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Heat flow variations in continental rifts

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ABSTRACT

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In the terrestrial thermal field, continental rifts stand out as rather narrow regional thermal anomalies in which augmented heat flow is unevenly distributed. Heat flow variations are discussed on the example of the Baikal, East African, Cordilleran and Rhine-Lybian rift systems.

Rift-related disturbance of the asthenosphere/lithosphere system is accompanied by a general increase in the surficial heat flow. Regional thermal anomalies are mainly caused by conductive heat transfer from the asthenosphere. Local thermal anomalies are caused by magmatic mass transfer into the crust and by fluid convection along porous fracture systems.

Introduction

The Cenozoic *Baikal rift zone* (BRZ) is located in central Asia. It is an isolated system that has no spatial links with other continental or oceanic rifts. The BRZ is over 1700 km long. It developed on the shield-type Baikalian (Late Precambrian) and Caledonian (Early Palaeozoic) basement complex of the Sayan-Baikal fold belt. The BRZ became activated some 30 Ma ago during the Oligocene. At present it is characterized by minor volcanic activity and a high seismicity. It is associated with distinct gravity, magnetic and thermal anomalies. The lithosphere of the BRZ is thinned to 40-75 km; under its central segment, corresponding to Lake Baikal, the crust ranges in thickness between 34 and 40 km (Lysak and Zorin, 1976; Peive et al., 1980; Logatchev and Zorin, 1984; Zorin et al., 1989).

The complex *East African rift system*, including the Red Sea rift, extends over a distance of some 6000 km. It consists of several individual rifts which are linked by transfer zones (see Rosendahl et al., 1992). This rift system developed at the boundary between the Proterozoic Ruzizi-Ubend and Mozambique fold belts and the Precambrian African craton. Rifting commenced during the Late Eocene and continues at Present, as evident by tectonic, volcanic, hydrothermal and seismic activity. Individual elements of this rift system came into evidence in different times. At Afar the East African rift is linked via the Gulf of Aden with the global system of intra-oceanic rifts (Milanovsky, 1976, 1983, 1987).

A system of Late Palaeozoic, Mesozoic and Cenozoic rifts transsects western Europe, the western Mediterranean and northwest Africa. Although it is realised that the various segments of this large rift zone developed clearly at different times and under different geotectonic settings, it is here referred to as the *Rhine-Lybian Rift Belt.* Its main constituents are the Permian Oslo graben which developed on Precambrian basement, the Mesozoic North Sea rift which evolved on Caledonian basement, the Cenozoic Rhine-Rhône-Valencia graben system which transsects Hercy-

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nian basement and the Alpine fold belts of the western Mediterranean, the Cretaceous and Cenozoic graben systems of Lybia and the Pelagian Shelf, which subsided on Precambrian and Hercynian crustal elements, and the Cretaceous rifts of Chad, Niger, Nigeria, and the Central African Republic which developed on Precambrian basement. At present only the Rhine–Rhône–Valencia and the Pelagian Shelf graben systems are tectonically active. The thermal regime of the individual elements of this heterogenous rift belt is understandably highly variable, mainly due to the different age of their rifting stages (Lysak, 1987, 1988).

The Cenozoic *Cordilleran rift system* of the western USA can be considered as forming part of the East Pacific system of intra-oceanic rifts and transform zones. The Cordilleran rift system extends in a N–S direction over a distance of some 4000 km and has a width of 100–1500 km. It is considerably wider than any other Cenozoic rift system of the globe. This rift system evolved immediately after the Cretaceous–Palaeogene Laramide orogeny on top of the Cordilleran fold belt; to the east it encroaches on the Precambrian North American craton. The structural style of the Cordilleran rift system is characterized by numerous rotated fault blocks and intervening deep, half-graben-shaped sedimentary basins (Basin-and-Range Province). Development of this extremely large, still active rift system commenced during the Late Eocene. Its evolution involved major crustal extension and intense volcanic activity. The Cordilleran rift system is characterized by locally high seismicity and an anomalously high heat flow (Reiter et al., 1986; Jones et al., 1992).

Heat flow and thermal anomalies in Baikal rift zone

The BRZ stands out by its heat flow against the adjacent South Siberian platform and the Trans-Baikal fold area which are characterized by mean heat flow values of 38 mW m^{-2} and 50 mW m^{-2}, respectively. The geothermal field of the BRZ is extremely varaiable with heat flow values ranging from 0 up to 150–475 mW m^{-2} and locally even higher (2.5–7.5 W m^{-2}, V.A. Golubev, pers. commun., 1991). The following discussion is based on studies carried out by Lysak (1968, 1976, 1978, 1984, 1988), Lysak and Zorin (1976), Lubimova (1968), Golubev (1982, 1987) and Duchkov et al. (1987).

Results of heat flow measurements in Lake Baikal and along its margins are given in Fig. 1. This map illustrates the great heat flow variation in the different parts of Lake Baikal. As a general rule, heat flow increases with decreasing water depth, is highest in coastal areas and decreases on the eastern rift shoulders to 60 mW m^{-2} and to 40 mW m^{-2} on the western one (Fig. 2). Lake Baikal is subdivided into a northern and a southern basin by the northeast striking subaqueous Academician ridge, which corresponds to a horst block (see Logatchev and Zorin, 1992, this volume).

The axial parts of the northern basin are characterised by heat flow values in the range 50–75 mW m^{-2} (average 77 ± 35 mW m^{-2}). Heat flow increases towards the shores to 100–400 mW m^{-2} and higher. A continuous narrow positive anomaly parallels the western faulted coast line, whereas the eastern coastal anomaly is discontinuous with high values occurring only in areas of onshore hot springs. The faulted Academician ridge is marked by strong variations in heat flow. The southern basin has a generally higher and more uniform heat flow than the northern basin; heat flow increases along its southeastern shore and reaches highest values in the south-western parts of this basin where they are generally above 100 mW m^{-2}. The western extension of the Lake Baikal depression underlies the Tunka valley, which is characterized by Quaternary volcanic activity; in this area heat flow values of 75–90 mW m^{-2} have been recorded.

The regional geothermal anomaly of the BRZ coincides with a zone of strongly attenuated lithosphere (40–75 km), decreased crustal thickness (34–40 km), anomalously low upper mantle P-wave velocities (7.7–7.8 km/s), high hydrothermal activity and a decreased Curie depth of about 18.5 km. In the BRZ, conductive heat transfer accounts for the observed regional heat flow anomaly that is in the 50–75 mW m^{-2} range; this anomaly is thought to be associated with the intrusion of melts to the crust/mantle boundary (Kiselev and Popov, 1992, this volume). Local, often sharp thermal anomalies are superimposed on this regional anomaly. These occur mainly in basinal areas and along fault zones which delineate Lake Baikal and control the relief of horst blocks. In these areas, additional energy is supplied from deep sources, mainly by fluid convection. Some of the largest anomalies coincide with tectonically active fractures and fault zones; these are presumably characterized by increased permeability. Additional anomalies are associated with areas of volcanic activity and possible intracrustal magma chambers (e.g. Tunka valley).

The central sector of the BRZ, corresponding to Lake Baikal, is tectonically still active (Sherman, 1992, this volume). Its high seismicity indi-

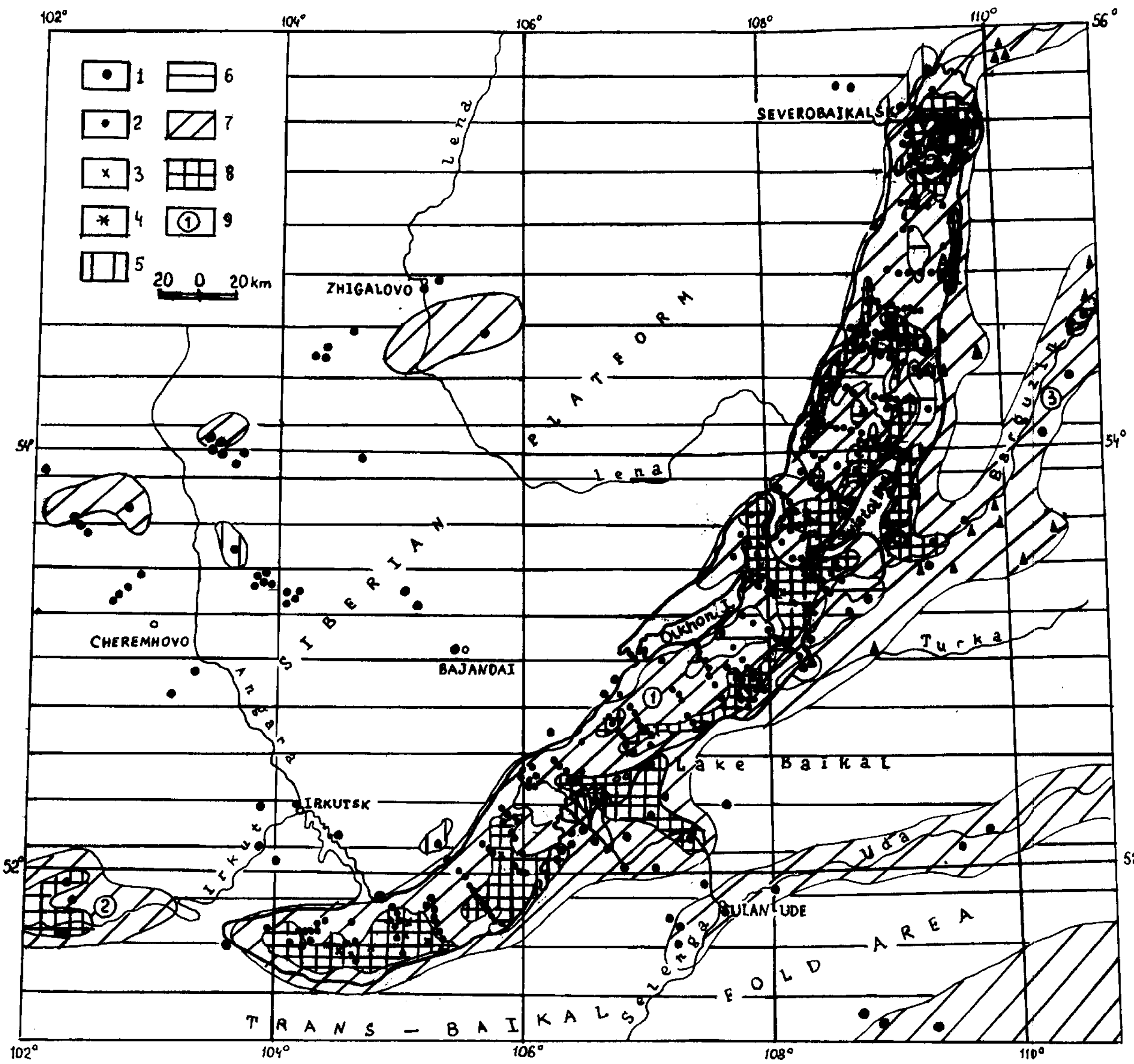


Fig. 1. Heat flow map of the Baikal rift zone (central part) and adjacent regions. Based on: Golubev, 1982, 1987; Duchkov et al., 1987; Lysak, 1988; etc. The sites of heat flow survey: *1* = in boreholes; *2–4* = in Baikal Lake, with heat flows: lower than 100 mW m^{-2} (*2*), higher than 100 mW m^{-2} (*3*), higher than 300–500 mW m^{-2} (*4*); *5–8* = regional heat flows: lower than 25 mW m^{-2} (*5*), from 25 to 50 mW m^{-2} (*6*), from 50 to 75 mW m^{-2} (*7*), higher than 75–100 mW m^{-2} (*8*); *9* = rifts: Lake Baikal (*1*), Tunka (*2*), Barguzin (*3*).

cates that crustal extension continues. Its deep thermal regime, combined with Quaternary uplift of the BRZ, suggests that lithospheric heating is still in progress (Logatchev and Zorin, 1984).

Heat flow and thermal anomalies in East African rift system

The following discussion on the distribution of heat flow in the East African rift system and in adjacent areas is based on publications by Von Herzen and Vacquier (1967), Erikson and Simmons (1969), Degens et al. (1971, 1973), Haenel (1972), Chapman and Pollack (1977), Skinner (1977), Verzhbitsky and Zolotarev (1980), Morgan (1982, 1983), Crane and O'Connell (1983), Ballard et al. (1987), Jones (1987) and others.

In the various segments of the East African rift system, the intensity of heat flow varies considerably. This can be attributed to difference in the stage to which rifting has progressed in the individual rifts. For instance, the Central African craton, which can be considered as being in a pre-rift stage, is characterized by heat flow values

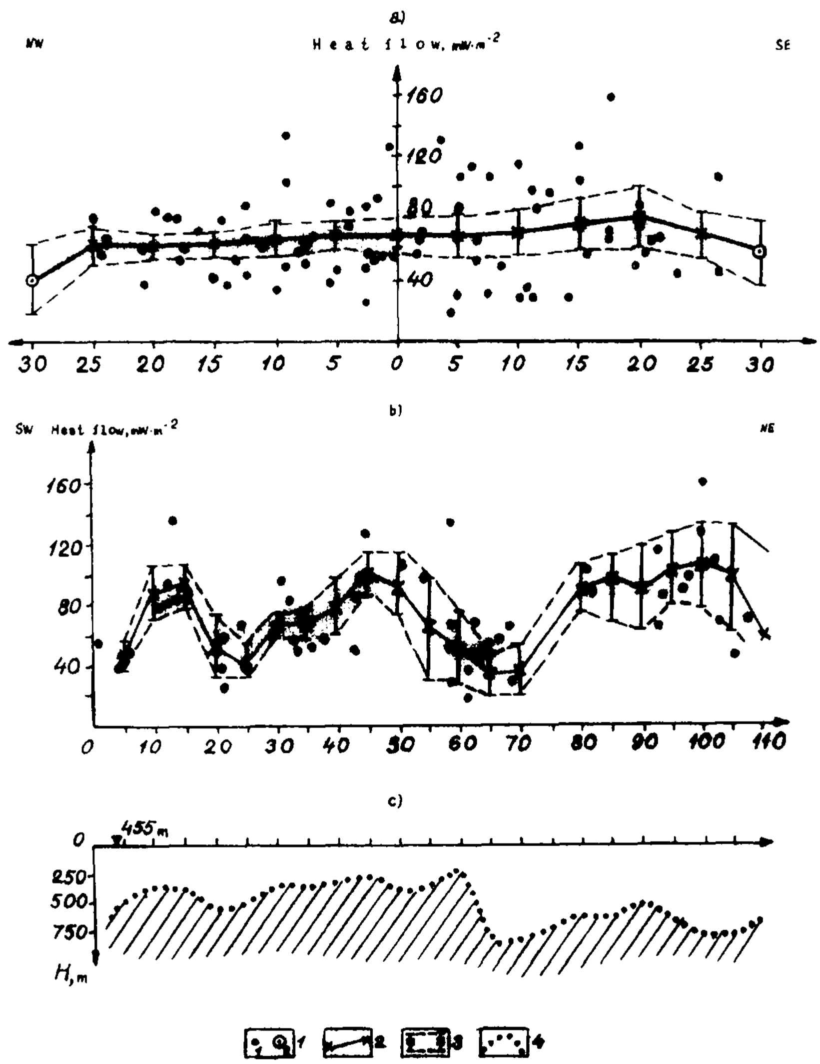


Fig. 2. Summarized geothermal profiles across the submarine Academician ridge in Lake Baikal (Golubev, 1982; Lysak, 1988). (*a*) Heat flow variations across the ridge. (b) Heat flow variations along the ridge. (c) Submarine topography of the Academician ridge. *1* = Observed heat flows through the Lake Baikal bottom (*1*) and mean on-shore flux (*2*); *2* = flux for each 5 km means along the profile; *3* = confidence intervals of averaging; *4* = water depths along the Academician ridge.

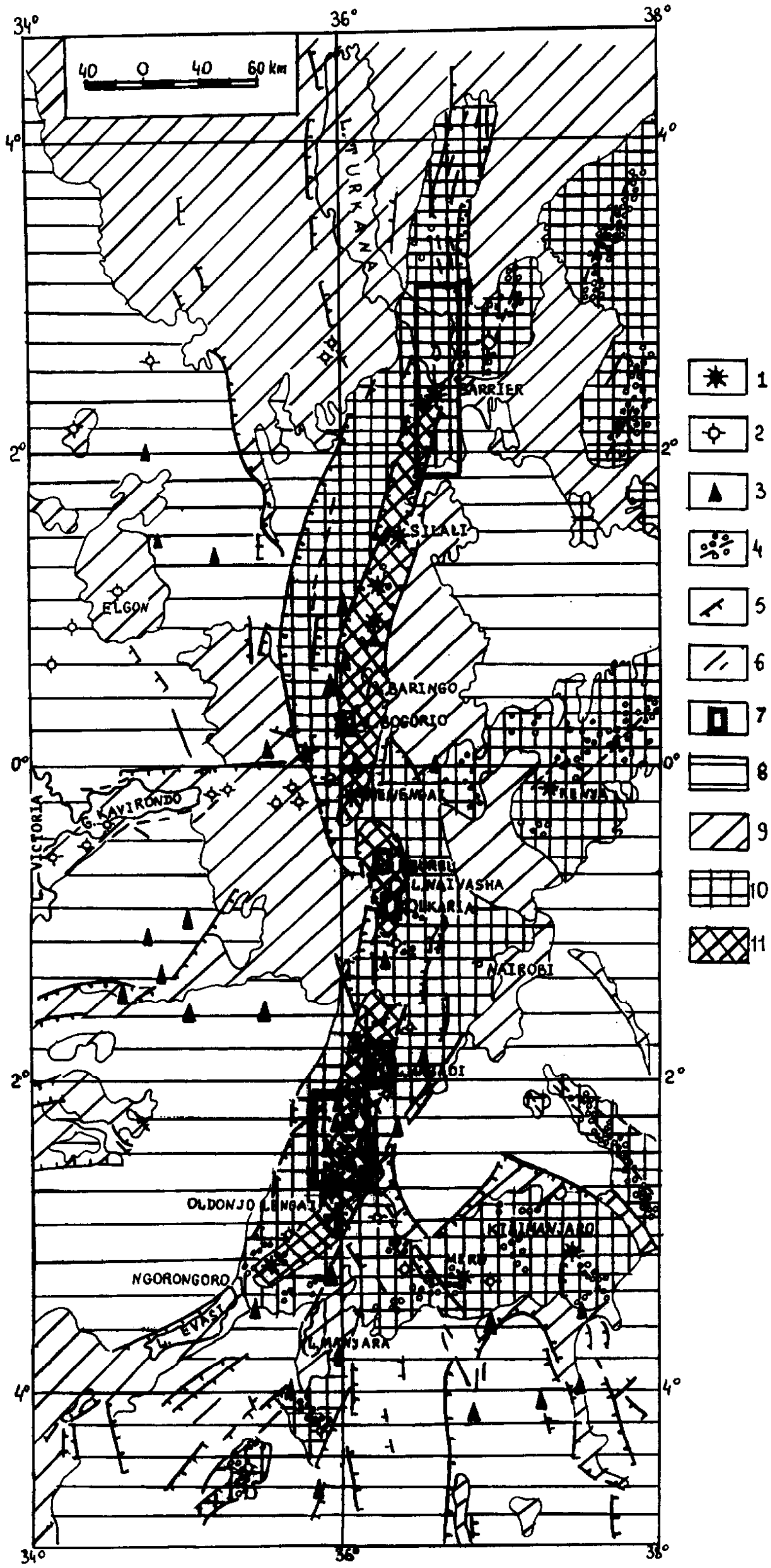
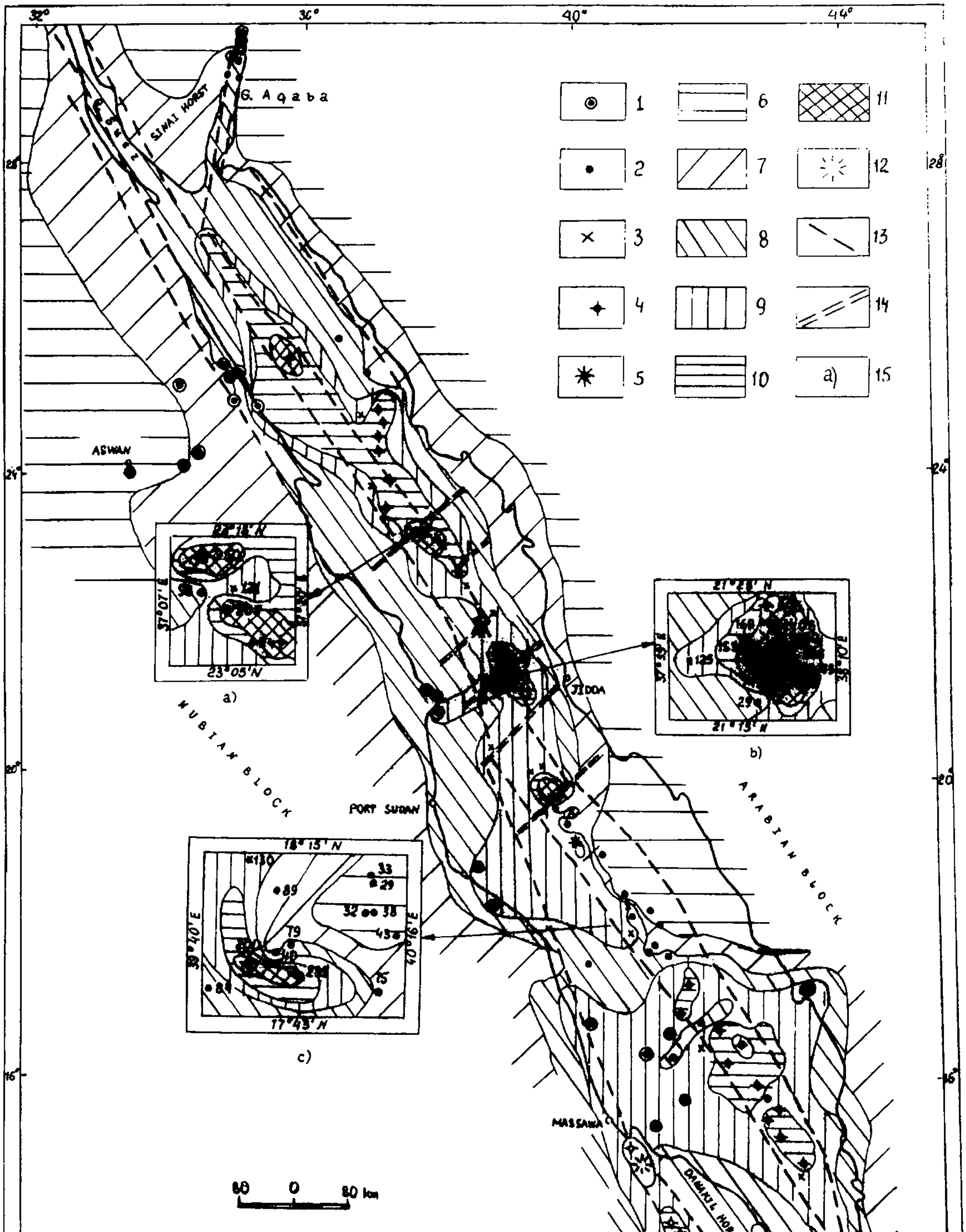


Fig. 3. A supposed regional heat flow distribution in Kenya rift zone. Based on: Baker and Wohlenberg, 1971; Tkachenko et al., 1978; Milanovsky, 1976; Logatchev, 1977; Crane and O' Connell, 1983; Lysak, 1988. The sites with anomalous heat flows. *1*, *2* = Volcanoes: active (*1*) or extinct (*2*); *3* = hot springs; *4* = zones with deep tensional fractures; *5* = thrust faults; *6* = other faults; *7* = area of detailed geothermal studies; *8–11* = supposed regional heat flows: lower than 50 mW m^{-2} (*8*), from 50 to 75 mW m^{-2} (*9*), from 75 to 100 mW m^{-2} (*10*), higher than 100 mW m^{-2} (*11*).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JIDDA
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80 0 80 km
32°
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of about 60 mW m^{-2}. The Lake Tanganyika and Rukwa–Malawi rifts, in which tectonic and volcanic activity is at a relatively low level, have heat flows of the order of 40–60 mW m^{-2}. In comparison, heat flow in the tectonically very active and in part highly volcanic Ethiopian and Kenya rift zones ranges between 75 and 100 mW m^{-2}. In the Red Sea, Gulf of Aden and Afar rifts, which have progressed to various stages of crustal separation and generation of new oceanic lithosphere, heat flow is at the level of 150–250 mW m^{-2}.

Heat flow is highest in areas where crustal separation has been achieved and asthenospheric material has reached the seafloor (Red Sea, Gulf of Aden) or the surface (Danakil rift). Regions of volcanic activity, fumarolas and hot springs are also characterized by high heat flow (Ethiopean and Kenya rifts). In undisturbed continental cratons, regional heat flow is generally higher than in rift-induced rapidly subsiding basins which are often characterized by high sedimentation rates (e.g. Lake Tanganyika and Malawi, Dead Sea).

In active rift systems, highest heat flow values are recorded in their axial grabens, as well as along fault zones and in volcanic areas; heat flow generally decreases in the rift shoulders and over major horst blocks. For instance, in the axial part of the Gregory rift (Fig. 3), the mean heat flow is about 105 mW m^{-2} and decreases across its western and eastern flanks to 57 and 39 mW m^{-2}, respectively. In the axial parts of the Red Sea rift, where submarine volcanism is associated with pools of hot brines, heat flow values have an extreme range (28 and 3300 mW m^{-2}); mean heat flow values are of the order of 500 mW m^{-2} and exceed locally 1200 mW m^{-2} (Fig. 4). Also in the Red Sea rift, heat flow decreases systematically away from its axial zone, remains generally elevated along its shores (> 100 mW m^{-2}), and

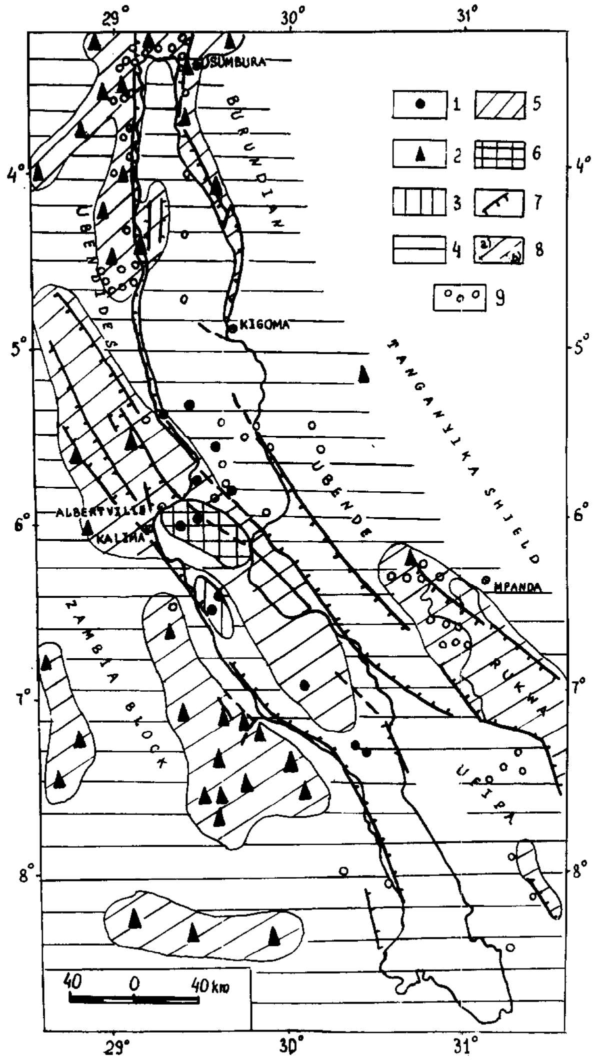

Fig. 5. Heat flow map of the Tanganyika rift. Based on: Baker and Wohlenberg, 1971; Degens et al., 1971; Milanovsky, 1976; Tkachenko et al., 1978; Lysak, 1988. *1* = Heat flow stations; *2* = hot springs; *3–6* = regional heat flows: lower than 25 mW m^{-2} (*3*), from 25 to 50 mW m^{-2} (*4*), from 50 to 75 mW m^{-2} (*5*), higher than 75–100 mW m^{-2} (*6*); *7* = normal faults; *8* = other faults: observed (*a*) and supposed (*b*); *9* = seismic foci for $M \geq 4$ events.

Fig. 4. Heat flow map of the Red Sea rift. Based on: Sclater, 1966; Evans and Tammemagi, 1974; Scheuch, 1976; Ben-Avraham et al., 1978; Verzhbitsky and Zolotarev, 1980; Lysak, 1988. The sites of heat flow survey. *1* = In boreholes; *2–5* = in Red Sea, with heat flows: lower than 100 mW m^{-2} (*2*), from 100 to 150 mW m^{-2} (*3*), from 150 to 500 mW m^{-2} (*4*), higher than 900 mW m^{-2} (*5*); *6–11* = regional heat flows: lower than 50 mV m^{-2} (*6*), from 50 to 75 mW m^{-2} (*7*), from 75 to 100 mW m^{-2} (*8*), from 100 to 150 mW m^{-2} (*9*), from 150 to 200 mW m^{-2} (*10*), higher than 200 mW m^{-2} (*11*); *12* = volcanoes; *13* = thrust faults; *14* = transform faults; *15* = sites of detailed survey [depressions: (a) *Nerus*, (b) *Atlantic II* and (c) sites studied by Soviet oceanographists].

reaches values of 50 mW m^{-2} and less in distal areas of its rift shoulders. In a number of rifts, major horst blocks, which are outlined by active faults and have only a limited sedimentary cover, are also characterized by an elevated heat flow (e.g. Makhali horst in Lake Tanganyika, central uplift in Lake Malawi with heat flow 75–100 mW m^{-2}; see Figs. 5 and 6). On rift shoulders, local thermal anomalies are either associated with volcanic centers, hot springs arranged along fracture zones (e.g. Afar, Ethiopia and Kenya) or with centers of increased radiogenic heat production, as seen in some areas of Central Africa.

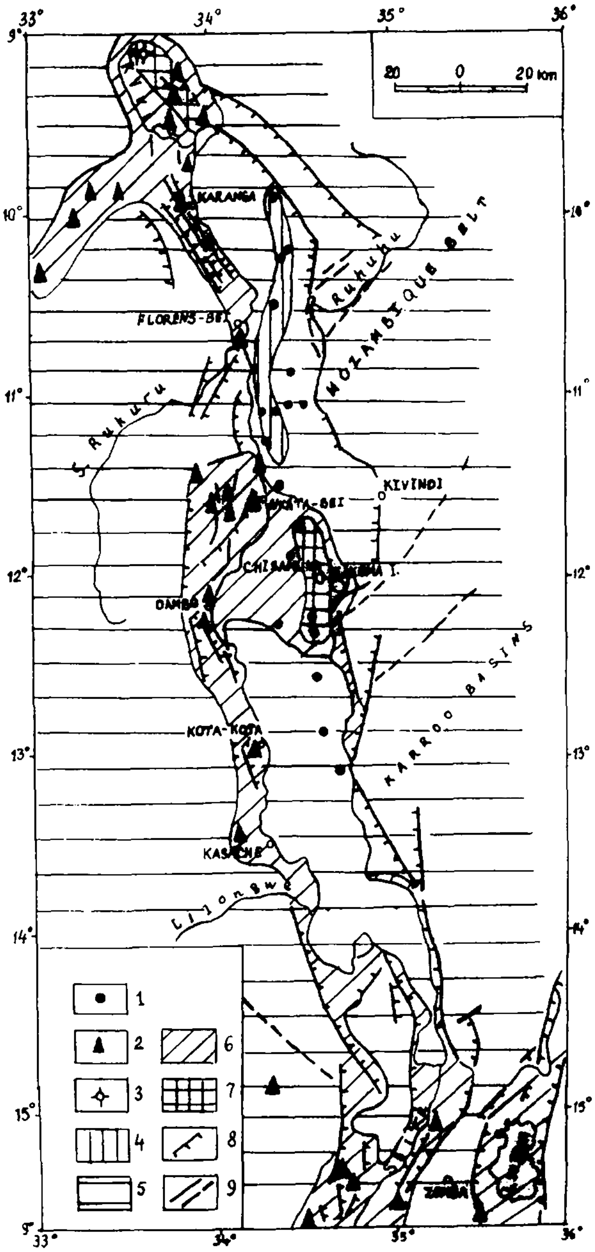

Fig. 6. Heat flow map of the Malawi rift. Based on: Von Herzen and Vacquier, 1967; Milanovsky, 1976; Logatchev, 1977; Tkachenko et al., 1978; Lysak, 1988. *1* = Heat flow stations; *2* = hot springs; *3* = extinct volcanoes; *4*–*7* = regional heat flow: lower than 25 mW m^{-2} (*4*), from 25 to 50 mW m^{-2} (*5*), from 50 to 75 mW m^{-2} (*6*), higher than 75–100 mW m^{-2} (*7*); *8* = normal faults; *9* = other faults.

Outside areas of recent volcanism and faulting, conductive heat flow predominates at values of about 45 mW m^{-2}. In rift shoulders, as for instance in the mountains flanking the Red Sea, heat flow increases locally to 70 mW m^{-2} and more; these anomalies, which are not associated with volcanic manifestations, can be attributed to convective heat transfer along permeable fracture systems.

In the active East African rift system, progressive rift-induced thinning of the lithosphere by mechanical stretching and thermal attenuation of the upper mantle was coupled with regional doming of the rift zones, the intrusion of melts into the lithosphere and the extrusion of major volumes of magmas. This magmatic activity, which is still persisting at present, was accompanied by the development of regional and local thermal anomalies.

Heat flow and thermal anomalies of the Rhine–Lybian rift belt

The following discussion of heat flow anomalies, which are associated with this heterogenous belt of rift systems, is based on papers published by Čermak and Hurtig (1982), Zolotarev and Sochelnikov (1980), Lucazeau et al. (1984) and others.

The entire area of the Rhine–Lybian rift belt, as well as adjacent regions, are characterized by an elevated heat flow of about 75 mW m^{-2} (Lysak, 1987). The magnitude of regional heat flow anomalies is closely related to the age and the rifting stage of the respective graben systems. In the active Cenozoic Rhine–Rhône rift zone, including also the Massif Central (Figs. 7 and 8), in the Neogene oceanic Algero-Provençal Basin and in the Thyrrenian, partly oceanic back-arc rift, heat flux exceeds 80–100 mW m^{-2}. In contrast, heat flow in the Mesozoic and Palaeozoic palaeorifts is at the level of 50–70 mW m^{-2}. In Cenozoic rifts, the mean conductive heat flow is of the order of 80–90 mW m^{-2} and above 100–180 mW m^{-2} only in anomalously heated areas. In these, a significant proportion of the deep thermal energy is transferred by fluid convection. Such anomalies are associated with hot springs and volcanic centers (e.g. Rhine Graben and grabens of the Massif Central in France).

Within the Rhine–Lybian rift belt, Pre-Cenozoic grabens yield heat flow values of 68 for fault zones and 84 mW m^{-2} for volcanic areas. Much higher flux has been recorded in Cenozoic grabens (about 96 mW m^{-2}) and along their

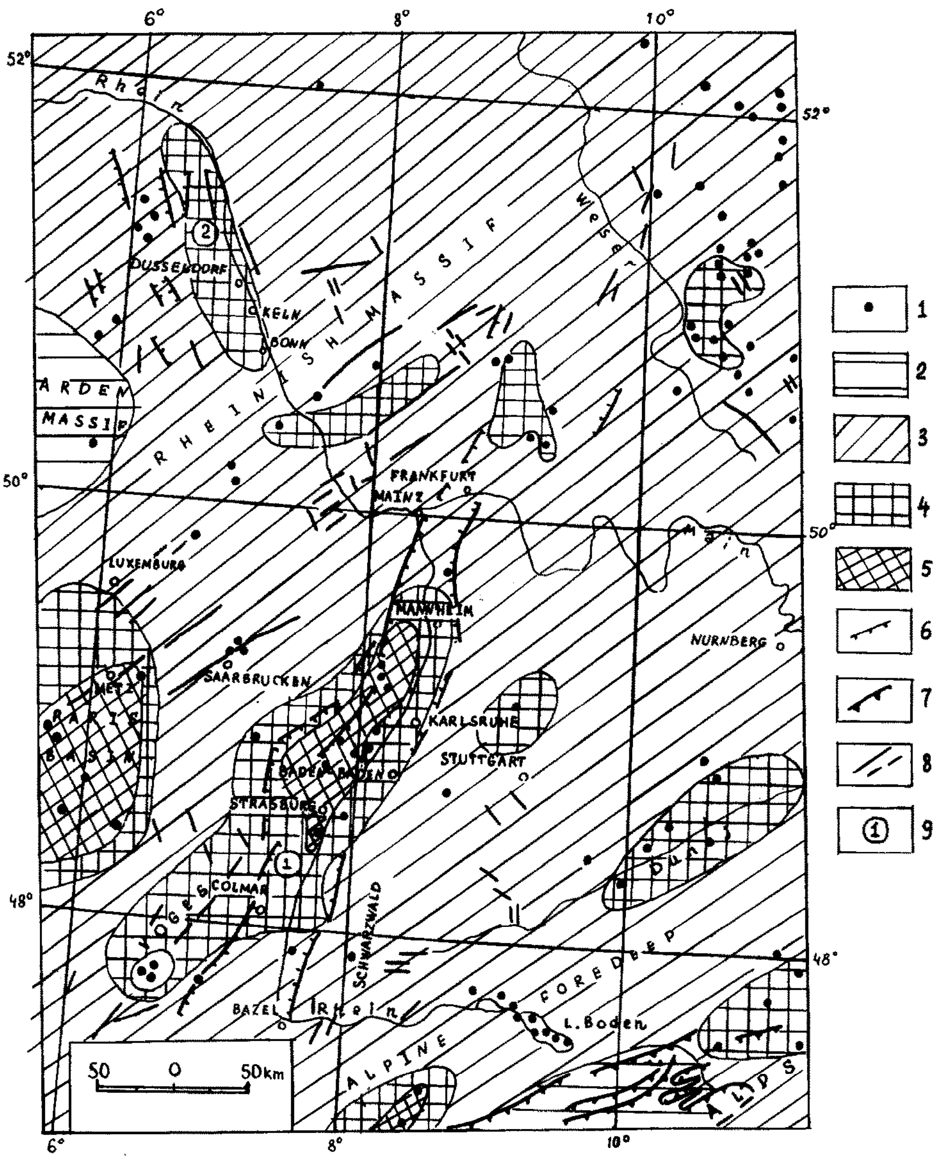

Fig. 7. Heat flow map of the Rhine rift zone. Based on: Haenel, 1971; Werner and Doebl, 1974; Bogdanov and Khain, 1981; Cermak and Rybach, 1979; Lysak, 1988. *1* = Heat flow stations; *2–5* = regional heat flow: lower than 50 mW m^{-2} (*2*), from 50 to 75 mW m^{-2} (*3*), from 75 to 100 mW m^{-2} (*4*), higher than 100 mW m^{-2} (*5*); *6* = normal faults; *7* = Alpine thrust faults; *8* = unspecified faults; *9* = rifts (*1*: Upper Rhinegraben, *2*: Ruhr Graben).

zones of active faulting and volcanism (107 mW m^{-2}). In rift shoulders and over major intragraben horst blocks of these rifts, the heat flow decreases generally to 60–80 mW m^{-2} but exceeds locally 75–100 mW m^{-2} in fault zones and in the vicinity of magmatic centers (Urach, Schwarzwald, Massif Central and Paris Basin). Local thermal anomalies, related to hot springs along fracture zones, play an important role in the Rhine–Rhône rift system. They are attributed to heat transfer by convective fluid flow. Convective heat flow plays a considerably smaller role in Mesozoic and Late Palaeozoic palaeorifts.

The Cenozoic Rhine–Rhône rift system is associated with broad domal uplifts which are transsected by graben structures. The Mesozoic

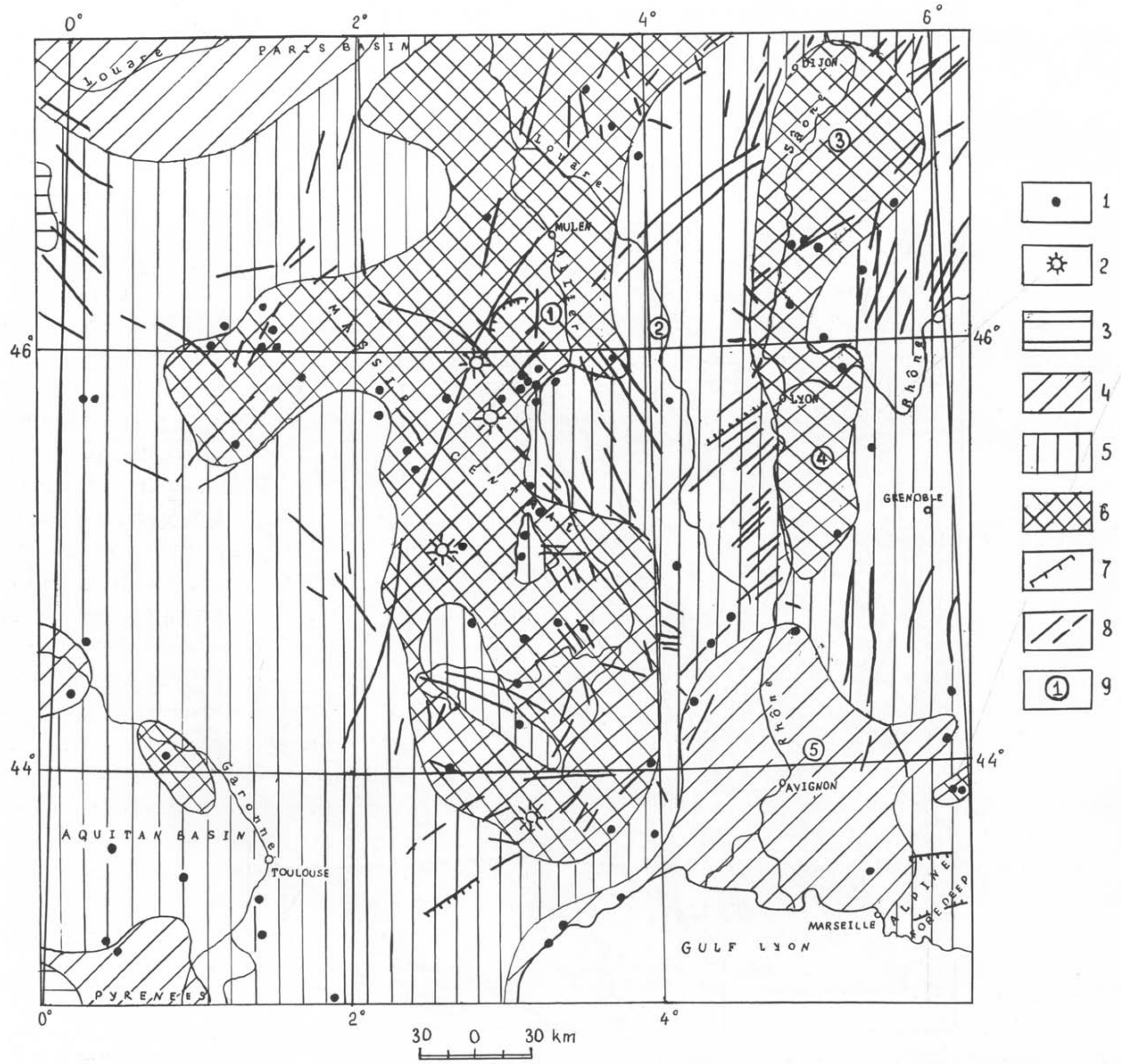

Fig. 8. Heat flow map of the Rhône rift zone and adjacent regions. Based on: Hentinger and Jolivet, 1970; Čermak and Rybach, 1979; Lucazeau et al., 1984; Lysak, 1988. *1* = Heat flow stations; *2* = extinct Cenozoic volcanoes; *3–6* = regional heat flow: lower than 50 mW m^{-2} (*3*), from 50 to 75 mW m^{-2} (*4*), from 75 to 100 mW m^{-2} (*5*), higher than 100 mW m^{-2} (*6*); *7* = normal faults; *8* = unspecified faults; *9* = rifts (*1*: Allier, *2*: Upper Louare, *3*: Bresse, *4*: Dauphine, *5*: Lower Rhône).

North Sea rift underwent a temporary doming stage during the mid-Jurassic (Ziegler 1992, this volume). The Cenozoic Malta–Pantelleria rift shows only minor regional doming. In most of these rifts thinning of the lithosphere appears to have been achieved by a combination of mechanical extension and thermal attenuation, involving upwelling of melts generated by decompression of the lower lithosphere and underlaying asthenosphere. Volcanic and hydrothermal activity promoted increased deep heat flow particularly in the axial graben systems.

The observed variations in heat flow in the different segments of the Rhine–Lybian rift belt are basically related to variations in crustal thickness, reflecting different stages of rifting and to the age of the rifting activity. Maximum heat flux is associated with the tectonically active Cenozoic rift systems which are characterized by intense volcanic activity and seismicity (Rhine–Rhône and Lybia–Pelagian Shelf rifts). Heat flow is much lower in the seismically quiescent Mesozoic and Late Palaeozoic palaeo-rifts, and particularly in those which showed only relatively minor volcanic activity during their rifting stage, as for instance the North Sea.

Heat flow and thermal anomalies in Cordilleran rift system

The heat flow data presented here are based on publications by Blackwell (1969), Combs and Simmons (1973), Decker and Birch (1974), Reiter et al. (1975, 1986), Bridwell (1978), Lachenbruch (1978), Jessop et al. (1984), Morgan et al. (1986), Sass et al. (1981) and others.

The North American craton is characterized by a relatively high heat flow of about 60 mW m^{-2} that increases in the Great Valley to 71 mW m^{-2}; an exception is the relatively cool Canadian shield (about 40 mW m^{-2}). In the Cordilleran rift system, on the other hand, heat flow values range between 24 and 302 mW m^{-2}. Values above 75 mW m^{-2} describe the so-called Cordilleran thermal anomaly (65–85 mW m^{-2}), the Basin-and-Range Province (about 92 mW m^{-2}) and the Rio Grande rift (about 107 mW m^{-2}). These areas stand out by their widespread young volcanic activity (Fig. 9). Outside these areas of intense volcanism, the heat flow decreases rapidly to 65 mW m^{-2} and less (Sierra Nevada and central Colorado Plateau).

In the Cordilleran rift system heat flow variations do not coincide with major structural features; there is no significant difference in heat flow between subsiding grabens, half-grabens and rift shoulders. In fact, in the Basin-and-Range Province and in the Rio Grande rift, thermal anomalies cross boundaries between basins and elevated blocks, particularly in areas of young volcanic activity; local anomalies are related to hot springs aligned with fracture zones and also to volcanic centers. Such anomalies are abundant in the Rio Grande rift, are less frequent in the Basin-and-Range Province and on the Colorado Plateau, and are almost absent east of the Rio Grande rift.

The high regional heat flow pattern of the Cordilleran rift system, as well as the presence of local anomalies, cannot be attributed to increased radiogenic heat production from crustal rocks. In the Basin-and-Range Province, partial melting within and at the base of the lithosphere, at depth between 45 and 75 km, is seen as the main source of the high heat flux. The emplacement of magma chambers in the crust and upper mantle, charged by melts generated at the base of the extended lithosphere, is seen as a further source of the observed thermal anomalies. Furthermore, local thermal anomalies are probably related to deep fractures, which serve as conduits for advecting magmas and thermal waters and thus facilitate the transfer of additional heat from deeper levels into the upper crust. In this respect it should be noted that there is a close relationship between areas of 10 Ma and younger volcanic activity and major thermal anomalies. The heat flow generally decreases away from these area and also in regions where crustal faulting is less intence, as for instance in elevated blocks separating and/or framing individual graben systems.

Combined heat flow and other geophysical and geological data show that heat flow increases south of the Rio Grande rift, toward the Trans-

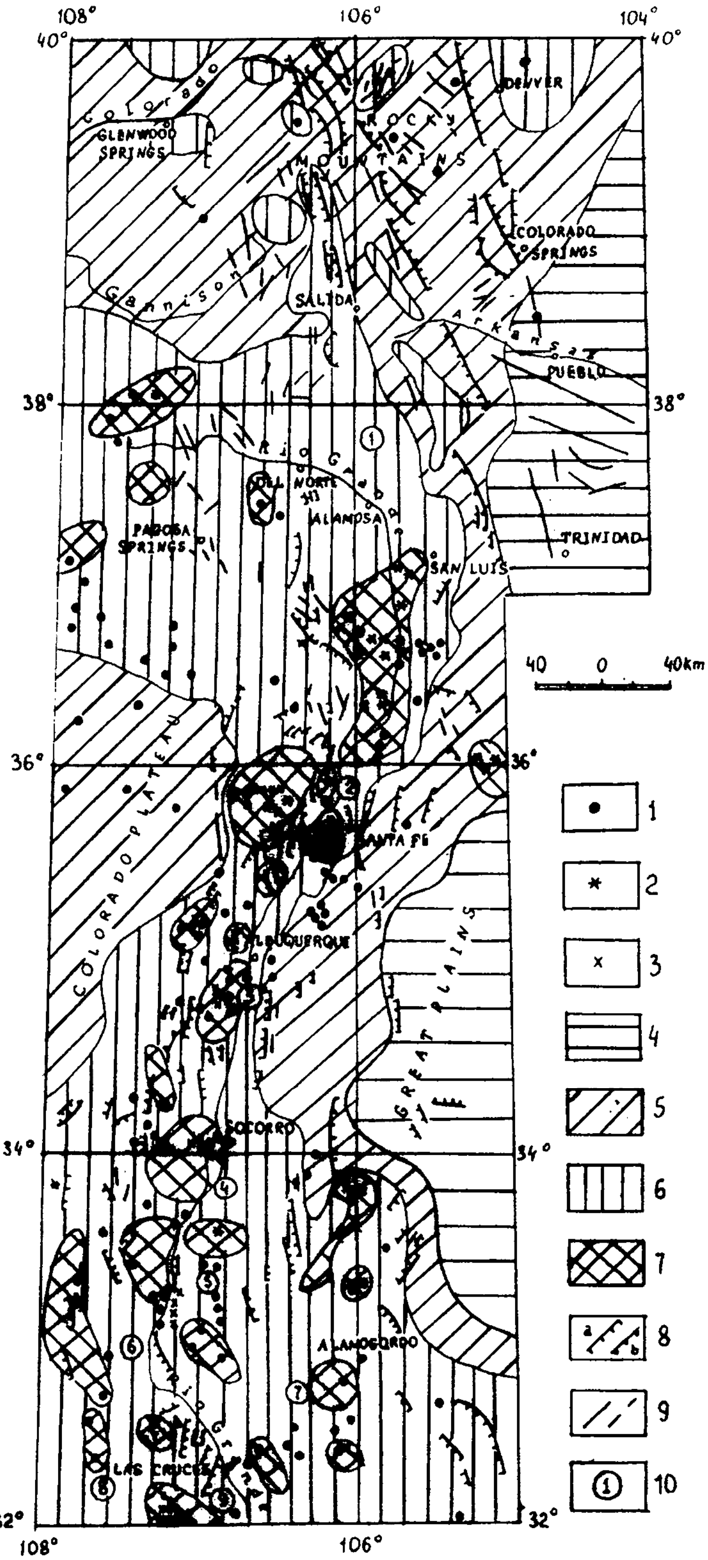

Fig. 9. Heat flow map of the Rio Grande rift. Based on: Roy et al., 1968; Sass et al., 1981; Combs and Simmons, 1973; Tweto, 1978; Reiter et al., 1979; 1986; Milanovsky, 1983; Sass and Morgan, 1988. *1* = Heat flow stations; *2,3* = volcanoes: Holocene (*2*) and Miocene (*3*); *4–7* = regional heat flow: lower than 50 mW m^{-2} (*4*), form 50 to 75 mW m^{-2} (*5*), from 75 to 100 mW m^{-2} (*6*), higher than 100 mW m^{-2} (*7*); *8,9* = faults: normal faults (*8a*) and thrust faults (*8b*), unspecified faults (*9*); *10* = rift basins: *1*: San Luis, *2*: Espanola, *3*: Albuquerque-Belen, *4*: San Marcial, *5*: Jornada, *6*: Palomas, *7*: Tularosa, *8*: Los Muertos, *9*: Mesilla.

Mexico volcanic belt and is likely to be related to rifting in the Gulf of California.

Discussion and conclusions

From the above it is evident that heat flow in intra-continental rift systems is highest in subsiding grabens, along active fault zones and around volcanic centers. On rift shoulders, heat flow generally decreases away from the axial graben system, whereby local anomalies are associated with volcanic activity and fracture zones punctuated by hot springs. In young, post-orogenic rift systems of the Cordilleran type, thermal anomalies are not so much controlled by the structural configuration of the rift than by the pattern of volcanic activity.

During the evolution of intra-continental rifts, heat flow increases in tandem with progressive lithospheric attenuation, and decreases again during their post-rift thermal relaxation phase. Palaeo-rifts are generally characterized by considerably smaller, remnant thermal anomalies than those of still active rifts (e.g. North Sea and Oslo grabens versus Baikal, Kenya and Rio Grande rifts). However, also palaeo-rifts have still an elevated heat flow as compared to their neighbouring areas.

Conductive heat transfer dominates the thermal regime of areas bordering the rift zones, such as rift shoulders, major horst blocks and transform zones linking graben systems. Under a steady-state thermal regime, conductive heat transfer produces a background heat flow consisting of a radiogenic crustal and a mantle component. Regions of active crustal extension (rifting) are characterized by a transient thermal regime of the lithosphere, in which convective heat transfer along fracture-induced zones of increased permeability, facilitating the ascent of deep fluids, plays an important role. In such cases, tectonic deformations are responsible for the development of sharply differentiated thermal anomalies.

Rifting involves thinning of the lithosphere by mechanical stretching and thermal attenuation of the upper mantle by conductive heat transfer and possibly also by convective processes in the rising asthenospheric diapir. The latter is thought to develop in response to decompression and partial melting of the lower lithosphere and the upper astenosphere as a consequence of mechanical extension of the lithosphere ("passive rifts"). Alternatively, the thermal state of the asthenosphere may change, leading to its partial melting and the diapiric ascent of melts into the lithosphere, whereby deviatoric stresses developing in the lithosphere cause the subsidence of rifted basins ("active rifts").

In either model rifting is associated with a profound disturbance of the asthenosphere/lithosphere system and an increase in the deep heat flow. With progressive attenuation of the lithosphere, heat flow increases and reaches its maximum at the moment of crustal separation. In view of this, analyses of the surficial heat flow regime of tectonically active rifts may provide insight into how far their development towards crustal separation has already progressed.

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