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JÁN BABČAN* — VIERA ZATKALÍKOVÁ**

TIME AND SPACE PARAMETERS OF MAGMATIC INTRUSIONS COOLING

(Figs. 13)

Abstract: This article presents new solution of magmatic intrusions cooling. The solution is based on the fact that heat storage of an intrusion is dispersed uniformly to surrounding rocks. Dispersion velocity of the heat and the space which the heat action interferes with are solved on computer using the method of "redoubling" volume what enables concretization and easy check on the computations.
Solutions of various hypothetical and concrete intrusive bodies are given as examples. Cooling of an intrusion depends, above all, on the size of the intrusion, its depth deposition in the earth crust, original temperature and kind of surrounding rocks.
The results of cooling and heat action of the intrusion on surrounding rocks compared with the results of temperature and pressure conditions under which samples taken away from particular distance between the metamorphic complex and the contact with intrusions originate are computed for two concrete cases — the intrusion Santa Rosa in Nevada and Bratislava granitic massif.

Резюме: Статья приносит новое решение проблемы охлаждения магматических интрузий. Это решение основано на том, что тепловой запас интрузии равномерно рассеивается в вмещающие породы. Скорость дисперсии тепла и пространство, которое затронуто тепловым воздействием, решатся в ЭВМ методом «удваивания» объема, что позволяет конкретизирование расчетов и их легкий контроль. Как примеры приводятся расчеты охлаждения разных гипотетических и конкретных интрузивных тел. Охлаждение интрузии зависит прежде всего от размера интрузии, ей глубинного положения в земной коре, исходной температуры и вида вмещающих пород. Для двух конкретных примеров — интрузии Санта Роса в Неваде и братиславского гранитного масива вычислены результаты охлаждения и теплового воздействия интрузии на вмещающие породы, которые сравнены с результатами PT условий образования проб, взятых из определенных расстояний метаморфического комплека от контакта с интрузиями.

Introduction

Magmatic intrusions become sources of heat energy gradually dispersed to surroundings and resulting in various changes in it after their ascend to the upper parts of the earth crust. A long time ago various geologists — experts have been interested in the character of these changes, their intensity, the time during which heat capacity of the intrusion has an effect and the space in which its heat action intervenes and causes the metamorphic changes. Com-

* Prof. Dr. J. Babčan, Dr.Sc., Department of Mineralogy and Geochemistry, Faculty of Natural Science of Comenius University, Paulínyho 1, 811 02 Bratislava.
** Dr. V. Zatkalíková, Geological Institute of the Centre of Geoscience Research, Slovak Academy of Sciences, Dúbravská cesta 9, 814 73 Bratislava.

plexity of these processes has not recently permited more than some "speculative" conclusions about time and space actions of the intrusions. However, modern computational technic enables many detailes of these processes to be considered simultaneously and to materialize them to a great extent on the basis of corresponding computations.

The heat action of the magmatic intrusion in surroundings depends, above all, on the amount of the heat brought by it and the depth it stops in. The amount of the heat is given by the size (volume) and the temperature of the intrusion. The depth in which the intrusion stops determines the part of the heat capacity that can be dispersed to surroundings. The part of the heat passing through surroundings in deeper parts of the earth crust where temperatures are higher than in the parts nearer to the earth surface is smaller because the heat action of the intrusion is finished in the moment when the temperatures of the intrusion and of surroundings are the same.

Time and space of the heat action of the intrusion depend not only on given parameters of the intrusion but also on physical properties of surrounding rocks, above all, on their rather different heat conductivity among individual kinds of rocks. Very important factor of these processes is the way how the heat is spread from the intrusion to surroundings, i.e. if it is caused by the contact between particles (conduction-leading) or if the heat is carried out by gases or liquids in convection (convection-flowing), or by the both processes.

Besides the mentioned facts solutions of the heat action of the intrusion should regard to also the shape of the intrusive bodies because e.g. if heat storage of a cylinder body and the heat storage of a plate body substantially elongated in one direction are the same, the parameters of the action of both intrusions will be different.

Several attempts at solutions connected with determination of time and space parameters or both parameters of the action of magmatic intrusions of various types have recently been found out. However, various authors have rather different approach to the solution of these problems, some of them prefer certain parameters, disapprove others etc.

On solving dynamics of heat exchange during magmatism Kadik — Jaroshevski (1971) take as a basis of the computations inner convective transmission of the heat occuring directly in magma, namely by its flowing upwards and also the fact that the heat is transmitted to surroundings in fact in the apical part of the intrusion. Although the heat transmission to surroundings supposed always as anisotropic, it can be covered in mathematical model with many difficulties only.

Theoretically Sharapov (1971) indicates some possibilities or complexities in the matter of solutions of magmatic intrusions cooling. For example, he refers to the fact that some high-temperature sources, genetically associated with particular intrusions, represent considerably higher original temperature than it corresponds to their position in relation to the intrusion. On the basis of these facts he concludes that the problem is very complex and at present it is not solvable (1971!) because many physical parameters requisite to the computations are missing. Later (for example Sharapov — Melamed, 1974) approach, after all, mathematical solution of the problems connected with magmatic bodies cooling, including magma chambers. Some results of their computations will be presented in discussion.

Dudarev et al. (1972) have done computations with relation to heat characteristics of dykes, consequently bodies elongated in one direction, practically infinitly. They suppose heat transmission from a dyke to surroundings by conduction. Computations are limited, above all, to dyke cooling only connected with the crystallization of its content. More detailed method of the computation is not presented, but for example the fact that the dyke the thickness of wich is about 20 m, with original temperature 1000 °C is cooled to the temperature of 450 °C (what should correspond to the total crystallization) in about 10 years may be read from graphs.

Goguel (1978) is concerned with the computation in relation to cooling of magmatic intrusion in detailes, takes the depth of the intrusion into consideration in the complex equation for the computation of cooling, its original and immediate temperature, heat conductivity of surrounding rocks, thermal gradient and other parameters but he does not consider the weight or volume of the intrusion. For example, cooling time for the intrusion of unknown size, the peak of which is in the depth 5 km has been computed to be 1,6 mil. years.

On the other hand Spera (1980) considers not only the size of the intrusion, but also the amount of water absorbed in magma and escaped in form of a fluid system during crystallization of the magma taking away particular amount of heat, i.e., the more water the magma containes, the faster it cools. However, his computations are limited only to the time of crystallization of the magma (so called solidification time) and do not take the position of the intrusion and corresponding geothermal continuities into consideration. According to his computations the solidification time with relation to a spherical intrusion of granodiorite magma, the radius of which is 5 km and the amount of water is 0.5 % is $3{,}3 . 10^5$ years and at the amount of water 4 % "only" $5 . 10^4$ years.

Golubev (1981), similarly to Sharapov (l. c.) indicates some possibilities of solving presented problems, points out various details in the matter of relations between magma and rock and problems connected with mathematical solution of these tasks but no particular examples are presented.

Parmentier and Shedl (1981) refer to interesting details connected with the solution of the problems in the matter of magmatic intrusions cooling. They point out e.g. the fact that besides conductive transmission of heat from the intrusion to surrounding rocks circulated meteoric waters have important function during cooling of the intrusion. However, the influence of the circulated waters is not considered in concrete computation in relation to cooling of the intrusion situated in the locality of Santa Rosa in Nevada. That is to say, the result stated on the basis of the amount of the isotope ^{18}O in waters was that the heat output caused by these waters (convection) would be too low. We shall return to the values computed by them in discussion.

Gillen (1982) considers factors of intensity of the raised transformations, i.e. size of the intrusion, original temperature of the magma, to be most important in evaluation of the influence of the intrusion on the course of contact metamorphism.

Theoretical explanation of proposed solution of the problems

Complexity of the solution connected with the problem of magmatic intrusions cooling as it was sketched in the previous part of this article and, above all, complexity of the mathematical solutions following these problems and affecting more or less various natural situations have made us for the idea to use a procedure principally different from the procedures given by the authors mentioned above for these computations. The procedure suggested by us and its realization enable effective control elimitating possible errors and contingent mistakes can be exactly defined for each singled out stage of the intrusion cooling of various types and for manifold parameters making dependent upon this cooling.

Complex differential equations of heat transmission using vector relations etc. are applied as a basis in existing computations connected with the problems of magmatic intrusions cooling. These equations do not consider moreover e.g. the size of the intrussion and possibly also other appropriatenesses mentioned above, so that the value of the computed cooling parameters is not too reliable.

Our computations come from the basic assumption — each magmatic intrusion brings some amount of heat, so called heat storage (Q), serving as a basis for next computation to the place where it stops. The heat storage Q presents the sum of so called pre-crystalline heat Q_a corresponding to the heat eased from the intrusion after its cooling from the original temperature of the magma (T_0) to the temperature of crystallization (solidification — T_s), next from so called heat of the exothermic phase reactions during crystallization of a melt (Q_b) and post-crystalline heat Q_c eased during intrusion cooling from the temperature T_s to the temperature of surrounding T_k. The relation below follows from these considerations:

$$Q = Q_a + Q_b + Q_c \tag{1}$$

The basic quantitative unit of the computations is the weight of the intrusion M computed from the original volume of the intrusion and the density of melt (ρ) for which the same value has been taken as for the solid intrusion (e.g. for granite $\rho = 2\,600\ \mathrm{kg\,.\,m^{-3}}$). The weight of the intrusion has been computed according to the relation $M = V_0 \,.\, \rho$. No further "supply" of the heat into intrusion has been considered in the computations, e.g. through inlet channel from underlying beds of the intrusion etc.

Particular partial parts of the heat storage with respect to the intrusion have been computed from relations:

$$Q_a = M \,.\, c_t \,.\, (T_0 - T_s) \tag{2}$$

where c_t is the specific heat of the granitic melt ($1.0467\ \mathrm{kJ\,.\,kg^{-1}\,.\,K^{-1}}$), the temperatures 1 200, 1 000 and 800 °C have been specified for the original temperature of the intrusion T_0 and $T_s = 1\,000$ °C for the crystallization temperature of the melt;

$$Q_b = M \,.\, L \tag{3}$$

where L is the latent crystalline heat of the melt; e.g. for granitic melt L = = 376.8 kJ . kg^{-1} (according to Dudarev et al., l. c.);

$$Q_c = M \cdot c_z \cdot (T_s - T_k) \tag{4}$$

where c_z is the specific heat of the granit, 0.8206 kJ . kg^{-1} . K^{-1} (Dudarev et al., l. c.).

Time and space actions of the cooling intrusion have been derived from the heat assumption that the heat storage is spread to surroundings uniformly according to the regularites in the matter of heat conduction. Simplified Fourier's relation (Horák et al., 1961) has been used for the calculation of the heat amount carried over by way of conduction through certain volume of the rock, defined planes F, the distance 1, at the thermal gradient ΔT ($\Delta T = T_1 - T_2$), where T_1 is the temperature of the plane situated nearer to the source, T_2 — of the further plane, at heat conduction of the medium situated between the considered planes λ per time τ during which the transmission is realized:

$$Q = \frac{\lambda \cdot F \cdot \tau \cdot \Delta T}{1} \tag{5}$$

Three types of environment in which the granitic intrusion could penetrate and for which appropriate values of the heat conduction have been used (crystalline schists, meta-pelites $\lambda = 1.6 \cdot 10^{-3}$, granitic rocks $\lambda = 2.5 \cdot 10^{-3}$, carbonates, metabasalts $\lambda = 3.2 \cdot 10^{-3}$ W . m^{-3} . K^{-1} (all according to the tables of Physical properties etc., 1984) have been considered in our computations.

It was considered that the proper process of the intrusion cooling consists of partial stages ($n = n_1 + n_2 + n_3 + \ldots$) characterized for the purposes of computation as the processes during which the heat is spread from the volume of the rock to the redouble volume with respect to the previous one (e.g. if the volume of the intrusion is V_0 at n_0, at n_1 the volume is $V_1 = 2V_0$, at n_2 it is $2 \cdot V_1$ etc.). The temperature at these enlarged volumes increases to the detriment of the heat of the original intrusion, whereby the amount of the heat and the time during which the heat is spread into so enlarged volumes of rocks is computed from the presented relations for Q (eq. 5) If we contemplate e.g. the shape of the intrusion to be cylindrical with the radius a_0 and the height b_0, the volume of which can be computed from the relation $V_0 = \pi \cdot a_0^2 \cdot b_0$, then the redouble volume is $V_1 = 2 \cdot V_0 = \pi \cdot (a_0 + r_1)^2 \cdot (b_0 + r_1)$, where r_1 presents appropriate increment in the matter of dimensions of the original cylinder. Provided the total heat storage remains always constant the time during which appropriate heat storage is transfered into so calculated volume increment is computed. The value 1 represents in fact the volume increment (i.e. the value r_1 in the example calculated above) in the equation 5.

Values of the thermal gradient ΔT are computed as differences between maximal temperatures of corresponding rock volumes in our computations. Like this for V_0 it is the temperature T_0, for the volume V_1 it is:

$$T_{\max 1} = \frac{Q}{M_1 \cdot c_z} \tag{6}$$

etc., whereby T_{max} is the maximal temperature the rocks can reach in particular distance from the intrusion.

Gradual "redoubling" of the volumes considered as partial units of the heat spreading will stop in the moment when T_{max_i} equals surrounding rock temperature defined from the depth in which the intrusion stops and from the value of the average geothermal gradient (30 °C . km^{-1}) at the temperature of the earth surface 20 °C.

The time during which the heat storage of the intrusion is spread to surroundings so that the temperature will come up to surroundings in the last stage of the computation is computed as the sum τ from the equations (5) and (6).

In the cases when the depth in which the intrusion stops has been chosen so that the heat spreading from the intrusion reached the earth surface before "arrangement" of the temperatures, heat escape from the surface to the space has been computed according to laws of heat radiation (H o r á k et al., l. c.):

$$Q = c_s \,.\, F \,.\left(\frac{T}{100}\right)^4 .\, \tau \tag{7}$$

where c_s is the coefficient of heat radiation (18.4184 kJ . m^{-2} . hour^{-2} . K^{-2}), F is the plane of the radiating surface and τ is the time in hours. Corresponding data in the matter of heat dispersion caused by conduction and radiation have been added in total computations of space and time parameters.

Proper computations have been done by means of the computer SIEMENS 4004/151 at the Institute of University Computational Techniques in Bratislava according to the program made by one of the authors (V. K.) and written in BASIC. The program enables computations at changing input values in large scale. Graphic dependences and derived corresponding conclusions have been arranged from the computed data.

Computational part

Prevailing majority of the models made for the computation of magmatic intrusion cooling parameters are based on the substantial quantitative value — the size of the intrusion. From the begining we strived to find a way how to apply the computations to real natural bodies but there were many difficulties connected with the definition of their size, above all, their thickness to be able to compute the weight of the original bodies — intrusions at certain simplification of these bodies (e.g. the geometrical shape is a cylinder, rectangular, ball etc.).

Introductory computations of intrusion cooling have been done partly for the bodies of hypothetical dimensions, partly for concrete intrusions, but also in this case some hypothetical parameters had to be used, above all, the thickness. Details connected with these computations will be presented in the next sections.

Cooling of the intrusion "hypothetical cylinder" which diameter is 1 km and height 3 km

The cooling (i.e. gradual equalization of temperatures with the surroundings) has been computed for the intrusion of presented dimensions with original temperatures of the intrusion 1 200, 1 000, and 800 °C, for the depths in which the intrusion stops being in 2, 3, 4, 6, and 8 km from the earth surface. It was supposed that the intrusion penetrated into various types of rocks in range from crystalline schists to carbonates or meta-basalts. 45 models with changing parameters have been computed on the whole. One part of the results is presented in Figs. 1 and 2 where boundary values are illustrated only; middle values, e.g. for the temperatures 1 000 °C, can be interpolated from Fig. 1.

According to the Fig. 1 it is evident that the time of the intrusion cooling is changing in wide scale, whereby the depth in which the intrusion stops has expressive influence in this point of view. It is connected with the fact that the intrusion has great heat storage with respect to low temperatures of surroundings in small depths (in the direction from the surface). Maximal time of cooling (9 000 years) belongs to the intrusion with the original temperature 1 200 °C, solidificated in the depth 2 km in the environment of "more acid" rocks — schists and meta-pelites.

The influence of the original temperature together with the depth where the intrusion stops appears in space action of the intrusion (Fig. 2). Different type of rock environment has no influence upon the distance in which the intrusion operates, the difference appears only in the time when maximal temperature reaches appropriate distance from the intrusion. Considered intrusion can operate to the distance maximally 900 m.

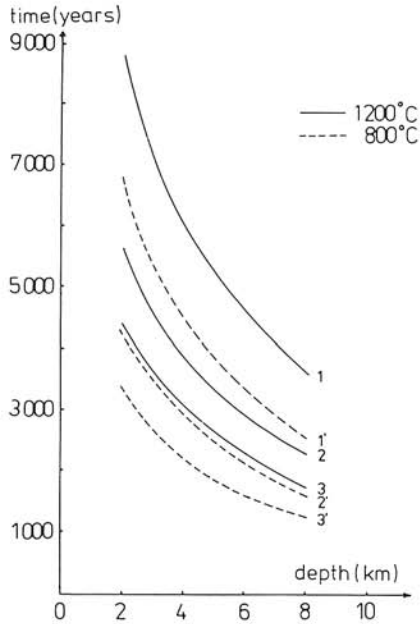


Fig. 1. Graphs illustrating dependences of cooling time of the intrusion "Hypothetical cylinder" on the depth deposition, original temperature and kind of surrounding rocks.
Explanations: 1,1′ — crystalline schists, meta-pelites; 2,2′ — granitic rocks; 3,3′ — carbonates, meta-basalts.

Cooling of the intrusion "Pluton of second size"

According to the classification of plutons (Cloos, 1951 in "Die Entwicklungsgeschichte der Erde", 1981) the area of the pluton of second size is 10^4 km^2. During computations 36 models have been obtained provided the pluton's shape is cylindrical, the thickness is 100 km and it cools in the depth 5, 7, 8, and 9 km. Results are presented in Figs. 3 and 4

The types of curves obtained for time dependences of pluton's cooling are different from the ones obtained on the basis of previous results. This fact follows from occuring of relatively fast escape of heat by radiation as well as fast cooling of the intrusion, because in this case the heat action reaches the surface of the Earth. It is showed objectively also in Fig. 4 where intense drop of temperature corresponds to heat escape by radiation. According to the circumstances, the time of cooling of the pluton is to be from 300 000 to 1.5 mil. years, whereby its heat action can reach, under the most optimal circumstances (original temperature 1 200 °C) the distance a bit more than 7 km.

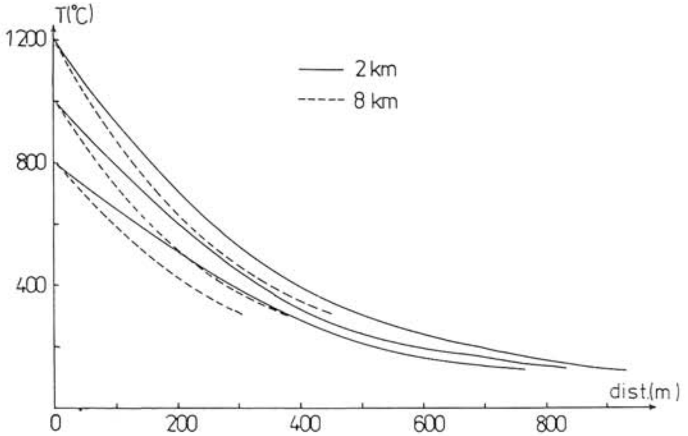


Fig. 2. Graphs illustrating dependences of space action of the intrusion "Hypothetical cylinder" on original temperature and depth deposition of the intrusion.

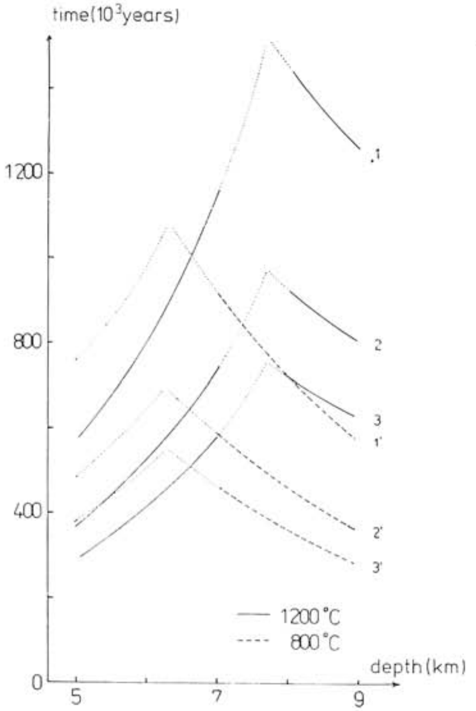
Cooling of the intrusion "Bratislava granitic massif"

For the aplication of our solution of magmatic intrusion cooling we used the well investigated Bratislava granitic massif (further only BGM) as a geographicaly well specified area, for which so called experimentally obtained temperatures of metamorphic action of intrusion to surrounding rocks (according to petrographic-chemical investigations) were at our disposal.

Our considerations were based on older theories applying to deep origin of the massif. We supposed that it would be possible to obtain some arguments for or against in the matter of the theory of the nappe origin of the massif (Maheľ, 1986), from comparison of computed and so called experimental values.

Basic dimensions of BGM — the surface of aproximate oblong shape and dimensions 24 × 6 km have been considered in computations. We had many problems with the thickness of the massif. According to data of Maheľ (l. c.) is the thickness of the nappe 1600—1800 m, according to Lanc (private information) 400 m. In our computations thicknesses of 0.4, 1. 5, 10 km have been taken into consideration. We considered, that intrusion presented above could crystallize at the depths of 2, 4, 6, 10, 12, 15, 18 km. Other input data are the same. Altogether we investigated 84 models of BGM cooling. A part of the results are sumarized in the graphs 5 and 6, further in the graphs 11, 12, 13.

According to the Fig. 5 the times of the intrusion cooling are the longest for the intrusion cooling in small depths. Maximal time of cooling is 40 000 years for the depth 2 km and 100 years only for the depth 18 km according to this. Similarly it is also with the distances of the action (Fig. 6) — a body occuring in the depth 2 km would operate by heat to the distance 1.5—2 km, in the depth 18 km only to the distance about 50—200 m.



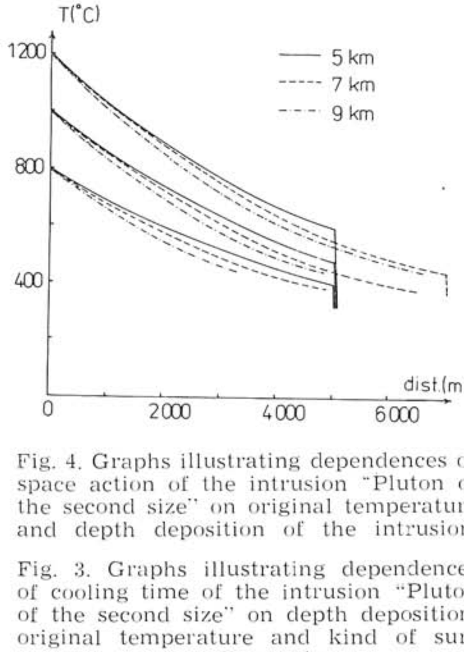


Fig. 4. Graphs illustrating dependences of space action of the intrusion "Pluton of the second size" on original temperature and depth deposition of the intrusion.

Fig. 3. Graphs illustrating dependences of cooling time of the intrusion "Pluton of the second size" on depth deposition, original temperature and kind of surrounding rocks.
Explanations are the same as in Fig. 1.

Cooling of the intrusion "Tatras"

Further geological area for which we strived to model the heat action was the granitic complex High Tatras, occupying the area 720 km² at estimated average thickness 1.2 km (G o r e k, private information). In computations the granitic body "Tatras" has been assimilated to a rectangular with dimensions 51 × 14 × 1.2 km. It was supposed that the intrusion could solidify in depths 5, 7, and 9 km. Other parameters conform with the previous computations. 27 model cases have been computed on the whole. A part of the results showing the cooling time is in Fig. 7. The cooling time of the intrusion "Tatras" is from 15 000 to 100 000 years for presented input data according to this. Space action of the intrusion for depths 5 and 9 km are illusrated in dependences in Fig. 8. The heat action of the intrusion can intervene to the distance 1—1.5 km, at the highest considered depth; at the smallest (5 km) to the distance 2—2.5 km.

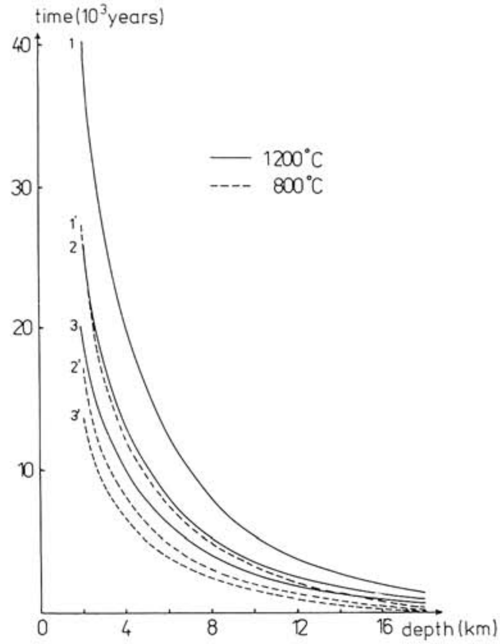


Fig. 5. Graphs illustrating dependences of cooling time of the intrusion "Bratislava granitic massif" on depth deposition, original temperature and kind of surrounding rocks
Explanations as in Fig. 1.

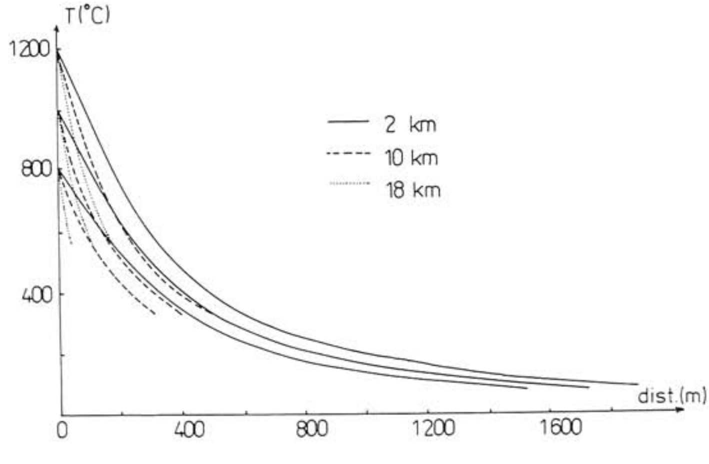


Fig. 6. Graphs illustrating dependences of space action of the intrusion "Bratislava granitic massif" on original temperature and depth deposition of the intrusion.

Discussion

Comon features of all models in the matter of magmatic intrusion cooling present their theoretical character and the fact that computed values can not be compared with real cases. Conformity of the data obtained by various

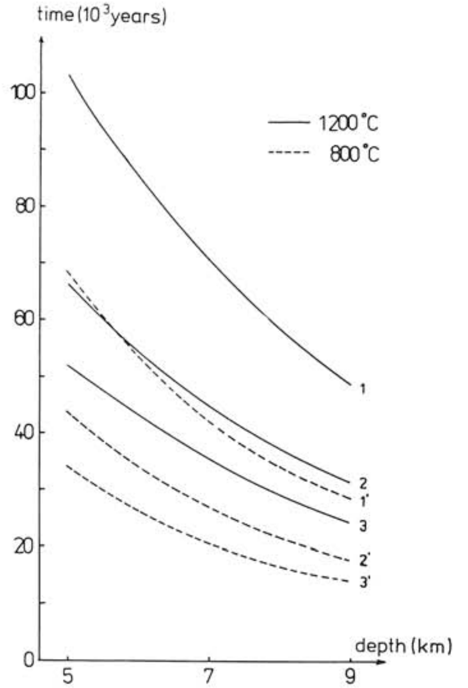


Fig. 7. Graphs illustrating dependences of cooling time of the intrusion "Tatras" on depth deposition, original temperature and kind of surrounding rocks. *Explanations* as in Fig. 1.

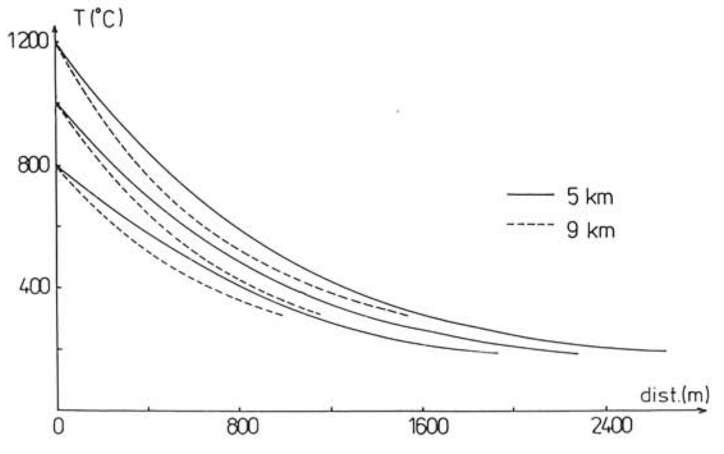


Fig. 8. Graphs illustrating dependences of space action of the intrusion "Tatras" on original temperature and depth deposition of the intrusion.

methods or by the methods following from various principles can be considered as certain criterion of correct computations. However, also in this case the comparision meets with differences among input data used for computations.

Our modelling of magmatic intrusion cooling has shown explicitly dependence of cooling, above all, on the size of the intrusion, next on the depth of "deposition" of the intrusion in space and on the original temperature of the intrusion whereby time and space actions of the intrusion cause petrographic character of surrounding rocks, concretly their heat conductivity on which depends the velocity of heat dispersion from the intrusion to surroundings.

The size of the intrusion together with its original temperature are decisive parameters of the heat action to surroundings because the amount of the heat being brought depends on these parameters. Also the shape of the body can influence the time of the heat action of the intrusion and its space extension, above all, in case of abnormity of a dimension (e.g. a dyke in comparison with a cylindrical body etc.).

The depth in which the intrusion occurs in the earth crust causes the time of its cooling and space action because in case of intrusions with the same parameters e.g. with the same heat storage, the intrusion dipped in greater depth will be in equilibrium with surrounding sooner than the intrusion occuring nearer to the earth surface. However, in case the intrusion reaches the surface in so distance that heat comes to the atmosphere directly or by so called radiation the equilibrium is reached very quickly.

The computation of concrete parameters in the matter of magmatic intrusion cooling can be found out in many works. The time scale of intrusions cooling computed by us conforms with the data quoted in introduction with respect to their exponents. Even next two data are noticable for the discussion in this sence.

Sharapov—Melamed (l. c.) have modelled mathematically the time of magma chamber forming and cooling and plutons linking up with them. It was computed that minimal time during which large magma chambers exist in the earth crust is between 10—15 mil. years, maximally 30—40 mil. years. According to these authors great portion of magma separated from the chamber dimensions of which correspond with the pluton (dimensions of the pluton are not presented) crystallize during 1/10 of these times, e.g. the pluton reaching 5 km in verticale profile should crystallize during less than 300 000 years. We remark that these times are valid for the case of solidification; the times for total equilibrium with surrounding would be substantialy longer.

Parmentier—Shedl (l. c.) have compared space parameters of cooling of the granitic body Santa Rosa in Nevada with Compton's data (1960) in the matter of heat history of 5 samples containing metamorphic rocks taken from certain distances from the contact of the intrusion. We have also tried to solve time and space parameters of the intrusion cooling (its dimensions according to the author's data: $16 \times 8 \times 4$ km) through "our" method with respect to quite exact dimensions of the intrusion presented in the quoted work of the authors. Computations have been done for various original temperatures of the intrusion, various depths of cooling (2, 4, and 6 km) and various surrounding rocks. Graphical illustration of appropriate dependences is in Fig. 9. The cooling time of the intrusion has been determined as 30 000—160 000 years depending on used input data. The time during which the intrusion cools has not been solved by the authors, space dependences will be discussed in next sections.

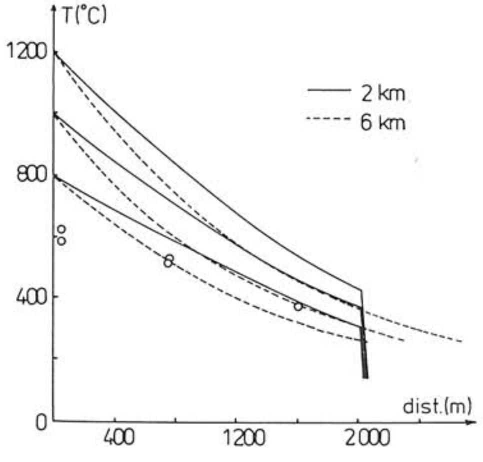


Fig. 9. Graphs illustrating dependences of space action of the intrusion "Santa Rosa" on original temperature and depth deposition of the intrusion; so called original temperatures of mineral associations obtained experimentally are illustrated as circles.

We have tried to confront computed parameters of magmatic intrusions cooling with the data containing heat action of concrete intrusions to surrounding in which these intrusions caused metamorphic changes. However, we were not able to find more than two cases among which the data requisite to the computation and simultaneously to the comparision could be obtained even with

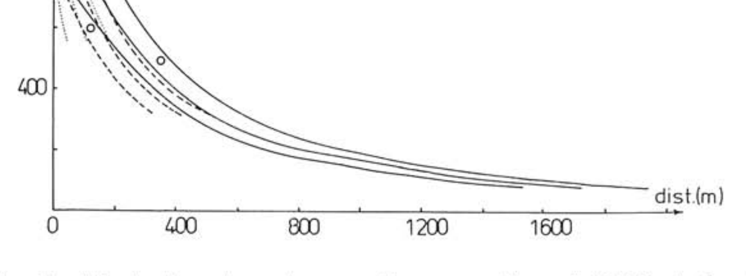


Fig. 10. Graphs illustrating dependences of space action of BGM at the thickness of original intrusion 0.4 km. The circles present conditions of the origin of so called experimental samples.

our best effort. If there are the data about conditions of the origin of certain metamorphic mineral associations at disposal in literature the data about the size of the intrusions or exact data about the place of samples taking are missing.

Only the data specified for the presented intrusion Santa Rosa and the data in the matter of BGM (Korikovski et al., 1984; Miklóš, 1985) have satisfied conditions requisite to the computation and comparison.

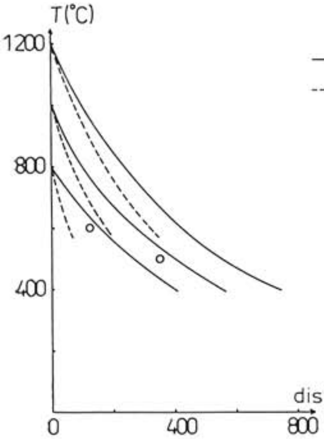


Fig. 11. The same as in Fig. 10 but at supposed thickness of the intrusion 1 km.

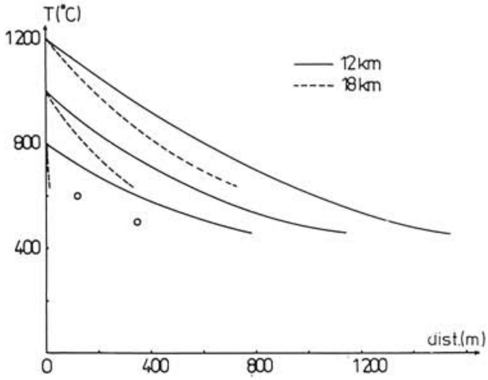


Fig. 12. The same as in Fig. 10 but at supposed thickness of the intrusion 5 km.

Nearby the intrusion Santa Rosa Compton (l. c.) has taken away 5 samples for which temperature and press conditions of the origin have been determined according to the petrographical-chemical analyses. Thus, the original temperature has been determined to be 580 and 620 °C at the pressure 100—200 MPa for two samples taken from the distance 50 m from the contact, for the samples from the distance 750 m the original temperature 515 and 525 °C (at the same supposed pressure) and for the sample from the distance 1 600 m from the intrusion the original temperature 375 °C.

If the presented values are "installed" to the graph illustating the dependence between the temperature, depth and the distance from the intrusion (Fig. 9) drafted for the intrusion Santa Rosa according to our computations further places where the samples are taken are illustrated in the existent fields of deeper horizonts wherby the samples situated near the contact lie considerably out of computed area. Number of reasons why may be more e.g. the method how the distances between the places where the samples are taken and the contact are measured etc.

We had two places of taken samples for which the original temperatures have been determined (Korikovski et al., l. c.; Miklóš, l. c.) placed at disposal to compare results of very detailed computations of BGM cooling. The original temperature determined by the authors is to be 600 °C for the sample taken away from staurolite—sillimanite zone from the distance 115 m of supposed contact with the intrusion and the original temperature 500 °C for the sample from staurolite—chlorite zone from the distance 345 m of the contact. Position of the presented two samples together with the original temperatures given in the graph of dependences computed by us are illustrated in Fig. 10.

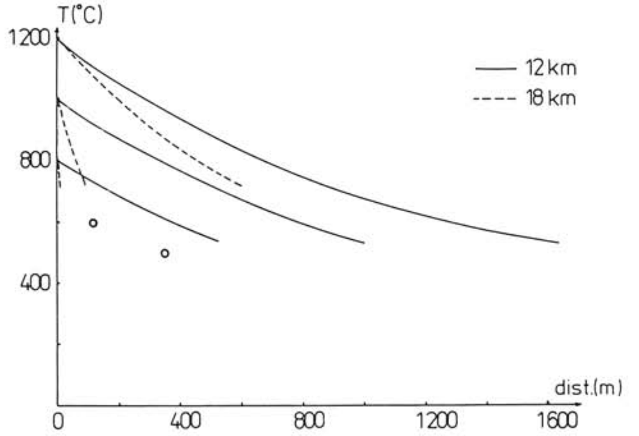


Fig. 13. The same as in Fig. 10 but at supposed thickness of the intrusion 10 km.

Although both samples are situated in computed field of the dependence temperature-depth-distance from the intrusion according to their space position, the estimation of the depth origin of the sample from the place nearer to the contact: 12—18 km (M i k l ó š, l. c.) is exaggerated according to our computations and it should lie in smaller depth than 10 km as it will be mentioned. The decision could be done on the basis of greater number of samples together with the determination of temperatures (and pressure) at which the samples origin and also their exact localization with respect to the intrusion.

The question about trustworthiness of the BGM thickness i.e. 0.4 or 1.6—1.8 km, has been discussed very often in the discussions dealing with presented problems in the matter of BGM. This is the reason why modelling computations have been done for various thicknesses of the intrusion — 1, 5, and 10 km. The comparison of the obtained results with so called experimental data determined by K o r i k o v s k i et al. and M i k l ó š (l. c.) illustrated in Figs. 11—13 realy shows much greater correspondence between theoretical and "experimental" values for substantialy smaller thicknesses of BGM.

In the discussion about space action of magmatic intrusions it is important to mention even G i l l e n's data (l. c.). As it has already been presented (in introduction) G i l l e n gives the data about the action of various intrusions without details namely depending on intrusion's size and its original temperature. For example, granitic intrusion which diameter is 5 km and original temperature 800 °C should cause metamorphic changes at the temperature 425 °C even in the distance 2.5 km. If we consider the fact that Gillen's granitic intrusion represents only about 1/5 of BGM with respect to size his data seem to be considerably exaggerated with respect to the greatest considered thickness of BGM.

Although in total evaluation of the usefulness in the matter of the method connected with the computation of the parameters of magmatic intrusions cooling proposed by us it is important to state the fact that the number of samples by means of which the correctness of the results in the matter of modelling of intrusions cooling has been verified is very small up to now (considering mathematical modelling) and proposed computational process seems to be well — founded, relatively simple and can be managed quite easy.

Conclusions

The present work represents principally new method of solving time and space parameters of magmatic intrusions cooling. Its simplicity consists in computational solution of gradual intrusion cooling through equilibration between temperatures and surroundings. It is based on the fact that the heat brought by the intrusion is dispersed uniformly to surroundings through conductive heat transmission. Time and space parameters of cooling as the functions of heat storage of the intrusion and heat conductivity of surrounding rocks are computed from simple relations in the matter of heat conduction through the system of solid materials.

Trustworthiness of the computations has been verified on the basis of two examples by comparison between theoretical computations and results in the matter of determination of the heat conditions under which mineral associations origin in contacts or near the contacts between intrusions and surrounding rocks namely the intrusion Santa Rosa in Nevada and Bratislava granitic massif.

Mathematical modelling confirmed the fact that intrusions cool depending on their size, original temperature, the depth of deposition in the earth crust and the character of surrounding rocks. These dependences are not, however, always direct, e.g. large intrusion near the earth surface cools substantialy sooner than the intrusion of the same dimensions but occuring in greater depth from which heat is not escaped to the atmosphere by radiation. Even the shape of intrusive bodies is considerably important, e.g. the shape of the intrusion elongated in one direction shortens the time of cooling.

The results presented in this work have been done on the basis of two hypothetical and three concrete intrusions. For hypothetical body of cylindrical shape the volume of which is $2 \,.\, 10^9\,m^3$ the time of cooling has been determined from 1 000 to 9 000 years and its heat action to the distance 300—900 m. Larger hypothetical body, so called pluton of the second size, the volume of which is $10^{14}\,m^3$ can cool from 300 000 to 1,5 mil. years and its heat action can reach the distance 7 km.

For the intrusion of type "Bratislava granitic massif" (dimensions of which are $24 \times 6 \times 0.4$ km i.e. $6 \,.\, 10^{10}\,m^3$) the time of cooling has been determined to be from 100 to 40 000 years whereby its heat action may occur in the distance even 2 000 m. The intrusion of type "Tatras" ($51 \times 14 \times 1.2$ km, volume 9 . 10^{11} m^3) can cool from 15 000 to 100 000 years according to the computations and its effects may occur in the distance 2.5 km.

The estimated thickness of the intrusion Santa Rosa in Nevada is greater at generally smaller volume what occurs in computations as longer cooling (30 000—160 000 years) but practically the same space action (2—2.5 km).

Translated by Z. Šupková

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