnika in gospodarstvo* 4, 17–32 (in Slovenian).

Dolar-Mantuani L. 1938b: Die Porphyrgesteine des westlichen Pohorje. *Geol. An. Balk. Poluost.* 15, 281–414.

Dolenec T. 1994: New isotopic and radiometric data of the Pohorje igneous rocks. *RMZ (Ljubljana)* 41, 147–152 (in Slovenian).

Dolenec T., Pezdič J. & Strmole D. 1987: Oxygen isotope composition in the Pohorje tonalite and cezlakite. *Geologija* 30, 231–243.

Faninger E. 1970: The Pohorje Mts. tonalite and its differenciates. *Geologija* 13, 35–9 (in Slovenian).

Faninger E. 1973: The Pohorje Mts. igneous rocks. *Geologija* 16, 271–315 (in Slovenian).

Fodor L., Jelen B., Márton E., Zupančič N., Trajanova M., Rifelj H., Pécskay Z., Balogh K., Koroknai B., Dunkl I., Horváth P., Horvat A., Vrabec M., Kraljić M. & Kevrić R. 2002: Connection of Neogene basin formation, magmatism and cooling of metamorphics in NE Slovenia. *Proceedings of the XII. Congress of CBGA*, Bratislava, 199–201.

Fodor L., Balogh K., Dunkl I., Horváth P., Koroknai B., Márton E., Pécskay Z., Trajanova M., Vrabec M., Vrabec M. & Zupančič N. 2004: Deformation and exhumation of magmatic and metamorphic rocks of the Pohorje-Kozjak Mts. (Slovenia): constraints from structural geology, geochronology, petrology, and paleomagnetism. *Geolines* 17, 31–32.

Fodor L., Gerdes A., Dunkl I., Koroknai B., Pécskay Z., Trajanova M., Balogh K., Horváth P., Jelen B., Vrabec M. & Vrabec M. 2007: Formation age, exhumation and deformation of the Pohorje pluton: implications for Cretaceous and Miocene deformations of the Eastern Alps-Pannonian basin junction. *8th Workshop on Alpine Geological Studies, Abstract Volume,* Davos, 18–19.

Germovšek C. 1954: Petrographic investigations on the Pohorje Mts. in the year 1952. *Geologija* 2, 191–210 (in Slovenian).

Harland W.B., Armstrong R.L., Cox A.V., Craig L.E., Smith A.G. & Smith D.G. 1990: A geologic time scale. *Cambridge University Press*, 1–263.

Hess J.C., Lippolt H.J., Gurbanov A.G. & Michalski I. 1993: The cooling history of the late Pliocene Eldzhurtinskiy granite (Caucasus, Russia) and the thermochronological potential of grain-size/age relationships. *Earth Planet. Sci. Lett.* 117, 393–406.

Hinterlechner-Ravnik A. 1971: The Pohorje Mts. metamorphic rocks. I. *Geologija* 14, 187–226.

Hinterlechner-Ravnik A. 1982: Eclogite from the Pohorje Mountains. *Geologija* 25 Vol. 2, 251–288 (in Slovenian).

Hinterlechner-Ravnik A. 1988: Garnet peridotite from the Pohorje Mountains. *Geologija* 30, 149–181 (in Slovenian).

Hinterlechner-Ravnik A. & Moine B. 1977: Geochemical characteristics of the metamorphic rocks of the Pohorje Mountains. *Geologija* 20, 107–140.

Hinterlechner-Ravnik A., Sassi F.P. & Visona D. 1991a: The Austridic eclogites, metabasites and metaultrabasites from the Pohorje area (Eastern Alps, Yugoslavia): 1. The eclogites and related rocks. *Rend. Fis. Acc. Lincei* 9, 2, 175–190.

Hinterlechner-Ravnik A., Sassi F.P. & Visona D. 1991b: The Austridic eclogites, metabasites and metaultrabasites from the Pohorje area (Eastern Alps, Yugoslavia): 2. The metabasites and metaultrabasites, and concluding considerations. *Rend. Fis. Acc. Lincei* 9, 2 175–190.

Itaya T., Nagao K., Inoue K., Honjou Y., Okada T. & Ogata A. 1991: Argon isotope analysis by a newly developed mass spectrometric system for K-Ar dating. *Mineral. J.* 15, 203–221.

Janák M., Froitzheim N., Lupták B., Vrabec M. & Ravna E.J.K. 2004: First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia. Tracing deep continental subduction in the Eastern Alps. *Tectonics 23*, *Amer. Geoph. Union* TC5014.

Janák M., Froitzheim N., Vrabec M. & Krogh Ravna R. 2006: Ultrahigh-pressure metamorphism and exhumation of garnet peridotites in Pohorje, Eastern Alps. *J. Metamorph. Geology* 24, 19–31.

Jelen M. & Rifelj H. 2003: The Karpatian in Slovenia. In: Brzobohatý R., Cicha I., Kováč M. & Rögel F. (Eds.): A lower Miocene stage of the Central Paratethys. *Masaryk University*, Brno, 133–139.

Márton E., Zupančič N., Pécskay Z., Trajanova M. & Jelen B. 2002: Paleomagnetism and new K-Ar ages of the Pohorje igneous rocks. *Geol. Carpathica*, *Spec. Issue* 53.

Márton E., Trajanova M., Fodor L., Koroknai B., Vrabec M., Vrabec M. & Zupančič N. 2004: Magnetic fabrics of the Pohorje igneous-metamorphic complex (Slovenia) related to deformation. *Contr. Geoph. Geodesy*, *Spec. Issue* 34, 91–92.

Márton E., Trajanova M., Zupančič N. & Jelen B. 2006: Formation, uplift and tectonic integration of a Periadriatic intrusive complex (Pohorje, Slovenia) as reflected in magnetic parameters and palaeomagnetic directions. *Geophys. J. Int.* 167 (3), 1148–1159.

Miller C., Mundil R., Thöni M. & Konzett J. 2005: Refining the timing of eclogite metamorphism: a geochemical, petrological, Sm-Nd and U-Pb case study from the Pohorje Mountains, Slovenia (Eastern Alps). *Contr. Mineral. Petrology* 150, 70–84.

Mioč P. & Žnidarčič M. 1976: Basic geological map of the SFRJ 1:100,000, sheet Slovenj Gradec. *Zvezni Geološki Zavod*, Belgrade (in Slovenian).

Mioč P. & Žnidarčič M. 1978: Explanatory notes for the sheet Slovenj Gradec. Basic geological map of the SFRJ 1:100,000. *Zvezni Geološki Zavod*, Belgrade, 1–74 (in Slovenian).

Mioč P. & Žnidarčič M. 1983: Explanatory notes for the sheet Ravne na Koroškem. Basic geological map of the SFRJ 1:100,000. *Zvezni Geološki Zavod*, Belgrade, 1–69.

Mioč P., Žnidarčič M. & Jerše Z. 1983: Basic geological map of the SFRJ 1:100,000, sheet Ravne na Koroškem. *Zvezni Geološki Zavod*, Belgrade.

Nagao K., Nishido H. & Itaya T. 1984: K-Ar determination method. *Bull. Hiruzen Res. Inst*. 9, 19–38 (in Japanese, with English abstract).

Pamić J. & Palinkaš L. 2000: Petrology and geochemistry of Paleogene tonalities from the easternmost parts of the Periadriatic Zone. *Miner. Petrology* 70, 121–141.

Sachsenhofer R.F., Dunkl I., Hasenhüttl C. & Jelen B. 1998: Miocene thermal history of the southwestern margin of the Styrian Basin: vitrinite reflectance and fission-track data from the Pohorje/Kozjak area (Slovenia). *Tectonophysics* 297, 17–29.

Sachsenhofer R.F., Jelen B., Hasenhüttl C., Dunkl I. & Rainer T. 2001: Thermal history of Tertiary basins in Slovenia (Alpine-Dinaride-Pannonian junction). *Tectonophysics* 334, 2, 77–99.

Sassi R., Mazzoli C., Miller C. & Konzett J. 2004: Geochemistry and metamorphic evolution of the Pohorje Mountain eclogites from the easternmost Austroalpine basement of the Eastern Alps (Northern Slovenia). *Lithos* 78, 235–261.

Steiger R.H. & Jäger E. 1977: Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth Planet Sci. Lett*. 36, 3, 359–362.

Thöni M. 1999: A review of geochronological data from the Eastern Alps. *Schweiz. Mineral. Petrogr. Mitt.* 79, 209–230.

Trajanova M. 2002: Significance of mylonites and phyllonites in the Pohorje and Kobansko area. *Geologija* 45, 1, 149–162 (in Slovenian).

Trajanova M. & Pécskay Z. 2006: Evolution of the calc-alkaline magmatism in the Pohorje Mt., Slovenia. In: Sudar M., Ercegovac M. & Grubić A. (Eds.): Proceedings of the 18th Congress of the Carpathian-Balkan Geological Association. *Serbian Geological Society*, Belgrade, 632–635.

Wilson M. 1989: Igneous petrogenesis. *Kluwer Acad. Publ.*, Dordrecht, 1–466.

Zupančič N. 1994a: Petrographic characteristics and classification of the Pohorje igneous rocks. *RMZ (Ljubljana)* 41, 101–112 (in Slovenian).

Zupančič N. 1994b: Geochemical characteristics and evolution of the Pohorje igneous rocks. *RMZ (Ljubljana)* 41, 101–112 (in Slovenian).

Zupančič N. 1994–95: Minerals of the Pohorje igneous massif. *Geologija* 37, 271–303 (in Slovenian).

Žnidarčič M. & Mioč P. 1988: Basic geological map of the SFRJ 1:100,000, sheets Maribor and Leibnitz. *Zvezni Geološki Zavod*, Belgrade.

Žnidarčič M. & Mioč P. 1989: Explanatory notes for the sheet Maribor and Leibnitz. Basic geological map of the SFRJ 1:100,000. *Zvezni Geološki Zavod*, Belgrade, 1–60 (in Slovenian).

Žurga J. 1926: Age of the granite on the Pohorje Mts. *Geograf. Vestn.,* 35–37 (in Slovenian).