INFERRING THE TEMPERATURE AND COMPOSITION OF THE CONTINENTAL LITHOSPHERE FROM GEOPHYSICAL DATA

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Thermodynamic modeling of phase relations and physical properties of multicomponent mineral systems was used to develop a method for solving the inverse problem of determining the composition, density and thermal structure (the temperature, heat flows, and heat generation) in the continental lithosphere from the totality of geophysical and petrological evidence. The goal of the inversion procedure is to find the a self-consistent petrological-geophysical model that minimize the discrepancies between the calculated and “standard ” petrological and geophysical models.

1. Introduction

There are two approaches to obtain information on the composition and internal structure of a planet. The first approach consists in forward modeling - computer simulation of phase equilibria and thermoelastic properties at high pressures and temperatures and a comparison of the calculated seismic profiles with seismological observations. A thermodynamic approach for computation of phase diagrams, equations of state of minerals, seismic properties and density from known thermodynamic conditions and mineralogies applied to the planetary interiors has been extensively described.

Another approach to solution of the problem of modeling the constitution of the planet consists in translating the observed seismic velocity profiles into the temperature and composition models [1-7] (inverse problem). In this paper, we propose a new formulation for solution of this problem which consists in retrieving the temperature and density distribution, chemical composition in the Earth continental lithosphere from the geophysical and metrological observations. A feature inherent in the solution of the thermophysical inverse problem obtained in this paper is the use of constraints derived from the temperature reconstruction by seismic data inversion. As a result, the dependence of the temperature on depth, the intensity of radiogenic heat sources in the crust, and heat flow components in the crust and lithosphere are determined.

2. Thermodynamic approach

From the thermodynamic standpoint, the composition and the physical state of the Earth can be characterized by several parameters determined from geochemical data and equations of state (ESs) of the multiphase mantle material. The apparatus of chemical thermodynamics allows one to use the bulk composition of rocks for a correct determination of the composition and physical properties of stable phase assemblages at high temperatures and pressures [8]. We use the method of the Gibbs free energy minimization adapted to calculations of phase equilibria in multisystems with phases of variable composition representing multicomponent solid solutions of minerals. The ESs of minerals are calculated in the Mie-Grüneisen-Debye quasiharmonic approximation, with the Born–Mayer potential approximating the ES potential part. Equilibrium compositions of phase assemblages, elastic wave velocities, and density were calculated with the use of the THERMOSEISM software complex [8]. The database contains self-consistent data on such thermodynamic parameters as the enthalpy, entropy, heat capacity, Grüneisen parameter, thermal expansion, and bulk and shear moduli of minerals and on mixing parameters of solid solutions. For the computation of phase diagram for a given chemical composition, we have used the well-known equation for the Gibbs free energy.

3. Determination of the Composition and Mantle Temperature from Seismic Velocities

The first step in our method is the determination of the temperature, composition profiles from absolute experimental P and S wave velocities: $T_{P,S}$, C_m, (m=FeO, MgO,Al_2O_3, CaO). The $T_{P,S}$ profile is then adjusted to a thermophysical model of conductive transfer [6,7].

The procedure for converting seismic profiles into compositions and thermal profiles in the Na_2O-TiO_2-CaO-FeO-MgO-Al_2O_3-SiO_2 multisystem with phases of a variable composition is based on the equations of state of mantle material taking into account phase transformations, anharmonicity, and anelastic effects. The inverse problem is based on the minimization of the functional:

$$\vartheta = \sum_{i=1}^{N} \sum_{F} \alpha_F (F_i^0 - F_i)^2 ,$$

($F=V_p$, V_s, T_{cond}, C_m), ($m=FeO$, MgO, Al_2O_3),

F_i^0 are the parameters of the "standard model", the T_{cond} is determined from the second step, F_i – calculated parameters. The functional is minimized by the Monte Carlo method. In making inverse problem, we require a non-negative density gradient in the mantle ($d\rho/dH > 0$) and assume using the arguments on $C_{Al_2O_3}/C_{CaO} = 1.25$ ratios in mantle [9].

4. Determination of the Temperature in the Crust and Lithosphere from Surface Heat Flows (The Forward Problem)

The proposed approach to the determination of the geothermal and heat flows is based on the model of conductive heat transfer. This means that the model comprises only the crust and lithosphere. The underlying region of convective heat exchange and the region of the temperature boundary layer are not considered. Formally, the model domain comprises the region from the Earth's surface to the thermal boundary of the lithosphere. This boundary is defined here by the intersection of the calculated temperature profile with the potential adiabat. The entire region of conductive heat transfer (crust + lithosphere) is divided into five computational zones: the upper crust (i=1, 2), middle crust (i=3), lower crust (i=4) and lithospheric mantle (i=5). The upper crust contains the D layer (i=1), in which the major portion of radiogenic elements is concentrated. The D layer is assumed to have an exponential distribution of intensity of radiogenic heat sources with depth H [10].

It is assumed that the nonstationarity effects are small compared to other uncertainties of the model. Therefore, following [10], we adopt a 1-D stationary model of heat conduction. The temperature profiles in the remaining zones (i = 1–5) are determined by the simple equations. The surface boundary conditions are fixed by values of the temperature and temperature derivative. From the simple dependences for calculating the temperature in the 1-D multilayer model determine the temperature in the crust and lithosphere as a function of the depth $T_{cond}(H)$).

5. Determination of Heat Flows, the Intensity of Radiogenic Heat Sources, and the Temperature in the Crust and Lithosphere (the Inverse Problem)

In sections 2-4, we described the methods of determining the temperature in the crust and lithosphere ($T_{P,S}$) from seismic data and the 1-D model of heat conduction ($T_{cond}(H)$). On the basis of these two approaches, we formulate the following inverse problem. Using the surface heat flow and the $T_{P,S}$ temperature profile, we have to determine the thickness of the D layer, heat generation in the D layer , heat generation in the upper crust, heat generation in the middle crust, and heat flows in the crust and lithosphere. This problem is solved by minimizing a functional F characterizing the misfits between the temperature profile $T_{P,S}$ derived from seismic data and the temperature profile T_{cond} calculated from the 1-D model of heat conduction. The functional F is minimized by the Monte Carlo method. The input parameters for the inversion procedure are the thermal conductivities in all model zones, the heat generation in the lower crust and in the lithosphere, the surface heat flow, the surface temperature T_0 and the temperature profile $T_{P,S}$ determined from seismic data. As a result, we find the temperatures along the geotherm (T_{geoth}) and heat flows in all model zones can be calculated by analytic formulas.

6. Results

The methods for the reconstruction of the thermal regime and composition in the mantle described above were used to calculate the composition, geotherm and the components of the total heat flow for the averaged (or normal) continental lithosphere. We have used the following "standard model" of the Earth upper mantle. Seismic velocity profiles as a function of depth have been given according to the most recent seismic velocity model IASP 91 [11]. We also have employed the petrological models in the "standard model": 80-200 km - average composition of the continental garnet peridotites [9], 200-370 km - average composition of the primitive mantle [9]. Composition, temperature profiles, values of crustal radiogenic heat sources, and heat flow components in the mantle are determined according to the procedure described in section 5.

The calculated velocity profiles agree with seismic profiles [11]. The calculated temperatures are within reasonable limits of all uncertainties involved in geophysical observations [10, 12]. Our analysis of the internal structure and composition of the upper Earth mantle leads to the following conclusion that model of the upper Earth mantle consists of two regions with boundary at depths of 200 km gives the best fit to the mantle seismic properties and chemical composition.

7. Conclusions

In this paper, a method is proposed for the calculation of the composition of the lithosphere and thermal regime of the crust and lithosphere (the temperature, heat flows, and heat generation) and is used to model the composition and thermal structure of continental lithosphere. The procedure of converting seismic profiles into thermal ones is based on the equations of state of mantle material taking into account phase transformations and anharmonicity and inelasticity effects. Our modeling results show good agreement with modern geothermal and petrological models.

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