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SPACE-TIME-TEMPERATURE PROFILES FOR CONDUCTIVE HEAT
FLOW IN COUNTRY ROCK SURROUNDING HOT INTRUSIVE BODIES *

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ABSTRACT

Temperature vs distances profiles during geological time have been calculated for a variety of realistically shaped magmatic bodies intruded into country rock. The calculations were made with a computerized finite difference formulation of the classical time dependent conductive heat-flow equation. The formulation can be adopted to numerous situations. These include: emplacement at different rates, variations in the shape of the intrusion, e.g. domed cylinders, cones, or even arbitrary shapes as determined by field measurements. The intrusions may remain in contact with or become isolated from the magma pool. Also, the thermodynamic properties of the intrusion may be adjusted, e.g. to include latent heat of fractional crystallization. The surrounding rock may be homogeneous or strata of different kinds of rock. The surface above the intrusion may assume any reasonable shape. Faulting in the surrounding rock is being included and magma convection will be added in the future.

Completed calculations of the surface heat-flow gradients are consistent with those found in regions of known geothermal activity. This calculational procedure, in conjunction with local surface and subsurface temperature and heat-flow measurements appears to provide a useful approach to evaluating geothermal energy sources and new techniques for geothermal exploration and characterization.

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INTRODUCTION

The increasing interest in geothermal energy sources has been the motivation for a number experimental and theoretical investigations of hot magmatic intrusions into the upper levels of the continental crusts. Described below is a procedure for calculating thermal histories for points both within and surrounding arbitrary shaped intrusions. These intrusions may vary in content and temperature and may be intruded into stratigraphically complex regions. Many features of this procedure are similar to those described in recently appearing publications. Other features are novel, especially those which have been introduced to facilitate computation for shaped bodies in a stratigraphic situation containing (mathematical) discontinuities corresponding to physical features such as faults.

Calculations which can furnish a realistic thermal history of an intrusion and the surrounding region are useful for many purposes. They can provide estimates, especially when abetted by physical measurements (e.g. knowledge of local geology, heat flow, seismic data etc), of the size, shape, temperature, total thermal content, time of emplacement and other physical properties of a given intrusion. They can also be used to evaluate measurement procedures such as fluid inclusion or thermoluminescence paleotemperature techniques.

BACKGROUND

The United States has a large number of localities which appear to contain thermal intrusions suitable for development into geothermal energy sources. (McGetchin, 1975; White and Williams 1975; Reynolds, 1976). The literature contains descriptions of several analytical methods for calculating temperature profiles in and around geothermal bodies. These include, for example, the early papers of Lovering (1935, 1936, 1955), the classic papers of Carslaw and Jaeger (1959) and Jaeger 1964. The last mentioned paper includes calculation of temperature as a function of time for several geologically realistic situations. It has recently been adopted to geothermal calculations of the Long Valley, California Caldera (Lachenbruch et al, 1976; this paper contains numerous pertinent references.) Included in the analytical methods are the recent steady state calculations of Horai (1976a, 1976b).

The analytical methods, such as those mentioned above, lack flexibility and are difficult to apply to the space and time dependent conditions encountered in geothermal calculations. However, numerical finite difference methods are particularly well suited to problems involving time dependent conditions and to discontinuities. For example, finite difference methods are readily adopted to handle the discontinuity in thermal conductivity at the interface between the intrusion and country rock, expansion or injections of the intrusion, etc. Most importantly, finite difference methods are readily programmed for the currently available large computers. In recent years, they have been utilized by McGetchin (1975) and Witsan (1976). In particular, McGetchin (1977) has used finite difference methods for calculations on the thermal intrusion at Fenton Hill on the edge of the Valles Caldera in the Jemez Mountains of New Mexico.

The numerical finite difference procedure outlined below has been formulated to describe realistic magmatic intrusions in a variety of cases. The body may have any realistic shape, e.g. cylinder, cone, sphere, spherically capped cylinder or an arbitrary shape. The intrusion may remain in contact with the magma pool, and fed rapidly or slowly by a pipe. Also the contact may be broken or reestablished at will. The surrounding rock can be arbitrarily stratified, faulted, and each segment (layer) given a set of thermal parameters. The thermal properties of the magma can be specified. Lastly, it is planned to include additional features such as convection in the magma body and the presence of water in the surrounding medium.

THEORY

First, the classical time dependent conductive heat flow equation is rewritten in finite difference form. It is then applied to each cell in a finite three dimensional net which includes the intrusion and the surrounding rock. The properties of each cell are established before the calculations is initiated. During the calculation they vary in accord with the appropriate physical conditions. Discontinuous phenomena such as latent heat are included by using Kronecker-like delta functions to account for the magnitude and direction of latent heat flow into or out of a cell.

During the calculations, both the cell size and temperature increments can be adjusted to remove the

instabilities inherent in finite difference calculations. Also, to optimize the computer usage, small cells and time steps may be used when the parameters, e.g. temperature, are varying rapidly and larger increments and cells used when the parameters change slowly.

With the present formulation, in each case it is necessary to determine if adequate boundary conditions have been established at the interface of the grid and the surrounding material. The upper surface, which represents the air-ground interface, does not pose a problem. The surface temperature is fixed at 0°C. It is assumed that the material outside of the grid other than at the air-ground interface is the same as the material at the grid surfaces. A number of different boundary conditions at the grid surface have been tested. For example it can be assumed that the second derivative of the temperature with heat conductive equation, i.e. the rate of heat flow across the boundary, is continuous. This assumption has been tested with a fixed size intrusion in grids of different size. Usually grids with edges that are 2 or 3 times the diameter of the intrusion appear to be adequate, larger grids do not produce appreciably different time temperature profiles.

RESULTS

Temperature-distance profiles at various times have been calculated for a number of physically realistic yet simply shaped basaltic and granitic intrusions into a granitic medium. The shapes included are solid cones, right cylinders and domed cylinders. It was assumed they were emplaced instantly. Numerical values for thermal conductivity, specific heat, etc., were obtained for Clark (1966). Also latent heat effects have been evaluated.

The geometry of the intrusions is illustrated in Fig. 1. The horizontal surface, corresponding to the air-ground interface is maintained at zero degrees C. The radiogenic heating is not included. Its effect can be included by superimposing an additional temperature gradient of approximately 25°C/km.

Table I- Typical Measured Surface Thermal Gradient Values

Location	Heat flow in HFU ($=10^{-6}$ cal/cm ² /sec)	
	Near Anomaly	On Fringe of Anomaly
Radiogenic	1.53	1.53
Valles Caldera	3.7-5	2.8
Socorro	10	2.5

Fig. 1. Lacolith geometries used for computations described in this paper. The bases of all intrusions lie 6km below the surface.

Fig. 3. Temperature vs time after insertion, on the roof of the lacolith and at a point on the center line.

Fig. 2. Temperature vs time after insertion, 100 m below surface and at a point on the lacolith centerline. All bodies were inserted at 1100°C.

Fig. 4. Temperature vs distance from surface along the centerline of the domed lacolith and at various times after insertion.

TABLE II
CALCULATED THERMAL GRADIENTS AT SURFACE^a

Intrusive Medium	Cylinder		Cone		Dome	
	Center	Fringe	Center	Fringe	Center	Fringe
Basalt (w/o latent heat)						
Peak	3.8	1.2	4.6	2.8	10.8	0.4
(Time)		(80 Ky)		(140 Ky)		(40 Ky)
400 Ky	2.2	2.2	2.3	2.4	2.8	2.7
1000 Ky	0.43	0.5	0.3	0.3	1	0.3
Basalt (latent heat)						
Peak	6	1.2	4.6	2.4	11.2	0.3
		(100 Ky)		(140 Ky)		(40 Ky)
400 Ky	2	2.1	2.2	2.3	2.8	2.8
Granite (w/o latent heat)						
Peak	8.3	2.5	not		15.8	0.6
		(100 Ky)				(40 Ky)
400 Ky	3.7	3.4	computed		5	4
1000 Ky	0.9	0.9			1.3	1.4

a. In heat flow units (1 HFU = 10^{-6} cal/cm/sec)

Fig. 5. Temperature vs distance from centerline of the domed lacolith, at the depth of the lacolith roof and at various times after insertion.

Thermal histories at a point 100 meters below the ground surface and centered over the intrusions are shown in Fig. 2. The bases of all bodies considered are 6km below the surface. In general, granitic inclusions produce higher temperatures than basaltic bodies. This is attributable to the greater specific heat of granites. At 100m below the surface, it is apparent that the inclusion of 100 Cal/gm latent heat in the intrusion does not produce a detectable effect. This illustrates an advantage of the numerical approach over an analytical one. To include latent heat effects in analytical calculations one usually employs an adjusted initial temperature or specific heat. The analytical approach tends to over compensate for the latent heat effects.

Thermal histories at the center of the top of various intrusions are shown in Fig. 3. Temperatures near lacoliths, at various times after intrusion, are illustrated in Figs. 4 and 5. The curves behave in the expected manner.

The reliability of these calculations is illustrated by comparing computed gradients with measured values. Typical measured values near or over known thermal anomalies, are given in Table I. Calculated values for cases in Figs 2 to 5 and additional ones are given in Table II. Clearly the measured and compiled values are comparable.

To summarize, the finite difference calculations described above appear to be both useful and practical. Furthermore, although not discussed above, they can be carried out with reasonable computer use; the execution times never exceeded 9 minutes and utilized only 1/3 of the available storage. Thus, it would appear that this technique can be developed into a useful tool for calculating numerous and varied characteristics of thermal intrusions.

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