Petrochemical Data as an Indicator of a Deep Heat Regime of Intraplate Continental Areas of Magmatic Activity

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Abstract: The petrochemical data on secular changes in depth of magma generation were used to reconstruct the heat flow supplied from the anomalous mantle to the lithospheric base in different regions of Cenozoic tectonic activity during rejuvenation. The results are presented for the East African rift, the north African domal uplifts, a vast region of Cenozoic orogeny in Middle Asia and Central Siberia, the French Massif Central, and the Rhenish massif.

The influence of a fluid regime of the upper mantle on the process of tectonic and magmatic activity is studied; numerical modelling is carried out for the upper mantle composition being peridotite with water and/or carbon dioxide; a case of a "dry" system is treated for a comparison. The value of the required heat flow from the anomalous mantle does not depend much on the degree of lithosphere material partial melting. However, it is very important to take into account the composition of the upper mantle material to get reliable estimates of the mantle thermal regime, especially at the very first stages of the tectonic process.

INTRODUCTION

The process of formation of intraplate continental areas of Cenozoic tectonic and magmatic activity, including continental rift zones, mountain areas, high plateaus and domal swells has been the focus of a number of investigations during the last decade. However, the amount of geophysical data available for these regions is still insufficient. Because of difficult geological conditions, some of them were not studied thoroughly; for some areas contradictory data were obtained by different authors.

Nevertheless, geophysical investigations over the past 25 years have revealed the main characteristic features of the lithosphere and upper mantle structure of continental rifts and high plateaus. Most of these areas have undergone an intensive process of tectonic and magmatic rejuvenation in Cenozoic. As a result, a contemporary relief was formed on the place of Mesozoic platforms (e.g., ZIPPELT and MALZER, 1981; ZORIN and FLORENSOV, 1979).

The most important feature of the deep structure of high plateaus and continental rifts is a presence of an anomalous material in the upper mantle of these areas. This phenomenon is typical of all continental regions of Cenozoic rejuvenation and thus allows us to consider the process of formation and evolution of continental rift zones and high plateaus in the frames of a single geodynamical model.

Geophysical investigations make it possible to determine the main properties of an anomalous zone in the upper mantle of tectonically activated areas.

Lithosphere thickness is usually estimated as a thickness of a layer above the low velocity zone in the upper mantle. However, there may be a difference in the lithosphere thickness estimates obtained during seismic studies, and the lithosphere thickness considered in rheological models. The areas of the Cenozoic tectonic and magmatic activity are characterized by high temperatures and partial melting in the uppermost mantle. That is why the layer of decreased seismic velocities is quite pronounced in these regions and a position of its upper boundary gives a good estimate for the lithosphere thickness.

The lithosphere of the intraplate continental areas of rejuvenation was thinned to 20-50% of its initial thickness (120-150 km—a value typical of stable platform areas) during the Cenozoic tectonic process (i.e. during the last 25-40 Ma) (CROUGH and THOMPSON, 1976; ILLIES et al., 1979; SPOHN and SCHUBERT, 1982). In some areas (Kenya rift, the Baikal rift) lithosphere was thinned to the crust (HEBERT and LANGSTON, 1985; ZORIN et al., 1988).

The anomalous mantle underlying the lithosphere is characterized by low seismic velocities (7.4 - 7.9 km/s instead of 8.1 - 8.3 km/s typical of

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stable platforms and Alpine-type mountain systems) and high attenuation (FAIRHEAD and GIRDLER, 1972; KELLER et al., 1979; VINNIK and SAIPBEKOVA, 1984). The thickness of the low velocity zone in the upper mantle is as much as 100-200 km (the Baikal rift, the Eastern Sayans, the Tien Shan, Kenya rift) (NOLET and MUELLER, 1982; RIABOY and DERLIATKO, 1984).

Important information about the physical properties of the lithosphere and the anomalous mantle material was obtained by gravity studies. They revealed that on a regional scale the areas of Cenozoic activation remain in approximate isostatic equilibrium (e.g., KAULA, 1972; ZORIN and FLORENSOV, 1979). The analysis of the gravity field has showed that no more than 1/3-2/3 of isostasy may be explained by a crust thickening. The remaining part of compensation cannot be explained by the models with realistic variations of density (ARTUYSHKOV, 1983). Thus, it is necessary to assume an existence of low dense masses in the upper mantle of activated areas.

The existence of anomalous mantle of a low density is proved by large negative Bouguer anomalies (about -150~250mgal for different areas of regional uplift) (e.g., GIRDLER, 1975). In some areas (e.g., the Tien Shan, high mountain regions of southern Siberia and Mongolia) a good correlation between different geophysical observations has been noted: lithospheric blocks with low seismic velocities in the mantle coincide with areas of large negative Bouguer anomalies, close to zero isostatic gravity anomalies, and with the areas of increased heat flow (ARTEMIEVA and GLIKO, 1989).

The areas of regional uplift are characterized by Cenozoic, mainly basaltic, volcanism which coincides with zones of low seismic velocities (e.g., Mongolia) (Continental volcanism of Mongolia, 1983); avolcanic continental rifts and high plateaus do not exist. That is why volcanism may be considered one of the most important characteristics of continental rifting and rejuvenation process and may provide essential information about these processes. Detailed data on Cenozoic magmatism of different areas of regional uplift will be presented in the next section.

**PETROLOGICAL DATA**

In almost the all areas of Cenozoic activity, it is possible to recognize some evolutionary trends in the composition of igneous rocks. As a rule, the magma composition changes in time from the deepest ultra-alkaline magmas generated at 80-100 km depth (melanephelinites, melaleucitites and derived carbonatites) to alkali olivine basalts generated at 60-80 km. In some areas the intrusions of magmas generated at depth of 35 - 50 km (low-Ca phonolites and trachytes) are known (RINGWOOD, 1975; YODER 1976, WENDLANDT and MORGAN, 1982) (Fig.1).

**The East African Rift System**

The tectonic activation of the East African region started in Neogene-Quaternary time when the domal uplift of the territory began, accompanied by a very intensive volcanism. According to seismic studies (e.g., FAIRHEAD, 1976; HEBERT and LANGSTON, 1985), the lithosphere beneath the East African domal uplift is thinned from 80-100 km to 55 km, beneath the rift axis - up to the crust (35-40 km). Thickness of the anomalous mantle layer is estimated to be about 160km (NOLET and MUELLER, 1982).

The East African rift system is characterized by an intensive magmatic activity, the areas of Cenozoic volcanism being associated with high domal uplifts (LEBKS, 1971). Investigations over the last decade have revealed a genetic dependence between kimberlite magmatism and consequent alkali basaltic volcanism and the process of tectonic activation of platform areas. Thus, some authors (WENDLANDT and MORGAN, 1982) believe that melting of kimberlites may be considered as the very beginning of tectonic activation (GLIKO and GRACHEV, 1987). The diamond-bearing kimberlites are known for northern Tanzania, their age being estimated of about 40 Ma.

Main magmatism in the Kenya-Ethiopian rift began in the early Tertiary (KING et al., 1972; DAVIDSON and REX, 1980; LE BAS, 1980). By Miocene time carbonatite-nephelinite volcanism become well established in this area. The oldest carbonatites are
about 30 Ma old, the depth of their generation being about 85-100 km (Kuo et al., 1972). Later on (about 20-35 Ma ago) an intensive intrusion of flood basalts with a generation depth of 50-70 km took place in Kenya (Bellienni et al., 1987). Low-Ca phonolites and trachytes generated at 40-50 and 35-40 km depth were intruded correspondingly 13 Ma and about 4-1 Ma ago (Wendlandt and Morgan, 1982; Baker et al., 1988). In the western branch of the East African rift system the maximum of magmatic activity took place about 6 Ma ago and coincided approximately in time with a change from tholeiitic to alkaline basalitic volcanism when trachytes and phonolites were intruded (Pastels et al., 1989).

North African High Plateaus

In the northern part of Africa some high plateaus around the Tchad basin are well known, among them being Hoggar, Tibesti, Air, Darfur and Adamawa plateaus. These domal uplifts are characterized by similar sizes, morphology, history of vertical movements, and volcanic activity (Girod et al., 1981; Crouch, 1981; Dautria et al., 1987; Lesquer et al., 1988). The one most studied among them is the Hoggar Massif in Central Sahara.

The latest stage of tectonic and magmatic activity of the Hoggar plateau began in the late Cretaceous-Eocene, when basic (may be transitional to alkaline) volcanism was developed in this area. Since the early Miocene it was replaced by typical intraplate alkaline-basaltic volcanism (Girod et al., 1981).

Petrological studies of the Hoggar plateau xenoliths (Dupuy et al., 1986; Dautria et al., 1988) have revealed that the upper mantle beneath the plateau is strongly heterogeneous. It may be explained by a different degree of partial melting of the mantle material: the estimates made on the basis of LREE content (Dupuy et al., 1986) gave values from 1 to 10% of melt, in some cases—up to 20% of melt. It is assumed that the process of the upper mantle material melting began beneath the Hoggar plateau not later than in the Miocene (most likely—in the Eocene) (Dautria and Lesquer, 1989).

Western United States

Despite a large number of geological and geophysical investigations in the western part of United States, many questions of geodynamical development of this area are still unclear.

All this part of the United States is characterized by anomalous structure of the lithosphere. According to seismic data there exists a thick layer with very low velocities on the depth 60-240 km (e.g., Krishna, 1988). During the Cenozoic activation the lithosphere beneath western United States was thinned from 120-140 km (lithosphere thickness beneath southern part of the Great Plains) to 60-70 km (e.g., the Colorado Plateau).

Cenozoic volcanism is typical heat regime of the western parts of the USA. In the early Cenozoic time calc-alkaline volcanism (andesites and rhyodacites) typical of active margins developed there. About 15-20 Ma ago the type of volcanism changed to bimodal basaltoid one typical of the rift zones of extensional tectonics (Thompson and Zoback, 1979).

However, an average composition of the basalts from Basin and Range Province almost coincides with the composition of OIB. Thus, petrological data for BRP contradict with the model of thermal thinning of the lithosphere, in which it is assumed that mantle lithosphere is replaced by asthenospheric material. The data may be interpreted either as a proof to the existence of a calc-alkaline trend in volcanism evolution due to melting of an ancient subducting lithosphere beneath western USA (Rio Grande rift, 1979), or may be explained by a lithosphere erosion due to the plume beneath the southern Rocky mountains (Fitton et al., 1991).

In a development of the Rio Grande rift volcanism the tholeiitic trend is well pronounced. The magmatic activity of the region was well established since the Oligocene when basaltic magmatism started (about 26 Ma ago). At that time nepheline and hypersthene normative lavas were generated (Thompson et al., 1991). The intrusions of trachybasalts, calc-alkaline andesites and rhyolites were replaced by alkali olivine basalts about 10 Ma ago (Seager et al., 1984). In Pliocene time volcanism of the Rio Grande rift was mainly tholeiitic, with a higher degree of partial melting of the mantle material than on the previous stages of activization (Thompson et al., 1991).

The basalts from the axial part of the rift have a composition close to that of typical abyssal tholeiites; this proves the existence of a very thin lithosphere at a time when they melted. Thus, the Rio Grande rift is characterized by a consecutive change in the basalts chemical composition from the most ancient undersaturated alkali olivine basalts to a younger tholeiite basalts (Rio Grande rift, 1979). The same trend may be observed when moving from south to north along the rift axis. According to geochemical and geophysical data a consecutive uplift of magma sources and lithosphere thinning occurs in this direction at a distance of about 600 km.

Thus, some authors assume (e.g., Perry et al., 1987) that the Rio Grande rift was formed due to a consequent substitution of a lithosphere by asthenospheric material. According to the Nd isotope
ratios interpretation, PERRY et al. (1987) have suggested that all volcanism of the Rio Grande rift may be considered as a result of the lithosphere melting.

The Baikal-Mongolian Region

Seismological data indicate anomalous properties of the upper mantle beneath the Baikal-Mongolian region on the depths of 50-250 km (RIABOY and DERLIATKO, 1984). Lithosphere thickness is estimated to be 75-80 km in Mongolia and 40-60 km in the Baikal rift zone (ZORIN et al., 1988).

According to the geochemical data the first outbursts of basaltic volcanism in the Baikal-Mongolian region were in the Eocene (45-50 Ma ago) and marked the beginning of the rejuvenation process. By the late Pliocene a tholeiitic-type magmatism of the early stages (with intrusions of alkali basalts, basanites, and olivine tholeiites) was replaced by a less intensive alkaline basaltic volcanism (GENSHAFT and SALTYKOV-SKY, 1985; KISELEV, 1987). Studies of the basalts and ultramafic xenoliths chemical composition together with MTS data revealed differences in the upper mantle composition of this area and indicated a consecutive uplift of magma sources from 55 km in Mongolia to 30-35 km in the Baikal rift zone (LYKOV et al., 1981).

The Tien Shan

The Tien Shan is usually considered to be one of the areas of Cenozoic tectonic and magmatic activation. By the properties of the upper mantle the Tien Shan is divided into two parts, the boundary between them approximately coinciding with the Talas-Fergana fault. Seismological data obtained for the western Tien Shan are typical of the stable platforms with cold upper mantle (VINNIK and SAIPBEKOVA, 1984).

The anomalous mantle zone is revealed beneath the Eastern Tien Shan on the depth from 60-80 km to 120-150 km (RIABOY and DERLIATKO, 1984). KHITAROV et al. (1985) pointed out that from 1 to 5-10% of melt may be present in the anomalous upper mantle of this region. During the rejuvenation the lithosphere of the eastern Tien Shan was thinned from about 120 km (value typical for the Hercynian platforms) to 60-80 km. Recent studies (ARTEMIEVA and GLIKO, 1989; ARTEMIEVA, 1991) showed that many peculiarities of the eastern Tien Shan geodynamical development in the Cenozoic may be explained in the frames of the model of thermal thinning of the lithosphere.

The Quaternary volcanic activity of the Tien Shan was not very intensive, because the extensional stresses in the lithosphere (that usually lead to rifting and associated magmatism) were compensated by a horizontal compensational stress due to the tectonic process in the neighboring Alpine-Gimalayan mountain system. In Eocene time (40-50 Ma ago) the alkaline magmatism began in the Tien Shan marked by more melaneosphelines and basanites, later it was followed by intrusions of alkali basalts (KNAUF et al., 1980).

The Rhenish Massif

Seismological data revealed the existence of large mantle velocity inhomogeneities on the depths 50-200 km beneath the Rhenish massif and lithosphere is estimated to be only 40-50 km thick there (PANZA et al., 1980).

The earliest volcanism known in the Rhenish massif began at the end of Cretaceous (about 108 Ma ago) (FUCHS et al., 1983) with extrusions of melilite nephelinites. The principal uplift of the area began in Miocene time (about 30 Ma ago) and coincided with a peak in the alkaline magmatism when nephelinites, basanites, alkali basalts, trachybasalts and trachyandesites were generated (LE BAS, 1987).

In the Miocene some carbonatite volcanic complexes developed in the region. Basaltic volcanism was not very intensive in the Pliocene, but it became active again in the Pleistocene in the Eifel. The joint analysis of petrochemical and geophysical data revealed that the uplift of magmatic sources in Pliocene-Pleistocene time took place with an average velocity of about 5-10 km/Ma (NEUGEBAUER et al., 1983). The studies of mantle xenoliths from the Rhenish graben showed that the degree of partial melting of anomalous mantle material beneath this area of activation was about 5-10% (MAALOE and PRINTZLAU, 1979).

The French Massif Central

Seismological data indicate an anomalous structure of the upper mantle beneath the Massif Central up to the depth of about 400 km (GRANET and CARA, 1988). In the depth range of 70-240 km low S-velocities were obtained (SOURIAU et al., 1980). Studies of the surface waves revealed that lithosphere under the Central Massif is thinned to 60-100 km (SOURIAU, 1981).

After the formation of Hercynian mountains (about 280 Ma), the Massif Central remained stable during the Mesozoic. Alkaline and some ultraalkaline volcanism began in the Eocene before the formation of the grabens (65-35 Ma) and consisted of only small volumes of undersaturated lavas (melilite nephelinites) (BROUSSE and BELLON, 1983; MASSE, 1983). Geochemical modelling (KAY and GAST, 1973) shows that magmas of such composition may be
generated at the base of the continental lithosphere (~150 km) with a very low degree of melting (less than 1%).

The second stage of volcanic activity began at the early Miocene (20 Ma) and had two peaks - about 7-4 Ma and 4-2 Ma ago, the lavas changing from undersaturated (nephelinites, basanites) to less alkaline olivine basalts. The latest type of volcanism is usually initiated at the continental crust with partial melting rates lower than 10% (Le Bas, 1987). Such chronological evolution of magmas composition was interpreted as a progressive ascent of magma sources during the rejuvenation processes (Brousse, 1971; Maury and Varet, 1980).

**FORMULATION OF THE PROBLEMS**

The characteristic features of the lithosphere structure of the areas of intraplate orogenic activity make it possible to connect the Cenozoic rejuvenation process with an ascent of large volumes of anomalously hot mantle material to the lithospheric base and development of diapirism.

An interaction of an uprising anomalous mantle with the lithosphere can be modeled by lithospheric thermal thinning (e.g., Crough and Thompson, 1976; Spohn and Schubert, 1982) or by Rayleigh-Taylor instability (e.g., Mareschal, 1983). The later can provide the required rates of the lithosphere thinning only when the viscosity of the lithosphere does not exceed $10^{23}$ poise (Neugebauer, 1983). Data on velocities and amplitudes of Cenozoic uplift of the Basin and Range Province agree well with the results of numerical modelling of the gravity instability development (Bird, 1979). In this area tectonically active regimes changed during a rather short time interval (~10 Ma) and the lithosphere remained heated and low-viscous by the beginning of the rejuvenation process.

In contrast, the process of thermal thinning of the lithosphere plays a significant role in the areas that were stable platforms before the rejuvenation and had cold lithosphere with viscosity greater than $10^{23}$ poise. Such situation is typical of all other areas of Cenozoic tectonic activity considered above (the East African rift system and the north African domal uplifts, the French Massif Central and the Rhenish massif, the Tien Shan and the Baikal-Mongolian region). According to the model of lithospheric thermal thinning a high viscous lithospheric material may be replaced by a more light material of anomalous mantle when the lithosphere is heated to a temperature close to the solidus and a sharp decrease of lithospheric viscosity occurs (e.g., Gliko et al., 1985; Artemieva, 1989). The thinning of the lithosphere leads to an isostatic uplift of lithospheric blocks and, thus, formation of high plateaus and domal swells.

Under certain thermo-mechanical conditions continental rifts may develop on the later stages of the process.

Heat flow data, MTS data as well as pressure and temperature estimates for the uppermost mantle show that anomalous mantle beneath continental rifts is a zone of basaltic magmas generation. All areas of Cenozoic tectonic activity (regardless of the volcanism intensity) are characterized by a well pronounced spatial variations in magma composition. As the lithosphere thickness and, hence, a depth of the anomalous mantle layer may vary from place to place within one region of rejuvenation, the composition of magmas may also differ, depending on P-T conditions in magma sources as well as on a fluid regime; moreover, some parts of continental rifts may be amagmatic due to insufficient melting rates for an extraction of melt from the matrix.

The comparative analysis of volcanism of different intraplate continental areas of Cenozoic tectonic and magmatic activity revealed the temporal decrease of magma alkalinity and of the concentration of incompatible and trace elements (Grachev, 1987; Wendlandt and Morgan, 1982). This trend corresponds to the composition of ultramafic xenoliths in lavas which changes in time from garnet to spinel lherzolites, the transition between them being at 70 km depth (Grachev, 1987).

Laboratory investigations of the physical and chemical conditions of magma generation in multicomponent silicate systems under adiabatic decompression (e.g., Kushiro et al., 1968) explain the observed evolutionary trend for igneous rocks composition and give a petrological basis for the model of anomalous mantle ascent and lithospheric thinning process.

Thus, complex petrological and geophysical investigations of the areas of Cenozoic volcanism reinforce a consecutive uplift of magma sources from the depth corresponding to the lithospheric base (100-150 km) to the crust (40-60 km) (Fig. 1). Such displacement of magma sources indicates a corresponding uplift of anomalous mantle material, the upper boundary of which being at a temperature close to the solidus and approximately coinciding with the lithospheric base. Thus, under the assumption that magma generation took place near the lithosphere-anomalous mantle boundary, the data presented in Figure 1 for different areas of Cenozoic rejuvenation could illustrate the data on lithosphere thinning during this tectonic process (Fig. 2).

Hence, the petrochemical data on temporal changes of depth of magma generation give a basis...
for a reconstruction of a heat regime evolution in the areas of Cenozoic tectonic activity. This idea was proposed by WENDLANDT and MORGAN (1982), and it was applied later for a calculation of a Kenya rift heat regime evolution by GLIKO et al. (1985), but only for the simplest case of a linear relationship of the solidus temperature with depth that is typical for "dry" systems.

However, a large amount of volatiles exists in the upper mantle material (the main being water and carbon dioxide) and influences greatly the melting conditions in the mantle (e.g., LAMBERT and WYLLIE, 1970; EGGLER, 1976). In the previous study (ARTEMIEVA, 1989), we have investigated the influence of volatiles on the dynamics of lithosphere thinning, implying a non-linear relationship between depth and the solidus temperature. Numerical analysis revealed that the upper mantle composition strongly influences the dynamics of lithospheric thinning process and must be taken into consideration in geophysical modelling.

The purpose of the present work was to solve numerically the inverse problem and to reconstruct a heat regime of different areas of Cenozoic intraplate tectonic and magmatic activity on the basis of petrochemical data and with account for the upper mantle composition. The mathematical formulation of the problem and the method used for its numerical calculation were described in detail in previous works (ARTEMIEVA, 1989; ARTEMIEVA and GLIKO, 1989), where the solution of the direct problem was considered.

In our formulation of the problem some assumptions were made to obtain the general estimates of the thermal regime during the tectonic process and to reduce the mathematical complexity when it was possible:

1) lithosphere was considered to be homogeneous;

2) before the beginning of the tectonic process the temperature distribution in the lithosphere was steady-state (that seems to reflect good enough the real situation in the lithosphere of the areas which during a time interval of an order of $10^7$-$10^8$ years have developed as platforms);

3) the tectonic process was initiated when anomalous mantle material ascended to the lithospheric base, resulting in a sharp increase of a heat flow supplied directly to the moving lower boundary of the lithosphere; thus, the steady-state thermal regime was terminated;

4) the temperature at the base of the lithosphere was assumed to be equal to the solidus at each given depth;

5) the energy balance at the lithosphere-anomalous mantle boundary was written in such a way that the heat supplied to the base of the lithosphere results in heating up the lower parts of the lithosphere to the solidus temperature and its partial melting. The degree of partial melting was assumed to be constant during the tectonic process.

Thus, the tectonic process was described as a non-linear boundary heat-conductivity problem of Stefan type. The changes of potential energy of lithospheric blocks related to their thermal expansion, partial melting and uplift have been taken into account. The problem was solved numerically by a modified Bubnov-Galerkin method (ARTEMIEVA and GLIKO, 1989). The heat flow from the anomalous mantle that could cause the observed lithosphere thinning (Figs. 1, 2) was calculated using the same model as in the previous work (ARTEMIEVA, 1989) and for the same values of numerical parameters.
RESULTS

The data on the temporal decrease of lithosphere thickness (Fig. 2) were used as the initial data for numerical modelling of a deep heat regime of high plateaus and continental rifts activated in Cenozoic time. One may see that curves of lithosphere thinning obtained for various regions of intraplate magmatic activity do not differ greatly: an ascend of anomalous mantle in Cenozoic time took place there with approximatelly the same velocities.

The curves in Figure 2 may be divided into two major groups. The first one includes data for the Hoggar domal uplift, the Rhenish massif, the Tien Shan and Mongolia. For this group, according to the available data on magmatic activity in these regions in Cenozoic time, lithosphere thinning seems to take place with almost constant velocity of about 1.5-2.5 km/Ma.

The second group includes the Kenya rift, the French Massif Central, and, probably, the Rio Grande Rift where the velocity of lithosphere-anomalous mantle boundary uplift decreased exponentially in time from about 5-8 km/Ma at the beginning of the process to about 1.5-2 km/Ma at the latest stage. However, it seems possible, that this difference between the two groups of data is apparent and is connected with the shortage of data on magmatic activity in some of the regions considered, as well as with some uncertainty in their interpretation.

Calculations were carried out for different fluid regimes of the upper mantle, the considered composition of the upper mantle material was peridotite with different content of volatiles (Fig. 3). These models correspond to partial melting of the roof of the upwelling diapir due to the presence of water and/or carbon dioxide. The case of a linear dependence of solidus temperature with depth ("dry" system) was calculated for a comparison.

Previous studies (ARTEMIEVA, 1989, 1991) have revealed that under the assumption that the mantle heat flow remains constant during the process of orogenic activity, the presence of a large amount of water in the upper mantle material causes an intensive thinning of the lithosphere and rapid isostatic uplift of lithospheric blocks, while the presence of carbon dioxide or a small fraction of water leads to a slowing-down of the thinning process. Thus, it was interesting to see, to what an extent the presence of volatiles in the upper mantle material may change the estimates of the mantle heat flow, required to cause the observed rates of lithospheric thinning.

The numerical calculations were carried out for three different sets of initial data: 1) Kenya rift, 2) the French Massif Central, 3) the third one included a large group of different areas of Cenozoic intraplate orogenic and magmatic activity for which the dynamics of the lithosphere thinning obtained on the basis of petrological data was very similar: the Rhenish massif, the Tien Shan, Central Siberian mountain area and Mongolia, domal uplifts of northern Africa (on an example of the Hoggar plateau). For the Rio Grande rift numerical calculations were not carried out because of the difficulty in choosing the initial point for the curve of the lithosphere thinning in this region (Fig. 2), i.e. for the lithosphere thickness just before the initiation of the rejuvenation process. Nevertheless, it seems very likely, that the values of mantle heat flow, required to cause the observed sequence of generated magmas in the Rio Grande rift, have to be between those calculated for Kenya rift and the French Massif Central.

During the numerical modelling of the tectonic process we calculated the mantle heat flow versus time, required to fit the data on lithosphere thinning (Fig. 2). The main results are presented in Figure 4 for the 3 groups of the initial data and for different fluid regime in the upper mantle.

According to the calculations, at the very beginning of the tectonic process a sharp change in the lithosphere thermal regime of the activated areas took place. As petrochemical data on the French Massif Central and Kenya rift indicate very high velocities of magma sources ascend at the initial stages of the tectonic process, numerical estimates show that the heat supplied from the anomalous mantle to the base of the lithosphere had to increase almost "instantaneously in these regions: by a factor of 8 – 15 (compared with the typical value for the plat-
Fig. 4. Calculated mantle heat flow as a function of time for different models of upper mantle composition and different areas of Cenozoic tectonic activity (for 10% of melt).

form areas ~10 mW/m²) during the first 5-8 Ma of the rejuvenation process. Later on, such high values of the mantle heat flow were not necessary to cause the magmatic activity known in these regions: the mantle heat flow 5-8 times higher than that typical for the platforms was high enough to result in melting of the lower parts of the lithosphere, a consequent ascend of magma sources and observed isostatic uplift of lithospheric blocks.

Despite a close similarity between the curves of lithosphere thinning of Kenya rift and the French Massif Central (Fig. 2), the curves of the mantle heat flow versus time calculated for these regions (Fig. 4) differ greatly. The reason for this is that during the tectonic activation of these areas the lithosphere-anomalous mantle boundary reached the regions of solidus maxima/minima of different times. The biggest difference between mantle heat flow calculated for the Kenya rift and the French Massif Central was obtained for the upper mantle composition being peridotite with carbon dioxide, because the solidus versus depth dependence for this system is a most nonlinear.

Numerical modelling, carried out for the third group of data which included the Tien Shan, the Rhenish massif and the Hoggar plateau, did not give such high estimates for the mantle heat flow as those obtained for the other two groups. This result is connected with lower and more constant velocity of the lithosphere thinning and anomalous mantle ascend in these regions. Nevertheless, the general picture remains the same: on the first stage of the tectonic process a large increase (by 5-10 times) of the heat flow supplied from the anomalous mantle to the base of the lithosphere took place; it achieved its maximum value at about 10 Ma after the start of the process. Later on, the mantle heat flow did not change greatly and remained almost constant, with the exception of the peridotite+CO₂ upper mantle composition. In this case a slow decrease of the mantle heat flow from its maximal value was calculated for the last 30 Ma of the process.

According to the results of numerical modelling of the process, the contemporary mantle heat flow in the areas of Cenozoic intraplate magmatic activity may vary from 50 to 100 mW/m² depending on the fluid regime in the upper mantle and on data on the lithosphere thickness.

As it follows from Figure 4, there is a significant difference between the values of mantle heat flow obtained for various upper mantle compositions. For example, the values of the mantle heat flow for the system peridotite+CO₂ may be 2-3 times higher than those calculated for peridotite with water, when the lithosphere - anomalous mantle boundary reaches the depth interval of strong nonlinearity of solidus temperature. At later stages of the tectonic process, when the lithosphere is thin enough and the depth dependence of solidus temperature is close to linear (Fig. 3), the difference between the results obtained for different upper mantle compositions is not so pronounced.

As mentioned earlier, the degree of partial melting of the mantle material may differ greatly in various regions of magmatic activity, as well as even in different parts of the same region; moreover, it may depend on the change during the process of anomalous mantle ascend. The estimates of the
degree of partial melting (e.g., MAALOE and PRINTZLAU, 1979; KHITAROV et al., 1985; DUPUY et al., 1986) for the Rhenish massif, the Tien Shan, the Hoggar plateau and other regions give values from 1 to 10% of melt, in some cases - up to 20%. Thus, it was interesting to see, how the degree of partial melting of the anomalous mantle material may influence numerical estimates of the mantle heat regime in these areas. Figure 5 illustrates the results calculated for all 3 groups of initial data (under the assumption that the degree of partial melting remained constant during the rejuvenation process). One may see that the difference between the curves is insignificant and does not exceed 10% between the cases of 1% and 20% of melt (Fig. 5).

In mathematical formulation of the problem the boundary condition on the ascending lithosphere-anomalous mantle boundary was written in such way (ARTEMIEVA, 1989) that a part of the heat flow, supplied to the lithospheric base, results in a partial melting of the lower lithosphere material (and is proportional to the lithosphere thinning velocity), while the remaining part of it goes to the lithosphere. Thus, Figure 6 was calculated, illustrating the temporal dependence of the heat flowing to the lithosphere.

**DISCUSSION AND CONCLUSIONS**

Petrochemical data on Cenozoic magmatic activity of some intraplate erogenic regions, including high plateaus and continental rifts, reinforce a consecutive uplift of magma sources from the depth corresponding to the lithospheric base of a stable platform areas to the crust during the last 35-50 Ma. These data are supported by geophysical investigations according to which the upper mantle of these regions possesses anomalous properties within the depth range 50-200 km; it is likely that at this depth the anomalous mantle presents, being characterized by low seismic velocities, low density and high temperatures.

The model of thermal thinning of the lithosphere is usually used to explain the mechanism of Cenozoic tectonic and magmatic activity of the areas that on the previous stages were developing like platforms. It has been shown earlier (ARTEMIEVA, 1991) that in the frames of this model even small peculiarities of geodynamical development of orogens in Cenozoic may be explained sufficiently.

The petrochemical data on temporal changes in depth of magma generation were used to reconstruct the lithosphere thickness of different areas of Cenozoic tectonic activity during the rejuvenation. Numerical modelling was carried out for the East African rift (using an example of Kenya rift), the north African domal uplifts (an example of the Hoggar plateau), European domal uplifts (the French Massif Central and the Rhenish massif), vast region of Cenozoic orogeny in Middle Asia and Central Siberia (including the eastern Tien Shan, Inner Mongolia, the Baikal rift zone).

The data on the temporal decrease of lithosphere thickness in these areas, obtained on the basis of evolutionary trend for igneous rocks composition and proved by seismic and MTS data, were used to reconstruct mantle heat flow that has to be supplied to the lithospheric base of these regions during the Cenozoic tectonic process to cause such lithosphere thinning.

The influence of a fluid regime of the upper man-
tule on the process of tectonic and magmatic activity was studied; numerical modelling has been performed for the upper mantle composition being peridotite with water and/or carbon dioxide. The consideration of the models with different content of volatiles in the upper mantle material gives higher values of the mantle heat flow that in the case of "dry" system, which, hence, may be considered as a lower estimate of a real thermal regime. The difference between the results obtained for a model "dry" system and the other curves, which seem to fit the present knowledge of the upper mantle composition, is most significant at the early stages of the process of tectonic activity.

According to the results of numerical calculations, the contemporary values of the heat flow supplied to the lithospheric base may be about 45-70 mW/m$^2$ for the Tien Shan, the Baikal-Mongolian region, the Hoggar plateau and the Rhenish massif; 55-70 mW/m$^2$ for the French Massif Central; 70-100 mW/m$^2$ for Kenya rift. These estimates were obtained under the assumption that the degree of partial melting of the upper mantle material remained constant during the tectonic process and was equal to 10% melt. In case of a lower (1%) or higher (20%) degree of partial melting, the values of mantle heat flow would be correspondingly lower or higher but not more than by 5-10%.

It is interesting to compare the model estimates of the mantle thermal regime with field heat flow data obtained for the same regions, though for the areas of tectonic and magmatic activity a strongly inhomogeneous heat flow field is typical.

The East African rift system is characterized by very high values of surface heat flow (on the average exceeding 80 mW/m$^2$) (VoN HERZEN, 1972). In the center of the French Massif Central an average value of the heat flow is about 110 mW/m$^2$, while it is only 80 mW/m$^2$ in the peripheral parts (VASSEUR, 1982). The estimates of the mantle heat flow in this region give values of about 60-70 mW/m$^2$ for the central part (LUCAZEAU and VASSEUR, 1981), that is in a rather good agreement with the model results described above. For the Rhenish massif the surface heat flow varies from 60-70 mW/m$^2$ in the outer parts up to 100 mW/m$^2$ in the center (HAENEL, 1983), the same as for the Rio Grande rift (THOMPSON and ZOBACK, 1979).

The Tien Shan is characterized by heat flow values varying from about 40 mW/m$^2$ in depressions (mantle heat flow being about 10-15 mW/m$^2$) up to 100 mW/m$^2$ in the zones of deep faults (mantle component about 35-40 mW/m$^2$) (LYSAK, 1988). The Baikal-Mongolian region is characterized as well by high heat flow values (about 60-80 mW/m$^2$, in the Baikal rift zone—up to 140 mW/m$^2$); mantle compo-

ment is estimated to be 25-35 mW/m$^2$ for the Altay and the Sayans and 40-84 mW/m$^2$ for the Baikal rift (LYSAK, 1988).

Thus, one may see that the results of numerical modelling of the process of Cenozoic intraplate tectonic and magmatic activation, based on the petrochemical data on igneous rocks composition in these areas, agree well with geophysical measurements of surface heat flow in these regions and with estimates of the mantle heat flow made on their basis. However, as it follows from the results, it is very important to take into account the composition of the upper mantle material to get reliable estimates of the mantle thermal regime, especially at the very first stages of the tectonic process.

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