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RADIOELEMENT DISTRIBUTION AND HEAT PRODUCTION OF TWO–MICA MONZOGRANITES FROM THE MOLDANUBIAN BATHOLITH OF THE BOHEMIAN MASSIF (CZECH REPUBLIC)

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ABSTRACT. The two–mica granites of the Eisgarn type of the Moldanubian batholith are peraluminous granites generated by partial melting of metapelites under the conditions of the lower to middle crust. The U and Th contents are controlled in these rocks either by the presence of accessory minerals (apatite, xenotime, monazite and zircon), or, in the case of uranium, also by adsorption of muscovite at the surface. The variability in the partial melting degree of the granites is reflected by a higher variability in both
production values. This variability is displayed not only among the individual defined subtypes, but also within the subtypes themselves.

KEYWORDS: Moldanubian zone, granites, Uranium, Thorium

1. INTRODUCTION

The Molda
of the
postorogenic two–m
youngest
designated as being of the
batholith,
of this magmatic
porphyritic phenocrysts into the Čímě̌r, Mrákotín and Landšteju subtypes (Koutek, 1925; Zoubek, 1949) (Fig. 1). Klečka et al. (1991) revised this subdivision and attempted
results
be controversial, and the term
subtype.

The Čímě̌r subtype comprises medium–grained, characteristically porphyritic two–mica
granites of the
of the Mrákotín (Deštná) subtype

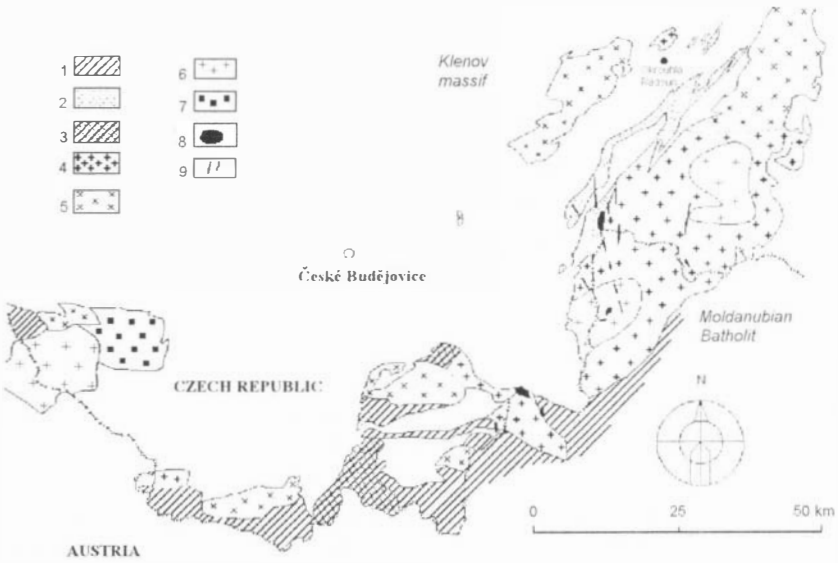

FIG. 1. Map of the granite type distribution in the Moldanubian batholith (after
author.
1 – Weinsberg type, 2 – Lásenice type, 3 – Freistadt type, 4 – Čímě
subtype, 5 – Mrákotín (Deštná) subtype, 6 – Landšteju subtype, 7 –
Rastenberg type, 8 – Homolka type, 9 – Subvolcanic dykes of granite
porphyre.

granites with occasional
which may be absent
formed by coarse-grained, again characteristically porphyritic, two mica granites.
In the course of geological mapping and exploration for uranium mineralization,
the monzogranites of the Čímě subtype have turned out to be
than the Mrákotín (Deštná) monzogranite subtype, the younge
the Landšteju monzogranites

In the granites
and Wedepohl (1994) have proved higher concentrations of
ments tha
(Haack, 1982). Unlike the two-mica granites of the French Massif Central and of
the Armorican massif, known for their important vein-t
(Friedrich, Cuney and Poty, 1987), the two-mica monzogranites of the Moldanubian
batholith have only one economically important occurrence of this mineralization
near Okrouhlá
monzogranites of the Eisgarn type in the Klenov massif and in the main body of
the Moldanubian batholith in the wider surroundings of the Čímě — type locality
were investiga (U, Th, K)
and mineral
subtypes.

An extensive radiometric survey using the anto-gamma method was carried out in the area of the Moldanubian batholith in the seventies. The survey revealed differences in radioactivity of the separate varieties of granites of the Eisgarn s.l. t
and anomalies associated above all with the shear zones at eastern margin of the Klenov massif. These zones of increased radioactivity were subsequently subject to follow-up exploration which did not, however, indicate any economically interesting uranium-ore concentrations. Radiometric survey has also proved a significant variability in the content of radioactive elements in the Mrákotín (Deštná) subtype in the Klenov massif (Veselý, 1970).

This area was covered also by
1 : 50 000, supplemented by checking some anomalous sections with ground gamma spectrometry (Dědáček et al., 1991). The airborne and ground gamma spectrometry has corroborated the previous results of the radiometric survey and helped to identify the reasons for the anomalous concentrations
in the various types of granites of the Moldanubian batholith. Some increased concentrations of total radioactivity can, according to gamma spectrometry,
cribed to the oscillating potassium content in the Mrákotín (Deštná) subtype. The areas in which the Číměř subtype
of thorium c
with the metamorphic rocks of the Moldanubian zone. A distinct decrease in thorium content has, on the contrary, been recorded in the areas of occurrence of the coarse-grained Landštejn subtype. The airborne gamma spectrometry has shown enrichment in uranium along sever
the Okrouhlá Radouň uranium deposit, nevertheless, it has not revealed any new anomalous linear structures.

2. Geological Setting

The Klenov massif forms the largest subsidiary single body of the Eisgarn type in the Czech part of the Moldanubian batholith. At its northeastern margin lies the Okrouhlá Radouň uranium deposit, which provided the opportunity to study the relations between the individual subtypes of monzogranites of the Eisgarn type over a distance
Three subtypes of monzogranites of the Eisgarn type were defined within the Klenov massif during exploration
body of the Klenov massif consists of equigranular, fine- to medium-grained, two-mica monzogranites of the Mrákotín (Deštná) subtype. Independent apophyses of the Číměř subtype occur at the northeastern margin of the Klenov massif. Some of these apophyses are also several hundreds of metres thick. The leucocratic aplite granites that form a transitional subtype between the Mrákotín (Deštná) subtype and the dyke aplites have been identified in the mine workings of the Okrouhlá Radouň ore deposit and in the surface boreholes. Two-mica monzogranites of both the Číměř and Mrákotín (Deštná) subtypes were sampled in the main body of the Moldanubian batholith.

3. Sampling and Analytical Methods

When possible, samples 2 to 5 kg in weight were collected for the study of the distribution of radioactive elements and of other components. Only samples of unaltered granites were collected. The concentrations of radioactive elements were determined using a Canberra multichannel gamma spectrometer. The samples were placed in aluminium casings 450 cm^3 in volume. A $3'' \times 3''$ NaI(Tl) scintillation detector was used for the measurements.
measuring the concentrations of the individual radionuclides: 85 – 105 keV (^{234}Th), 215 – 265 keV (^{212}Pb) and 1400 – 1520 keV (^{40}K). Our own standards and those of the IAEA (RGU–1, RGTh–1 and RGK–1) were used for standardization. Measurements of the U, Th and K concentrations were made in the MEGA laboratories (Uranium Industry) at Stráž
ples were collected
Nová Bystřice, in the main body of the Moldanubian batholith. The calculation of the radiogenic heat production was based on the Rybach (1976) formula using the following density values: granite of t
(Deštná) subtype
of major and selected
was analysed by X–ray spectrometry
Janáčková).

4. Petrology

Monzogranites
granites with alumina saturation index values between 1.18 and 1.23. The monzogranites of the Čímě̌ř subtype contain roughly the same amounts of K–feldspar and plagioclase (An_{8-20}), quartz,
muscovite. The total amount of micas oscillates around 10 %. Accessory minerals comprise andalusite, apatit
over zircon. The occurrence of porphyritic K–feldspar phenocrysts, 1 – 3 cm in size, is characteristic. They form about 5 % of the rock.

The monzogranites of t
clase (An_{7-12}), quartz, biotite and muscovite. Accessory minerals are represented by andalusite, zircon, xenotime, monazite, rut
opaque minerals represent
mica monzogranites
minera
from this subtype
ture. The An value of plagioclase is lowest in comparison with the two other subtypes, being An_8 on average. Besides andalusite, also cordierite and
ite occur. Monazite has been analysed and identified by detailed investigations of the two–mica granites (Jalovec, 1992; Finger et al., 1996; Göd, Oberlercher and Brandstätter, 1996).

The geochemical studies of Vellmer and Wedepohl (1994), Heřmánek
Breiter

by partial melting of metapelites under conditions of the lower to middle crust. The homogenization of the granitic melt and the separation of parts of the magma took place during partial melting. The influence of different
along with a varying
(Čímě and Mrákotín
mica granites with
subordinate
the Moldanubian batholith. Varying proportion of the original
nent is reflected either in the fluctuation of the alumina saturation index, or in the oscillation of the andalusite or cordierite, sillimanite or garnet contents. Var degrees of partial melting were, therefore, probably the dominant proc genesis of the two-mica

5. Distribution of Radioelements in Granites

The radioelement analyses were statistically processed and the results are presented in Table 1. Owing to the limit
used to calculate
of radioactive elements to occur in the Čímě subtype of the main body of the Moldanubian batholith.
the Čímě subtype from the northeastern margin of the Klenov massif.
rium content.
(Deštná) subtype. The granites of the
massif show the lowest thorium contents.
aplite granites
highest Th/U ratio has been reported in the monzogranites f
of Čímě in the subtype of the same name consisting of
zogranites (5.17). The lowest one is characteristic for
the Klenov massif (0.6
same direction.

The highest
in the Čímě subtype of the main body of the Moldanubian batholith. Nevertheless, these values are lower by one half
the
Distinctly
of the main body of the Moldanubian batholith and in all subtypes of t
type of the Klenov massif.
detected by a
marked difference between the Čímě subtype of the main body of the Moldanubian batholith and the Klenov massif as a whole.

The study of the distribution of radiogenic elements in granites of the Moldanubian ba
garn type not only as regards the U and Th contents, but also the K content. The highest values of radiogenic heat production observed so far have been found in the Eisgarn type on Austrian territory (Vellner and Wedepohl, 1994; Gnojek and

TABLE 1. Distribution of the U, Th, K and radiogenic heat production in the studied granitoids of the Moldanubian batholith (median — Me). *s* — standard deviation

	U (ppm)		Th (ppm)		K (wt. %)		Heat production (μWm^{-3})		Th/U	Number of samples
	Me	*s*	Me	*s*	Me	*s*	Me	*s*		
Klenov massif – Číměř subtype	6.00	1.14	13.90	1.35	3.85	0.29	2.83	0.29	2.32	17
Klenov massif – Deštná subtype	5.80	2.87	4.10	3.14	3.80	0.44	1.96	0.83	0.71	39
Klenov massif – aplitic granite	4.90	3.44	3.00	1.25	3.89	0.30	1.94	1.08	0.61	9
Číměř subtype	4.90	2.82	25.35	10.49	4.40	0.35	3.50	1.06	5.17	12
Mrákotín subtype	5.60	1.81	19.30	10.69	4.35	0.35	2.83	1.07	3.45	11
Eisgarn type (Vellmer, Wedepohl, 1994)	16		35		4.40		6.82		2.19	4

Breiter, 1996). These values are markedly lower in the area of the Klenov even lower than those

The association v- v based on the geochemical study of the rocks of the Klenov massif. Correlation analysis was used for this purpose. This analysis tween the Th content and the contents of TiO_2, MgO, Ba, Zr and Ce (Table 2). No correlation between U and Th contents was established in the porphyritic granites and a positive correlation between the two elements was found in the even-grained and the aplitic tween the U and Th contents and the content of Pb. The results of the correlation analysis show U and Th to be associated above or xenotime. The ThO_2 content in the monazite from the Eisgarn-type granites is 7–13 % (Göd pers. comm.: Jalovec 1992). The significant correlation between Th and MgO is caused by the fact that most of the monazite is enclosed in biotite grains. The relation of the U and Th contents to that of the rock-forming minerals was investigated in the two-mica monzogranites of the Klenov correlation between the content of U and that of muscovite (correlation coefficient 0.33) and the content of Th and biotite (correlation coefficient 0.45) was observed.

6. DISCUSSION

The results of the the study of the concentration of major and trace elements in the Klenov agree with the previous results of the airborne and ground gamma spectrometry.

TABLE 2. Correlation coefficients for U and Th of the two-mica granite from the Klenov massif ($n = 39$)

	Th	U
TiO_2	0.42	0.23
MgO	0.46	0.28
P_2O_5	0.16	−0.08
Rb	0.35	0.09
Ba	0.49	0.03
Sr	0.41	−0.09
Zr	0.54	0.27
Ce	0.41	−0.15
Y	−0.08	0.11
Th		0.31

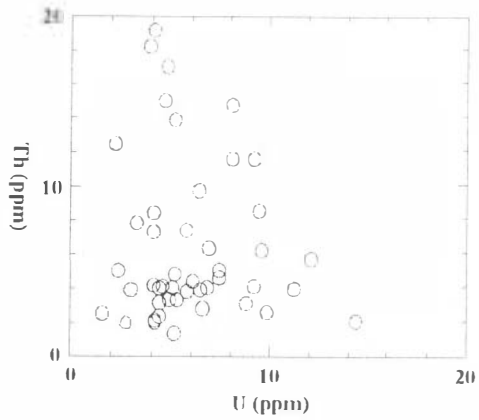

FIG. 2. Content of U and Th in the two-mica granites of the Klenov massif

These results suggest that the highest concentrations of radioactive elements occur in the Čímeř subtype of the main body of the Moldanubian batholith. The results of the ground gamma spectrometry on the Czech–Austrian border and on Austrian territory (Breiter and Gnojek, 1996) and the analysis of U and Th in the granites of the Eisgarn-type on Austrian territory (Vellmer and Wedepohl, 1994) show the concentrations of both elements, but of thorium in particular, to increase southward. Higher concentrations of thorium were associated with higher concentrations of monazite in the porphyritic two-mica granites of the subtype Čímeř, or of the Eisgarn-type on Austrian territory, and with the content of sphene and monazite in the two-mica granites of the Deštná subtype in the Klenov massif. The distinctly positive correlation between the content of MgO and U in the porphyritic granites of the Čímeř subtype (Fig. 3) and between the content of MgO and Th in the

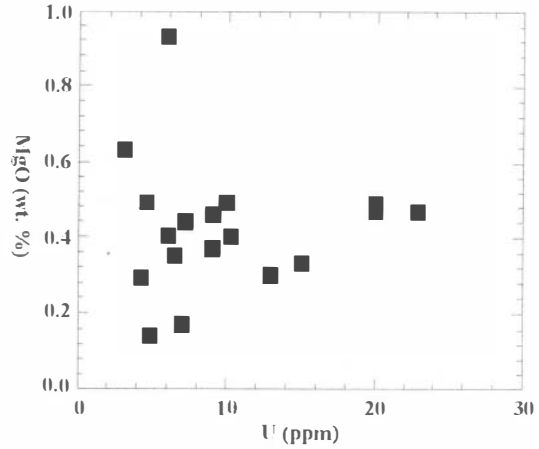

FIG. 3. Content of U and MgO in the two-mica granites of the Čímeř subtype

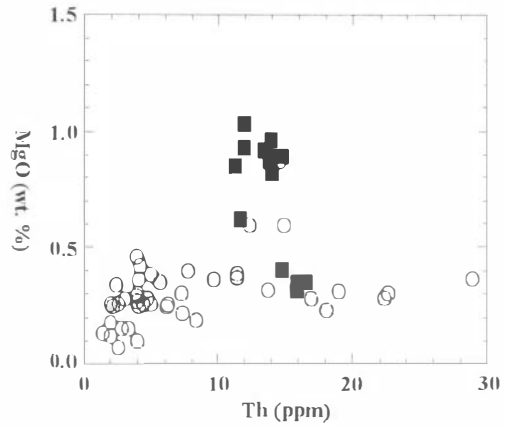

FIG. 4. Content of Th and MgO in the two-mica granites of the Czech part of the Eisgarn type
○ – Deštná (Mrákotín) subtype, ■ – Čímeř subtype

all subtypes of two-mica granites of the Moldanubian batholith (Fig. 4) suggests monazite to be enclosed above all in biotite and its content to increase with that of biotite, a fact proved by the correlation-coefficient value. This is also supported by the positive correlation between the contents of Th and Rb. Williamson et al. (1996) mention a similar correlation observed in the Millevaches pluton of the Massif Central and they ascribe this to the presence of small amounts of biotite restite, producing high Rb and containing inclusions of monazite, producing high Th. The geochemical investigation has proved U and Th contents to be controlled above all by the presence of accessory minerals (apatite, zircon, monazite, xeno-

time, rutile and sphene). The U content in the two-mica monzogranites of the Deštná subtype from the Klenov massif is also controlled by the muscovite content. Part of the uranium could have been adsorbed at the surface of muscovite. According to Friedrich, Cuney and Poty (1987), zircon, monazite and apatite bind 25–35 % of the whole-rock U content. According to Bea (1996), in low-Ca peraluminous granites, U resides mostly in xenotime (about 50–60 %), followed by uraninite, monazite, pyrochlore and zircon. Monazite, with about 65–80 %, is the most important Th reservoir, whereas zircon, xenotime and apatite account for about 1–2 % each (Bea, 1996). The low solubility of monazite, apatite and zircon in melts of peraluminous granite (Green and Watson, 1982; Watson and Harrison, 1983; Rapp and Watson, 1986; Montel, 1986) induces their early fractionation with plagioclase and biotite during partial melting. In comparison with the peraluminous leucogranites of the French Variscides (plutons St. Sylvestre, Guérande and Grandrieu) (Friedrich, Cuney and Poty, 1987), the U and Th contents in the investigated granites of the Moldanubian batholith are lower than those in the granites of the St. Sylvestre pluton and similar to those in the Grandrieu and Guérande plutons. Lower contents of radioactive elements in the two-mica monzogranites of the Moldanubian batholith can be best explained by their lower uranium ore potential (the total reserves of the Okrouhlá Radouň U-deposit were 1300 t U according to Šuráň and Veselý (1997)) in comparison with that of the St. Sylvestre pluton, whose potential can be expressed in terms of 38 000 t of uranium reserves (Friedrich, Cuney and Poty, 1987). These authors assume that the U enrichment of peraluminous silicate liquids during partial melting will depend critically on the amount of U located outside the lattice of weakly soluble accessory minerals (zircon, monazite, apatite). This U will display a marked incompatible behaviour and will strongly fractionate in favour of the anatectic melts. The results of the study of U distribution in the two-mica granites of the Deštná subtype suggest an important part of U to be adsorbed at the surface of muscovite.

7. Conclusion

The two-mica monzogranites of the Eisgarn type make up the largest portion of the Czech part of the Moldanubian batholith. With regard to its grain size and texture, this type can be subdivided into further subtypes. The Číměř and Mrákotín (Deštná) subtypes are the most important among them. As to the content of natural radionuclides — U, Th and K, the Číměř subtype displays the highest concentrations of Th and K, having also the highest values of heat production. Lower values of both elements have been detected in the Mrákotín (Deštná) subtype, particularly in the Klenov massif. The lowest contents of K and Th are characteristic for the aplitic monzogranites of the Klenov massif. The Th content is controlled above all by the presence of monazite, that of uranium is partly controlled by the Zr content and partly by its adsorption at the surface of muscovite.

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DISTRIBUCE RADIOAKTIVNÍCH PRVKŮ A TEPELNÁ PRODUKCE DVOJSLÍDNÝCH MONZOGRANITŮ MOLDANUBICKÉHO BATOLITU ČESKÉHO MASÍVU (ČESKÁ REPUBLIKA)

Miloš RENÉ

Dvojslídné granity typu Eisgarn moldanubického batolitu představují peraluminní monzogranity, které vznikly parciálním tavením metapelitu v podmínkách spodní až střední kůry. Hodnota indexu saturace hliníkem kolísá v rozmezí 1.18–1.23. Dvojslídné granity typu Eisgarn, které jsou součástí nejmladší podskupiny granitoidů moldanubického batolitu jsou podle své zrnitosti rozdělovány na subtyp Číměř, Mrákotín (Deštná) a Landštejn. Granity subtypu Číměř představují muskovit–biotitické porfyrické granity, pro něž je charakteristická přítomnost porfyrických vyrostlic K–živce, které tvoří cca 5% horniny. Dvojslídné granity subtypu Mrákotín a Deštná jsou středně až drobně zrnité stejnozrnné granity. Granity subtypu Landštejn jsou porfyrické, hrubě zrnité granity, které nebyly v rámci této práce studovány. Studována byla distribuce U, Th a K pomocí gamaspektrometrie v monzogranitech typu Eisgarn v hlavním tělese moldanubického batolitu a v samostatném klenovském masivu. Největší koncentrace radioaktivních prvku se vyskytují v subtypu Číměř hlavního tělesa moldanubického batolitu. Vyšší koncentrace thoria jsou spjaté s vyššími koncentracemi monazitu v granitech subtypu Číměř. Jeho obsah stoupá s obsahem biotitu, což lze prokázat výraznou pozitivní korelací mezi obsahy MgO a obsahy U a Th. V ostatních subtypech dvojslídných granitů je obsah U a Th kontrolován především přítomností akcesorických minerálu (apatitu, zirkonu, monazitu, xenotimu, rutilu a titanitu). V případě dvojslídných granitů subtypu Deštná je obsah uranu kontrolován rovněž obsahem muskovitu. Lze předpokládat, že část uranu by mohla být adsorbována na povrch krystalu muskovitu. Nejnižší obsahy U a Th jsou charakteristické pro aplitické granity klenovského masivu.

Nejvyšší hodnoty radiogenní produkce tepla byly zjištěny ve zkoumané oblasti v subtypu Číměř hlavního tělesa moldanubického batolitu. Výrazně nižší jsou hodnoty

produkce tepla jednak v subtypu Mrákotín hlavního tělesa moldanubického batolitu, jednak ve všech subtypech typu Eisgarn klenovského masivu. Z výsledku korelační analýzy vyplývá, že U a Th jsou vázány především na monazit, titanit, zirkon, případně xenotim. Obsah ThO_2 v monazitu z granitů typu Eisgarn je 7–13 %. Variabilita obsahu radioaktivních prvků v jednotlivých subtypech je způsobena především variabilitou parciálního tavení původních metapelitů, které byly jedním z hlavních zdrojů granitové taveniny moldanubického batolitu. Tato variabilita se projevuje jak mezi jednotlivými definovanými subtypy, tak v rámci těchto subtypů.