Depth of Origin of the Gas Content in Thermal Waters

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ABSTRACT

The gas composition of recent thermal waters is in perfect conformity with their geologic-tectonic positions.

The composition of gas-liquid ([1]) inclusions in the basic-hyperbasic xenoliths of basaltoid lavas depends on the depth from which xenoliths are supplied. (The depth is determined by using the methods of geological thermobarometers).

By comparing available data we came to the conclusion that the gas compositions of thermal waters reflect the depth of generation of deep fluid which heats them and depends on the penetration depth of the fluid-conducting fissure zones.

INTRODUCTION

Hydrothermal systems occur all over the world in regions of Recent or Quaternary volcanism. At present a lot of new data are known on the structure of the upper parts of hydrothermal systems, but the character of their relation to deep processes remains obscure. The authors of the present paper suggest using analogies in compositions of gases in microinclusions of basic-hyperbasic low-crustal and mantle xenoliths, on the one hand, and in gas composition of hydrothermal waters, on the other hand, as indicators of P-T conditions of fluid generation which in its turn gives rise to hydrothermal activity.

([1]) Inclusions consisting of two phases, namely glass and gas.

ORIGIN OF HYDROTHERMAL FLUID

Schemes of relation of hot waters to the earth's interior may be the following: 1) hydrothermal solutions are separated from magmas at the late stage of crystallization; 2) thermal waters are the vadose waters penetrated to (or into) the magma chamber, heated there and then uplifted to the surface; 3) hydrothermal solutions are formed by mixing of vadose water with juvenile high temperature heat-transfers (fluids) rising from the interior independently of magmatic melts and 4) hydrothermal solutions are separated from rocks during the process of thermal metamorphism. We believe that at different stages of the hydrothermal system development all these processes may take place. But in all cases, in order to explain the heat discharge observed at relatively small in area regions of the formation of hydrothermal systems, we have to assume supply into these systems of high-energy heat transfers. The discussion of the problem of deep fluids has led scientists to a conclusion about existence of the subcrustal concentrated heat transfers that can warm up rocks up to their melting point (AVERIEV, 1967; KUZNETSOV and IZOKH, 1969; VELINSKY, 1970). While interacting with rocks and vadose waters, the juvenile fluids form a series of hybrid waters whose composition depends on the composition and volume of mixing components as well as on the conditions of their subsequent migration.

Almost all of the mineral components diluted in thermal waters can be account-

ed for by their supply from water-bearing rocks (WHITE, 1965). At the same time there are no forcible arguments for disproving the opportunity of supplying some of these components in fluid from the sub-crustal areas. The salt composition reflects rather the geological section of the hydrothermal system masking the true correlation of the vadose waters with deep fluid. The most general regularities of thermal water genesis are reflected in their gas composition (IVANOV, 1960; 1961). Developing IVANOV's classification (1960), based on the contents of the main gases it is suggested to distinguish the following water types in the areas of recent and current volcanism: hydrogen (H$_2$), nitrogen – carbon dioxide, carbon dioxide – nitrogen (CO_2 - N_2), nitrogen (N_2), carbon dioxide (CO_2), etc. The areal distribution of each gas type of waters is in agreement with geologic and tectonic environments (Figs. 1, 2).

Below we shall attempt to appraise some geological peculiarities of each gas-hydrochemical zone comparing two rather geologically different volcanic regions – Iceland and Kamchatka.

The neovolcanic zone crossing Iceland serves as a direct continuation of the Mid-Atlantic Ridge, and the island itself is considered by various authors as both an outcrop of the Ridge to the surface (PALMASON and SAEMUNDSSON, 1974) or a fragment of the ancient continent with the superimposed rift zone (BELOUSSOV, 1975; MILANOVSKY, 1976). The island on the whole is composed of basic volcanic rocks whose age increases away from the rift zone axis. Intrusive formations and acid volcanites are considerably less abundant (THORARINSSON, 1967). The hydrothermal activity is manifested over the whole territory of Iceland (Fig. 1) in gigantic high temperature hydrothermal systems spreading in the neovolcanic zone and in smaller-scale hydrothermal systems of the regions of Pleistocene volcanism.
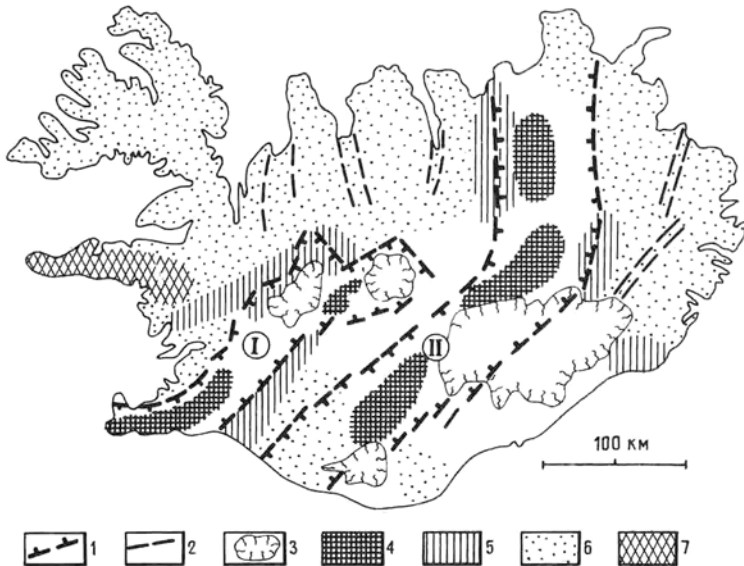

FIG. 1 - Scheme showing gas zoning of the Iceland thermal waters. 1 - boundaries of the neovolcanic and deep-fault zones; 2 - faults of the second order; 3 - glaciers; 4 - hydrogen thermal waters (for Kamchatka: nitrogen - carbon dioxide thermal waters with the presence of hydrogen); 5 - nitrogen - carbon dioxide thermal waters; 6 - nitrogen thermal waters; 7 - carbon dioxide thermal waters. I, II - western and eastern branches of the neovolcanic zone, respectively.
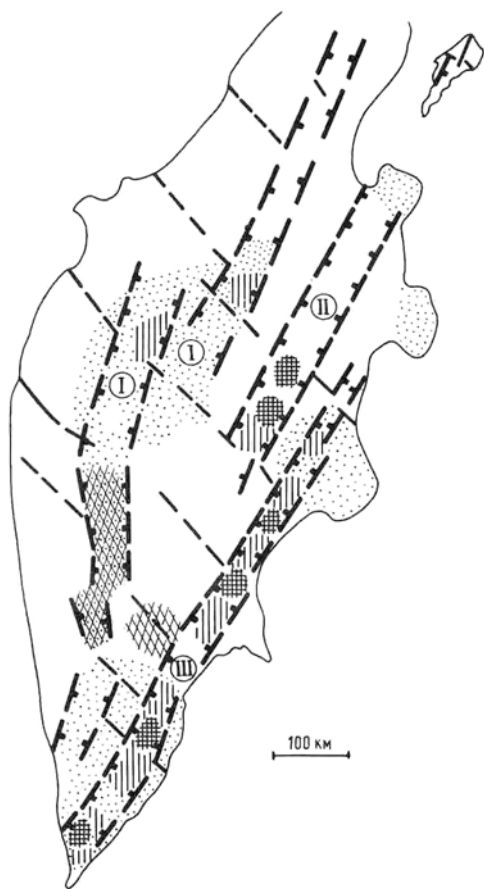
FIG. 2 - Scheme showing gas zoning of the Kamchatka thermal waters. Symbols as in Fig. 1. I - western, II - middle, III - eastern Kamchatka volcanic zones.

Kamchatka is situated within the zone of junction of the continent and ocean. It has a thick (30 km) crust of the continental type with the developed «granitic» layer. The geologic structure of Kamchatka is notable for its complexity. This region has passed all the stages of geosynclinal development up to the early orogenic. The Kamchatka zones of Quaternary volcanism are related to the regional deep faults of the Pacific belt.

The hydrothermal activity in Kamchatka is concentrated within the zones of Quaternary volcanism, and the largest hydrothermal systems tend to occur near the largest long-existing volcano-magmatic centres originated at least in the Pre-Miocene time and earlier (VASILEVSKY et al., 1974). The emplacement of the centres along the regional fault zones is controlled by large deep, cross-cutting fault zones of transverse trend.

In Iceland and Kamchatka, despite their great geotectonic difference, one can recognize the same gas types of thermal waters and almost identical gas-chemical zoning (see Table 1, Figs. 1 and 2). The gas-chemical zoning of the Iceland thermal waters was investigated by ARNARSSON et al. (1974). The similar zoning of the Kamchatka thermal waters was deduced from our new concepts on the structure of its volcanic regions as well as from data of our and Kamchatka geologists' hydrochemical investigations (HYDROGEOLOGY OF THE USSR, t. XXIX, 1972).

Below we shall give general geological characteristics of the conditions of distribution of the above mentioned water types in terms of their gas composition, neglecting the local deviations that take place along with general regularities.

Hydrogen thermal waters are the most typical in Iceland. In gases of these thermal waters the hydrogen content reaches 60% of their volume but more often it is close to 10%. The rest of the gas volume is represented by CO_2, H_2S and N_2. The distinctive peculiarities of hydrogen thermal waters in comparison to other hot waters are the maximum temperature and high capacity of hydrothermal systems. Thermal waters containing hydrogen in amounts of a few percent occur also in Kamchatka. Here hydrogen has been revealed in the gas composition of nitrogen – carbon dioxide waters within the vast and high temperature hydrothermal systems.

Nitrogen - carbon dioxide (carbon dioxide - nitrogen) thermal waters are the most abundant in the regions of Quaternary volcanism all over the world. Excluding CO_2 and N_2, the gas composition of these thermal waters is characterized by

TABLE 1 - Typical composition of gases in thermal waters.

Types of thermal waters and their representatives	T (°C)	CO_2	N_2	H_2	H_2S	CH_4	He
Hydrogen							
Iceland, Namafjall	B.P.	66.62	1.78	31.12	0.31	0.16	0.0015
Nitrogen-carbon dioxide							
Iceland							
Reykholt	B.P.	11.60	85.00	0.00	0.00	0.27	—
Geyzir[1]	B.P.	77	21.0	0.0	0.0		0.0057
Kamchatka							
Pauzhetka	B.P.	63.98	25.50	3.40	1.40	5.20	0.0005
Valley of Geysers	B.P.	61.72	31.00	0.28	—	5.00	—
Mutnovsky	B.P.	81.28	12.25	5.40	0.50	0.32	—
Nitrogen							
Iceland							
Varmahlid[1]	B.P.	0.8	97.0	0.01	0.0	1.0	—
Tjorsalaug[1]	70	0.21	97.72	0.00	0.00	0.35	0.016
Kamchatka							
Kronotsky Pen.	64	0.03	99.77	0.00	0.00	0.20	0.0091
Paratunka	82	0.0	99.7	0.0	0.0	0.3	—
Hodutka	78	3.22	95.52	0.01	0.00	1.31	0.0070
Carbon Dioxide							
Iceland, Lysuholl	57	98.38	1.56	0.00	0.06	0.06	0.0005
Kamchatka							
Nalachevo	74	93.38	5.85	0.00	0.01	0.73	—
Semyachinsky	48	93.58	3.11	0.23	0.00	2.00	0.000

B.P.: boiling point;

—   : not included in author's total;

[1]   : ARNORSSON et al., 1974.

the presence of H_2S and CH_4 in amounts of a few percent. In Iceland these thermal waters «border» the areas of hydrogen thermal waters, manifested in the peripheral parts of the neovolcanic zone and in the adjacent regions of Pleistocene volcanism. In Kamchatka the large hydrothermal systems of nitrogen - carbon dioxide waters are situated in the central portions of the long-existing volcano-magmatic centres (Fig. 2, III).

Nitrogen thermal waters are notable for very constant gas composition N_2 (98%) and very low gas content. In Iceland the waters of this type are spreading over the whole area of Pre-Quaternary plateau-basalts. They form large deposits of thermal waters in the Reykjavik region. In Kamchatka the occurrences of nitrogen thermal waters are naturally located in the peripheral parts of the long-existing magmatic centres. The fluid participation in the formation of these thermal waters is doubtful, however, He^3/He^4 isotopic ratios in the Iceland nitrogen thermal waters testify to participation of deep heat-transfers in warming up these waters (KONONOV *et al.*, 1974). The investigators of the nitrogen thermal waters of Kamchatka (MANUKHIN and VOROZHEIKINA, 1976) are also of the opinion that there is a convective supply of deep heat into the water-head systems of nitrogen waters.

Carbon-dioxide thermal waters occur both in Iceland and Kamchatka close to obvious or concealed intrusives of Post-Paleogene age (see Table 1). Carbon dioxide has the magmatic or thermometamorphic origin (OVCHINNIKOV, 1963). The carbon-dioxide thermal waters do not occupy a definite position within the other gas-chemical zones.

GAS COMPOSITION
OF THE LITHOSPHERE

In Iceland and Kamchatka the largest geothermal areas and recent volcanic centres are located in the zones of the same deep faults. (see Figs. 1, 2). One may assume that the zones of deep faults are at the same time a zone of draining deep gases. When ascending to the surface, the latter mix with metamorphogenetic gases enriching themselves mainly in CO_2 and water steam.

The qualitative composition of gases of the lithosphere at the levels of basalt magma generation is also characterized by samples of «real» magmatic gases of recent eruptions (Table 2). Despite the undoubted pollution by atmospheric gases,

they contain hydrogen in significant amounts to 30%) (CHAIGNEAU, 1962; TAZIEFF, 1966; MENYAILOV *et al.*, 1976; etc.). The experimental data and thermodynamic calculations also have led many investigators to the conclusion about the predominance of hydrogen and nitrogen in the composition of deep fluid (PERCHUK, 1973; LUTS, 1973).

Along with basalt lava, volcanoes also supply to the surface the rock fragments-xenoliths. The latter may be both the fragments of near-surface (overwhelming majority) or deep-seated rocks of the lower crust and upper mantle.

The second group of xenoliths is characterized by a series of mineral parageneses that could emerge only at *P-T* conditions corresponding to the depths from 20 to 130 km (MACGREGOR, 1968; SOBOLEV, 1973; LUTS, 1973; PERCHUK, 1973, etc.) (Table 3). About 1500 samples of deep-seated xenoliths collected in Kamchatka were available. They allowed us to get an idea of the bulk composition, density and state of rocks of the deep lithosphere beneath Kamchatka.

The most deep-seated rocks are represented by high pressure associations composed of diopside, garnet (pyrope) and forsterite. The rocks of the group of spinel

TABLE 2 - Volcanic gases collected from erupting craters, lava lakes and flows (in vol. %).

Sample No.[*]	Location and date of collection	T (°C)	Content of water vapour in initial gas (vol. %)	CO_2	CO	CH_4	H_2	H_2S	N_2	O_2	NH_3, HCl, HF, S, SO_2 SO_3
S8	Kilauea volc. lava lake Halemaumau, 1917	1100±	75.08	61.3	1.80	–	2.80	–	4.05	–	30.00
A-1 (9081)	Showa-Shinzan. Usu volc. 7.07.1959	750	99.25	62.80	–	0.08	24.15	0.10	3.43	0.01	9.43
E[1]	O-Shima volc. lava lake. 04.1951	1000±	–	0.80	–	–	25.90	–	72.5	0.0	–
4	Nyragongo, lava lake. 1959	990	–	72.70	4.50	–	1.90	–	14.10	3.10	3.70
1	Sicily, Etna volc. lava flow.20.10.1961	–	–	18.3	0.3	0.6	10.9	–	46.9	1.3	21.7
13	Surtsey volc.	–	79.2	46.34	0.36	–	23.46	–	3.65	–	23.17
10	Kamchatka, Tolbachik lava flow.21.12.1975	1020	93.73	8.02	–	–	11.90	–	73.66	–	6.42
11	Kamchatka, Tolbachik lava flow.22.12.1975	1020	94.02	8.30	–	–	30.60	–	33.70	–	27.4

S8, A-1 (9081), E[1]: WHITE and WARING, 1963; 4: CHAIGNEAU et al., 1960; 1: CHAIGNEAU, 1962; 13: SIGVALDASON and ELISSON, 1968; 10, 11: MENYAILOV et al., 1976.

[*] : Numbers refer to sample numbers in original publications.

– : Not included in author's total.

TABLE 3 - Gas composition of individual inclusions (vol. %).

Name of volcano	Mineral, rock	Temperature of homogenization °C	Calculated depth interval, km	H_2S, SO_2 SO_3, HF, HCl	CO_2	CO	H_2	N_2+i
Kronotsky	basalt scoria	−	-	0.0	78.8	14.4	7.0	0.68
Avachinsky	basalt lava	−	-	0.0	65.8	25	tr	1.5
Mal. Semyachik	plagioclase	1120	20-40	5.5	4.5	0.0	0.0	90.0
Il'insky	plagioclase	1295	20-40	5.2	7.0	0.0	0.0	88.0
Il'insky	plagioclase	1310	20-40	0.0	16.3	0.0	0.0	83.7
Il'insky	plagioclase	1380	20-40	0.0	4.5	0.0	0.0	95.5
Il'insky	plagioclase	1460	20-40	0.0	2.5	0.0	0.0	97.5
ZHELTOVSKY	plagioclase	−	20-40	0.0	12.0	0.0	0.0	88.0
Zheltovsky	plagioclase	−	20-40	0.0	13.4	0.0	0.0	86.6
Ksudach	plagioclase	−	20-40	0.0	71.0	24.2	4.2	0.4
Zhupanovsky	olivine	1530	40	0.0	3.6	25.8	58.0	12.4
Avachinsky	olivine	−	40	0.0	0.2	26.8	69.6	4.5
Kozelsky	olivine	−	40	0.0	12.7	27.8	57.8	1.0
Zheltovsky	olivine	−	40	0.0	9.3	37.7	54.9	1.9

− : not analysed;   tr: traces

peridotite lying above the latter are followed by pyroxenites which at the Moho level are replaced by amphibole (lamprobolitite) associations (KUTYEV, 1976). The lower crust is represented by essentially gabbroid associations (Table 4). Of great interest are the so-called carcass or porous xenoliths (KUTYEV, 1976; KUTYEV and KUTYEVA, 1975). These xenoliths of basic-hyperbasic composition represent a rigid carcass of crystals of olivine, diopside, anorthite, etc. with jointing angles, edges and faces. The rock represents a porous, permeable substratum, the pore sizes reaching a few millimetres in diameter. Such minerals as germanite and troilite which are formed under exceptionally reduced conditions have been revealed on the pore

TABLE 4 - Gas composition of rocks of the mantle, lower crust and upper crust, P-T conditions and mineralogic paragenesis.

The lithosphere zone	Mineral paragenesis	T^oC	P Kb	Corresponding depth, km	Gas composition of inclusions
Upper crust	Quartz, amphibole, plagioclase, biotite, almandine	< 900	0-8	0-20	CO_2, O_2, (H_2S)
Lower crust	Magnetite, anorthite, hypersthene, diopside, chrysolite, ilmenite	900-1450	8-14	20-40	N_2, (CO_2, H_2S)
Upper mantle	Forsterite, enstatite, pilolite, pyrope, chrome-diopside	> 1500	> 14	> 40	H_2, (N_2, H_2S, CO)

walls. These facts indicate that in the upper mantle a filtration of reduced high temperature fluid is possible. The homogeneity temperatures for microinclusions in xenolith minerals are within the interval of temperature of mineral trasformation, namely from 1300 ± 20°C for basites of the lower crust to 1500°C for mantle hyperbasites (BAKUMENKO *et al.*, 1975; KUTYEV. 1976). The predominant part of gases in the mantle xenoliths is represented by hydrogen (more than 70%) with admixture of nitrogen and rare gases, while in the low-crustal xenoliths nitrogen predominates reaching 80-99%, the rest of the volume is represented by CO_2, HCl, H_2S and by rare gases (Table 4). Thus, the nitrogen and hydrogen gaseous media are characteristic of the two lithosphere levels, namely of the lower crust and upper mantle, respectively. Gases in rocks of the upper crust are represented by CO_2, O_2 and, less so, by H_2S.

While comparing the gas composition of thermal waters of various types and the gases of rocks of various depths, one can mark a general tendency to changing their composition from hydrogen to nitrogen. In thermal waters this change occurs in the lateral direction from the sites of maximum permeability of the crust (defined by the axis of the rift, the deep fault, or the central portion of the volcano-magmatic centre). In gases of deep xenoliths the same zoning is observed in the vertical direction. All these facts allow us to assume that the gas composition of thermal waters is caused by the depth from which these gases are delivered, *i.e.* by the penetration depth of draining faults (compare Fig. 3 and Table 1).

CONCLUSIONS

The areas of fluid feeding high temperature hydrogen, nitrogen and carbon dioxide thermal waters lie in the upper mantle, lower crust and upper crust, respectively. The cross section of the zone of deep faults is shown in the diagram (see Fig. 3) in which the axis parts of the fault, comparing to the peripheral ones, one the
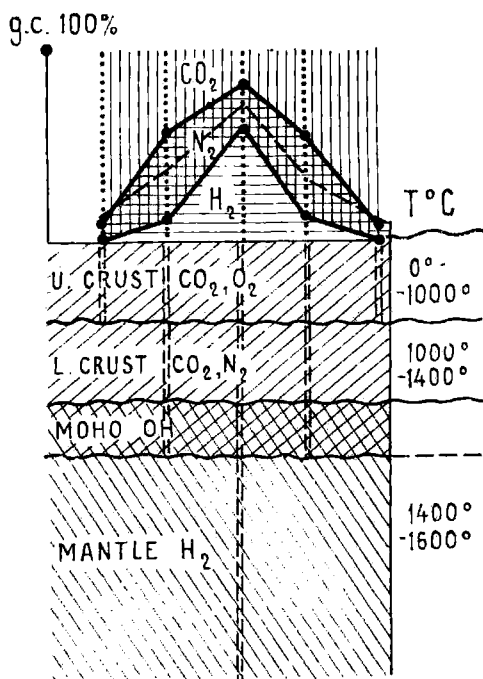

FIG. 3 - Scheme showing gas zoning of the lithosphere, the rate of the deep fault fluid permeability and the correlation of gas constituent in thermal waters.

most permeable.

We can construct a qualitative transformation scheme of the flow of deep materials ascending to the upper crust.

Since the deep faults are originated in the upper mantle (BELOUSSOV, 1976), the intratelluric flows of substances in atomic state (KUZNETSOV and IZOKH, 1969) rising up these faults appear to have the essentially hydrogen composition and hence a large heat capacity. They create the heat anomalies in the upper mantle and upper crust. This is also promoted by exothermic reactions of the water synthesis type. The «Moho» discontinuity, near which hydroxyl-bearing rocks (phlogopitic eclogites and lamprobolitites) appear at first, may be considered as the deepest level of the existence of «hydroxyl» water. Thus, the fluid becomes hydrous somewhere at the discontinuity level, *i.e.* the initial thermal waters emerge there. As fluid rises, it

becomes richer in waters, gases and mineral components released from rocks due to changing of P-T conditions and geochemical environment and due to thermal metamorphism. Finally, the transformed and essentially hydrous fluid penetrates to the water-head systems of infiltration waters thus forming recent hydrothermal systems.

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