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HELIUM ISOTOPE TRACER OF GEOTHERMAL ACTIVITY

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ABSTRACT

As an indicator of crust-mantle interaction, helium isotopic composition ($^3He/^4He = R$) in subsurface fluids was studied in the East-European segments of the Alpine-Himalayan fold belt, in Baikal rift zone, and in the Transmexican volcanic belt, as well as in the adjacent areas. The *R*-value distribution correlates with tectonic pattern, magmatic manifestations and their Sr-isotope marks, background heat flow density (*q*), and the lithosphere thickness.

1. INTRODUCTION

Thermal subsurface fluids are the optimal object to search for an influx of mantle-derived components to the crust. The best indicator of such influx is the value of helium isotope ratio, $^3He/^4He = R$. Due to fundamental studies by H. Craig, I.N. Tolstikhin, R.K. O'Nions and many other scientists, now it is well known, that this ratio differs sharply in radiogenic He originated within the crust rocks (canonic radiogenic $R \sim 10^{-8}$) and He occurred in the mantle ($R \sim 10^{-5}$). There is, however, a difference in *R*-values between the depleted mantle considered as the MORB reservoir ($\approx 1.2 \times 10^{-5}$) and the primitive mantle producing "hot spot" plumes ($\sim 5 \times 10^{-5}$). In the atmospheric He, this ratio is of the intermediate value, $R \approx 1.4 \times 10^{-6}$ (Mamyrin et al., 1970).

In principle, mantle-derived mass flux must transport deep heat as well. The comparison of background conductive heat flow density, *q*, and helium isotopic composition in subsurface fluids confirmed this concept (Polyak et al., 1979; Sano et al., 1982). Therefore helium isotope data carry an information on geothermal conditions of the regions under study. Such an information is especially useful for a tentative assessment of geothermal resources in the regions where the direct thermal measurements are not available.

During last decades, this approach is applied in the Geological Institute of the Russian Academy of Sciences, RAS GIN, to research of geothermal activity in the mobile belts of different types. The paper summarizes some results obtained in the Northern Caucasian and Eastern Carpathian segments of the Alpine fold belt and in the Baikal-Mongolian region of continental rifting (Fig. 1), as well as in the Transmexican volcanic belt and its surrounding.

2. METHODS

2.1 Experimental

The free gases spontaneously escaping from underground fluids discharged on the earth surface through natural springs or bore holes are the objects of the present study. Most of the gas samples were collected by the field research teams of the RAS GIN (Moscow) in glass containers of 220 cm^3 by volume by a simple replacement technique. The samples were analyzed in mass-spectrometric labs of the Geological Institute of RAS Kola Scientific Center (Apatity), the RAS Ioffe Physical-Technical Institute and All-Russian Oil Prospecting Institute (both from St. Peterburg), and the RAS Vernadsky Institute of Geochemistry and Analytical Chemistry (Moscow) with participation of I.N. Tolstikhin, I.L. Kamenskii, E.M. Prasolov, and A.B. Verkhovskii following the procedure described repeatedly (e.g., Tolstikhin et al., 1991). Besides $^3He/^4He$ ratio, He and Ne contents and $^4He/^{20}Ne$ ratio were measured in the same sample. It enabled us to correct the measured $^3He/^4He$ value for contamination by atmospheric helium; in most cases the corrections were negligible.

2.2 Data Processing

The studies were aimed at revealing the regularities in lateral variations of helium isotope ratio. It is impossible to do without a preliminary analysis of the ratio fluctuations in the observation sites with time and depth (such an analysis is also "a must" for the mapping of heat flow density). Both repeated sampling of the same objects and sampling of different depth intervals in bore holes showed that a single specimen, as a rule, could be considered as a representative one for a given locality regardless sampling time or depth (see Figs. 2 and 3 as the examples).

3. RESULTS

3.1 Northern Caucasus

This region embraces the Greater Caucasus Orogene, Indol-Kuban and Terek-Caspian foredeeps and epi-Hercynian Scythian Plate including the Stavropol Arch. The sampled fluids represent mud volcano emanations, hydrocarbon fields, and thermomineral waters. More than 220 samples of free gas phase from the fluids discharged through natural springs or bore holes were collected in 152 sites of the region at different times. The range of *R*-values in the samples comprises three orders of magnitude, from 1.5×10^{-8} to 0.9×10^{-5}, whereas He content, [He], varies from 1 to 12900 ppm.

The regular lateral variations of *R*-values were noted in the region (Fig. 4). CH_4-rich gases from Ciscaucasian foredeeps show the lowest *R*-values fitting canonic radiogenic value. The average R_{av} value is slightly higher in the similar gases of Scythian Plate beyond Stavropol Arch. Within the arch, the elevated $R = (1.6 - 4.5) \times 10^{-7}$ in the same gases indicates an input of mantle-derived helium, although any manifestations of magmatic activity are not yet known there. Such manifestations (trachyrhyolites ~8 Ma old) are observed to the south of the arch, in the Caucasian Mineral Waters area (CMW), where the input of mantle-derived helium in fluids becomes all the more evident: $R_{av} = (7.6 \pm 0.9) \times 10^{-6}$. The highest *R*-values, up to $(0.6 - 0.9) \times 10^{-5}$ distinguish CO_2-rich gases in the central segment of Greater Caucasus where Neogene-Quaternary volcanism occurred (as the active Elbrus volcano, etc.). The enhanced *R*-values spread from this segment both along and across the strike of the Greater Caucasus Orogene far beyond the area of superficial manifestations of young volcanism regardless the crust thickness.

3.2 Eastern Carpathians

Sampling of bore holes and natural springs from 44 sites in the region including both the Flysch Carpathian Orogene, as such, and the framing troughs (Ciscarpathian Foredeep and Transcarpathian Depression adjacent to Pannon Basin), revealed [He] variations from 0.1 to 249 ppm and the rather wide range of the *R*-values: from 1.8×10^{-8} to 3.2×10^{-6}.

Here too the regular lateral *R* variations are observed (Fig. 5). The lowest (crustal radiogenic) *R*-values distinguish CH_4-rich gases from Ciscarpathian Foredeep. The highest *R*-values (up to ~0.3×10^{-5} are found in CO_2-rich gases from Transcarpathian Depression where N-Q volcanism manifested itself, whereas the similar fluids from the Flysch Carpathians are characterized by the intermediate *R-val*ues despite the absence of recent volcanic manifestations. As Fig. 5 suggests, there is no correlation between *R-val*ues and the crust thickness.

3.3. Baikal-Hövsgöl Rift Zone

The *R*-values were measured in 133 fluid samples collected at 102 sites on the territory of Russia and Mongolia by research teams from RAS GIN (Polyak et al., 1992, 1998) and the Earth Crust Institute of the RAS Siberian Branch (Pinneker et al., 1994; 1995). The studied region incorporates both the Baikal-Hövsgöl Rift Zone (BHRZ) proper stretching from NE to SW over the length of ~2000 km from Chara Depression to Hangayn Nuruu Range and its framing: the pre-Riphean Siberian Plarform on the west and Transbaikalian Paleozoic tectonic units on the east. The latter units were locally subjected to Mz-Kz tectonic and magmatic re-activation. The range of *R*-values is here even wider than that in the Northern Caucasus: from 1.4×10^{-8} to 1×10^{-5} at the widest [He] spectrum: from 0.28 to 22000 ppm.

The *R*-values vary regularly both along and across the BHRZ strike. They indicate an input of mantle-derived helium to thermomineral fluids in both the zone proper and its eastern flank. The highest *R*-values near to those in MORB, are inherent to the fluids from Tunka Basin situated to the west of southern end of Lake Baikal and distinguished by Holocene volcanism. Along the rift axis in both direction from this basin, *R*-values gradually decrease down to typical crustal (radiogenic) magnitude (Fig. 6) in some accordance with the M-discontinuity subsidence (Polyak et al., 1992). Such a variability of *R*-values is typical of continental rift zones in general. This feature differs drastically these zones from mid-ocean ridges where *R*-values are very uniform along the strike and characterize the MORB reservoir. Transverse profile (Fig. 7) demonstrates the sharp contrast between the Siberian Platform and BHRZ. However, despite a rarity of volcanic manifestations to the east of the zone, *R*-values remain there as high as at its axis and begin to decrease only outward at the distance of some hundreds kilometers in inverse correlation with the lithosphere thickness (Polyak et al., 1998).

3.4 Transmexican Volcanic Belt

85 samples of gases from thermal fluids were collected at different times at 56 sites located in the belt and its surrounding (including the Eastern, Western and Southern Sierra Madre ranges) and Baja California Peninsula as well (Fig. 8). The *R*-values cover the range from 2.2×10^{-7} to 0.95×10^{-5} and [He] content varies from 0.3 to 1790 ppm.

In the Mexican fluids, the distribution of helium isotopes relates to the age of volcanism and the composition of gas phase. The Pliocene-Quaternary Transmexican Volcanic Belt (TMVB) is marked by CO_2-rich hydrotherms containing the abundant mantle helium (up to 80% of total [He] in the largest hydrothermal systems). The distribution of atmospheric Ne, Ar, and Xe in these fluids reflects high temperatures in reservoirs. Outside the belt, N_2-rich hydrotherms are spread; many of them hold excess (non-atmospheric) N_2 whereas helium from these fluids contains no more than 10% of the mantle component.

4. DISCUSSION

4.1 *R*, tectonics and magmatism

The distribution of *R*-values in the studied regions indicates that helium isotope composition in subsurface fluids is related everywhere to tectonic pattern and magmatic activity. In the Northern Caucasus, the *R*–tectonics relation is manifested in the systematic distinctions of the R_{av} values estimated for different tectonic units (Fig. 4). The similar distinction is seen in the Eastern Carpathian as well (Fig. 5). The over-radiogenic *R*-values in the relatively young framework of TMVB can be considered as one more evidence of the same relation (Fig. 8). The *R* variations along the BHRZ strike (Fig. 6) evidently reflect a specific feature of continental rifting as compared with ocean spreading.

From the regional investigations, it is also obvious that the *R*-value highs correlate with young volcanic manifestations (the TMVB, Tunka Basin of the BHRZ, Transcarpathian Depression, Elbrus area in the Caucasus). Moreover, the elevated *R*-values indicate the magmatic activity in the places where its superficial manifestations are absent. One of such places is the central segment of the Northern Caucasus from Elbrus volcano to the Stavropol arch of the Scythian Plate. Hydrodynamic simulation showed that the halo of the enhanced *R*-values observed in this segment is related to input of mantle-derived helium from the deep-seated foci (Yakovlev et al., 1998). The same situation is observed in the Baikal-Mongolian region (Figs. 6 and 7).

4.2 *R* and $^{87}Sr/^{86}Sr$ in volcanics

The *R* magmatism relation is supported by the correlation between the isotopic compositions of helium in fliuds and strontium in volcanics of the same locality. The prominent example of this correlation is observed in the same central segment of the Northern Caucasus. Fig. 9 shows the inverse correlation between $^3He/^4He$ ratio in fluids and the $^{87}Sr/^{86}Sr$ ratio in Neogene-Quaternary volcanics from the Elbrus and CMW areas. Such a correlation is manifested in other regions as well (in Italy, Indonesia, etc.) and evidences the common transfer of He and Sr from the mantle by magmatic melts.

4.3 *R* and *q*

Mantle-derived melts transport not only material substance but heat energy accumulated in this substance as well. For this reason, the direct correlation exists between background values of helium isotopic ratio, *R*, in subsurface fluids and conductive heat flow density, *q* (Polyak et al., 1979; Sano et al., 1982). This regular relationship is well-marked in the studied regions. It is clearly visible in the Eastern Carpathian: the lowest values of both parameters distinguish Ciscarpathian Foredeep, the highest ones mark Transcarpathian Depression holding with Neogene-Quaternary volcanic manifestations, whereas the Folded Carpathians are characterized by the intermediate *R* and *q* values despite the extensive thrusting (Fig. 5). The same relationship is observed along the BHRZ axis (Fig. 6), as well as in the rifts of Eastern China (Du, 1992).

The direct correlation between *R*- and *q*-values is also well pronounced in the Northern Caucasus (Fig. 10). As in Carpathians, the minimum R_{av} and background *q* values characterize the foredeeps; Scythian Plate is distinguished by the enhanced *R*- and *q*-values which are even higher in the Stavropol arch. The highs of both parameters coincide with the central segment of the Greater Caucasus orogene re-activated by young volcanism.

4.4 *R* and apatite fission track ages

Representing two consequences of the same reason – mantle-derived heat-mass flux discharge – the background *R* and *q* values change organically in time (Polyak et al., 1979). The temporal evolution of the *R-values* is quite evident in the Greater Caucasus. As indicated by Fig. 11, these values decrease to the west of the Elbrus volcano in accordance with the increasing apatite fission track ages, FTA, available for the pre-Alpine basement of the orogene (Kral and Gurbanov, 1996). The most plausible reason of such a relation appears to be a relaxation of thermal and geochemical anomalies inherited from «island-arc» stage of the orogene development. It is this relaxation that can cause the cooling of the crust, i.e the subsidence of isotherms, along the orogene strike from the west toward its central segment.

4.5 R and major gases

Helium isotope studies shed light on the origin of other fluid components. The R vs. [He] plot exemplifies this approach (Fig.12). The inverse R–[He] correlation observed in the regional data sets is properly caused by the mixing of He from the mantle and crustal end-members. However, a departure of empirical data from theoretical trend indicates a dilution of this mixture by another crustal gases and, in addition, a fractionation of dissolved components between gas and liquid phases. Because ^{3}He is almost entirely of the mantle origin, the calculation of $[X]/[^3He]$ values in fluids under study (where X denotes a component involved) and the comparison of these values with the corresponding estimates for the mantle provide the evidence for the mantle contribution in the [X] content. The latter approach is of considerable current use for carbon-bearing gases: CH_4 and CO_2.

5. CONCLUSION

Helium isotope distribution correlative with tectonic pattern and deep structures of the regions under study characterizes spatial and temporal features of geothermal activity related to hidden discharge of heat-mass flux from the mantle into the crust. Such an information is especially important in the search for geothermal resources in the regions devoid any superficial geothermal manifestations. The correlation between $^3He/^4He$ ratio in fluids and the $^{87}Sr/^{86}Sr$ ratio in rocks from the same areas evidences the common transfer of He and Sr from the mantle by magmatic melts. Coupled with [He] data, *R*-values clarify the origin of major gases in fluids.

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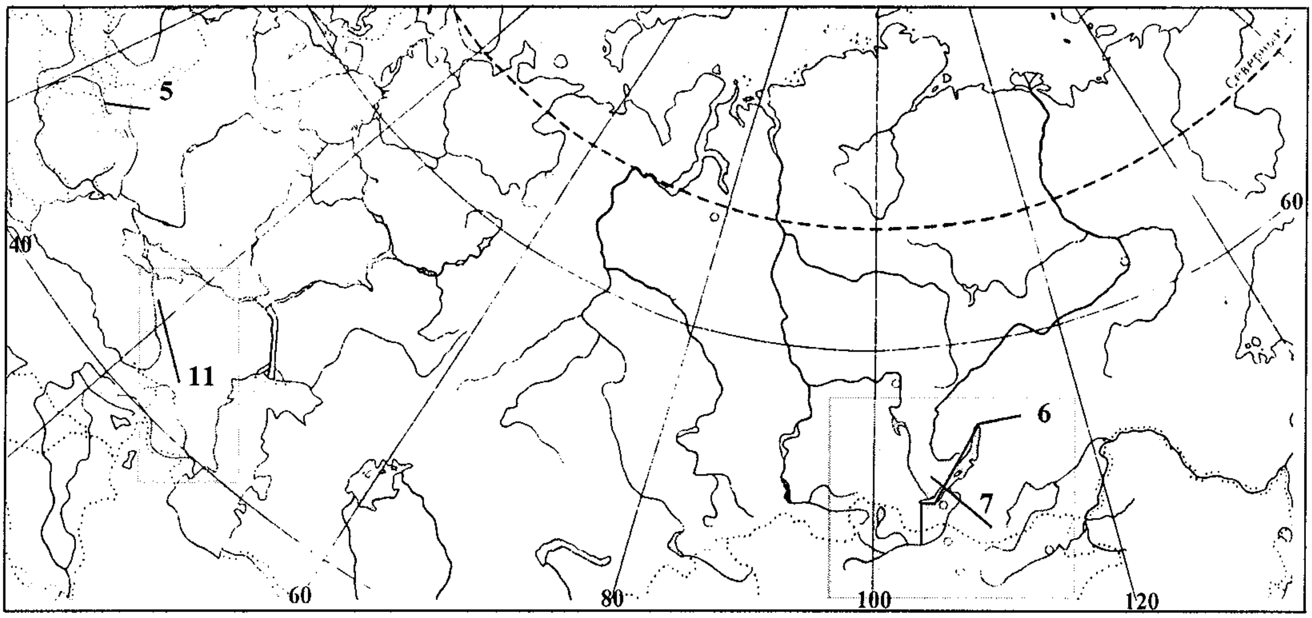

Figure 1. The FSU regions under discussion. Numbers denote the profiles lines shown on Figs. 5-7 and 11.

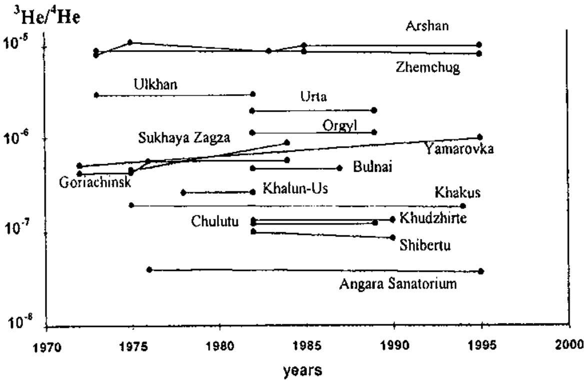

Figure 2. The 3He/4He fluctuations in fluids with time (Baikal-Mongolian region).

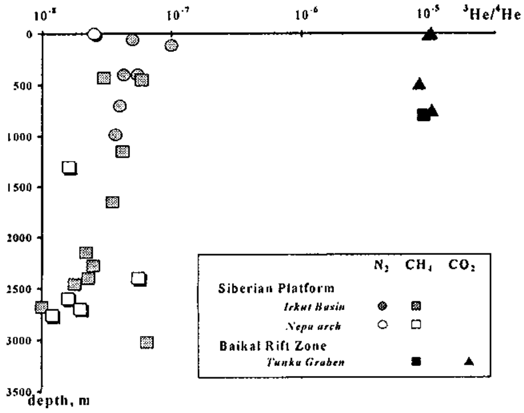

Figure 3. The ^{3}He/^{4}He variations in fluids along the depth.

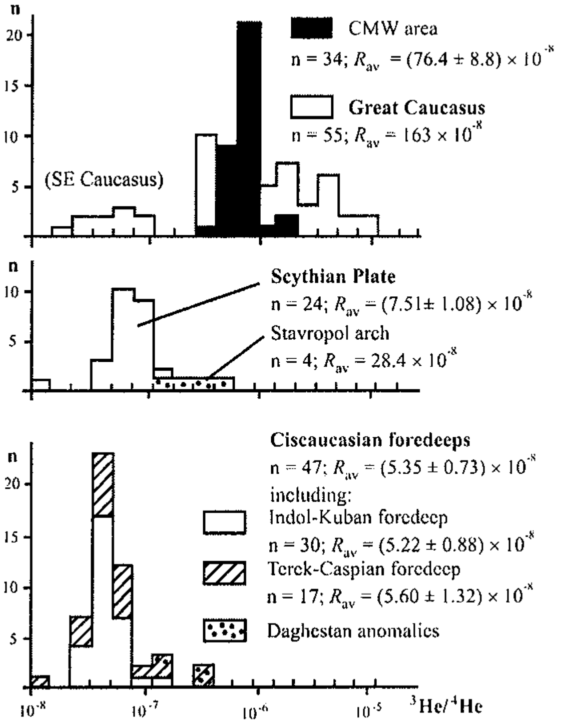

Figure 4. Bar charts of the *R* distribution in different tectonic units of the Northern Caucasus.

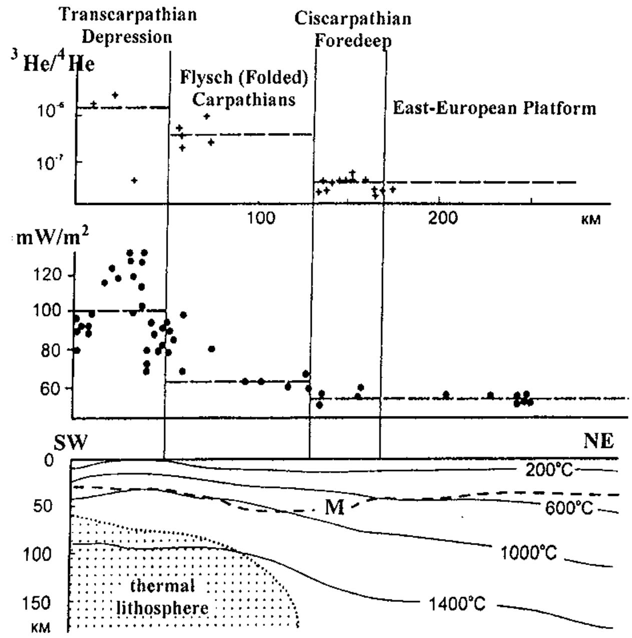

Figure 5. *R* and *q* distributions across the Eastern Carpathians strike (Line 5 on Fig. 1).

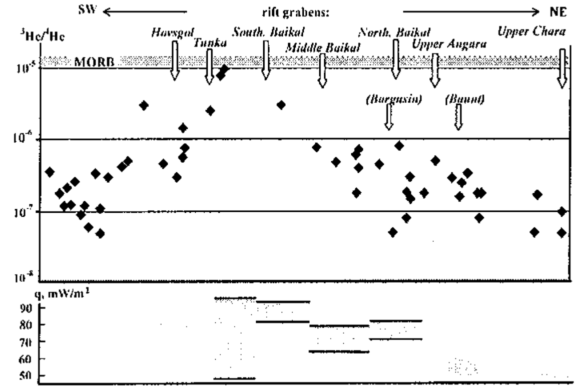

Figure 6. *R* and *q* distributions along the BHRZ (Line 6 on Fig. 1).

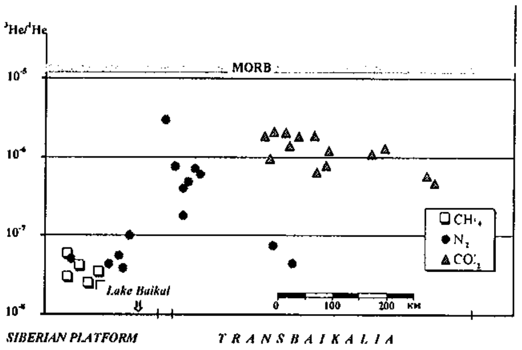

Figure. 7. *R*-value distribution across the BHRZ strike (Line 7 on Fig. 1).

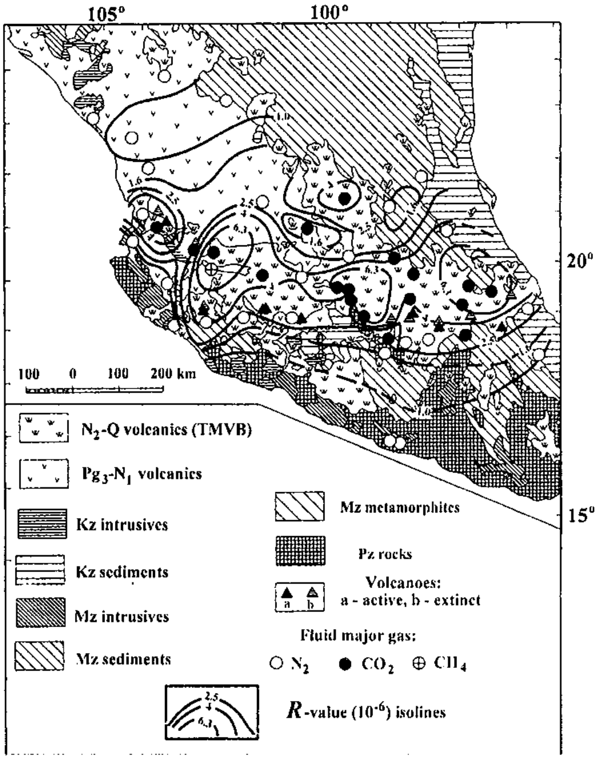

Figure 8. R-value distribution in thermal fluids of Mexico

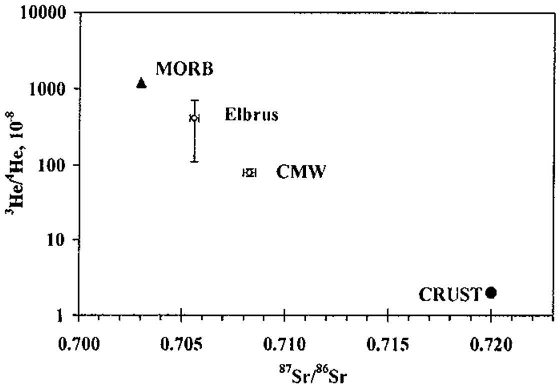

Figure 9. Plot of R in fluids vs. $^{87}Sr/^{86}Sr$ in N-Q volcanics of the Northern Caucasus.

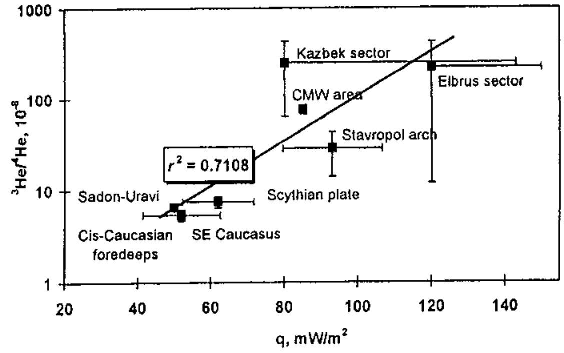

Figure 10. *R* vs. *q* plot for the Northern Caucasus.

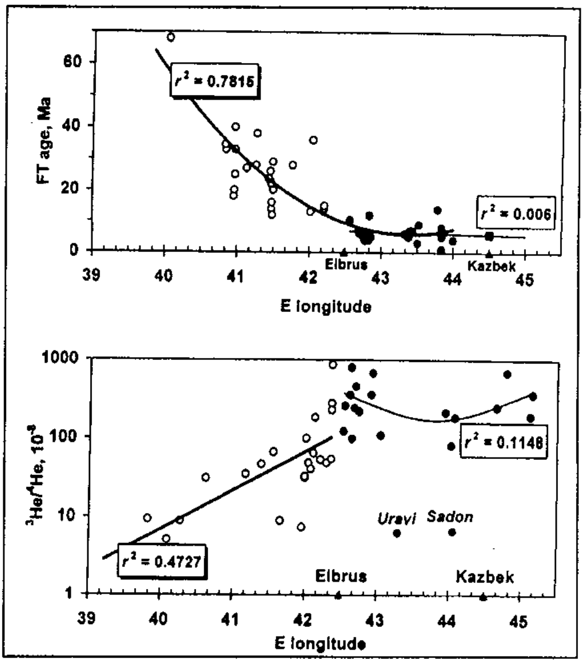

Figure 11. *R* and *q* distribution along the Northern Caucasus Orogene strike (Line 11 on Fig. 1).

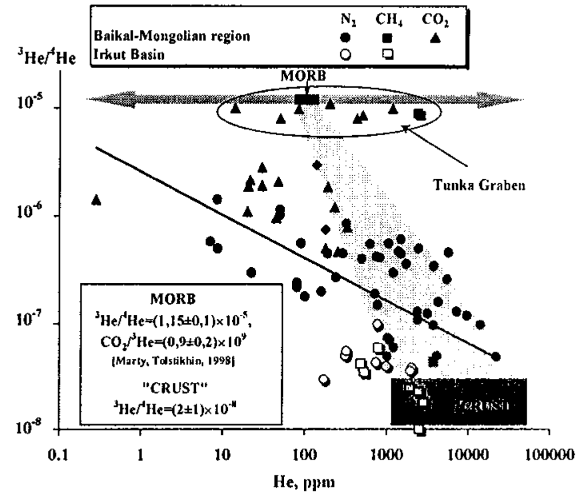

Figure 12. *R* vs. [He] plot in the BHRZ fluids