Helium and carbon isotopic compositions of hot spring gases in the Tibetan Plateau

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Abstract

The Tibetan Plateau is one of the most active geothermal areas in the Himalayan Geothermal Belt. However, the heat source of the geothermal manifestation is unknown because of a lack of Quaternary volcanoes in this area, except in western Yunnan and northern Tibet. In order to unravel the heat source and the origin of volatile components in hot spring gases in the southern Tibetan plateau, we have measured helium and carbon isotope ratios of hot spring gases from Yangbajain district and some northern sites. The observed helium compositions in the hot spring gases are explained by the mixing of an air component and underground components whose mean end-member $^3He/^4He$ ratio is 0.12 R_{atm} for Yangbajain and 0.22 R_{atm} for the northern sites, respectively. Despite the lack of Quaternary volcanism, such $^3He/^4He$ ratios are an order of magnitude higher than that of stable continental crust (0.02 R_{atm}). These results may imply the existence of intrusive magmas that contain mantle helium in the thick Tibetan crust. The mantle helium with high $^3He/^4He$ ratio may have been diluted to the observed values by radiogenic helium produced in the crust. The observed high $CO_2/^3He$ ratios of the samples (10^{10}–10^{12}) relative to that of MORB (2×10^9) indicate that most carbon dioxide in the samples is derived from crustal materials, such as organic matter and marine carbonate minerals. Regional differences are observed not only in the mean end-member $^3He/^4He$ ratios of the underground components, but also in the $\delta^{13}C(CO_2)$ values of the hot spring gases between Yangbajain (-9.1 to -6.3‰) and the northern sites (-4.3 to -1.0‰). These features suggest heterogeneity among basement rocks. The lower $^3He/^4He$ ratio in Yangbajain may be due to a larger addition of radiogenic ^4He from basement rocks that are enriched with uranium and thorium. The higher $\delta^{13}C(CO_2)$ value of the hot spring gases from the northern sites may be due to the addition of carbon dioxide from underlying sedimentary rocks containing more marine carbonate minerals. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: isotopic composition; hot spring gases; Tibet

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1. Introduction

The Tibet–Yunnan geothermal zone, extending from western Tibet to the Tengchong geothermal field in the Yunnan province of China, is one of the most active geothermal areas in the world that has a variety of hydrothermal phenomena, such as hydrothermal explosions, geysers, fumaroles, boiling springs and hot springs (Kearey and Wei, 1993). However, because of a lack of Quaternary volcanoes in this zone except for the Tengchong field and northern Tibet, the source of the geothermal activity is not well known. Several geophysical studies, including heat-flow measurement studies (Francheteau et al., 1984), seismic analysis (Wei et al., 1981) and magnettelluric studies (Pham et al., 1986), have been performed to solve this problem. The results indicate the existence of partial melting zones in the crust the cause of which remains unclear.

Useful information on the origin of geothermal fluids may be provided by helium isotope ratios (^{3}He/^{4}He, denotes as R) because they vary by more than three orders of magnitude in terrestrial samples. Helium produced by the decay of uranium and thorium in the crust has an extremely low R value of 0.02 R_{atm} (R_{atm} denotes the ^{3}He/^{4}He ratio of air, 1.4×10^{-6}). In contrast, helium from the mantle has a much higher value of 8 ± 1 R_{atm} (Lupton, 1983). Thus, helium has been used for the detection of hidden mantle-derived magma bodies. For example, mantle-derived helium with high ^{3}He/^{4}He ratios of up to 5.2 R_{atm} was found in the Tengchong geothermal field, in the eastern part of the Tibet–Yunnan geothermal belt (Xu et al., 1994). The high ^{3}He/^{4}He ratios are distributed within a circular structure in the center of the geothermal field beneath which the presence of a hidden magma body has been suggested by seismic reflection studies and micro-earthquake observations (Liao and Guo, 1986). On the other hand, geothermal fluids away from the circular structure are found to contain mainly radiogenic helium. These results confirm the existence of a mantle-helium supplying magma body beneath the circular structure. In the European continent, helium isotope studies on natural gases and ground waters (Oxburgh et al., 1986; O'Nions and Oxburgh, 1988) indicate that mantle-derived helium is often detected in areas where no surface volcanism is recognized.

The injection of the mantle component in such cases has been attributed to hidden magma bodies at depth in the crust. In the present study, we attempt to constrain the heat source during the geothermal activities in the Tibetan plateau by measuring helium isotope composition of hot spring gases.

2. Geological setting

The study area is located in the Lhasa Terrane between the Bangong–Nujiang suture and the Indus–Zangpo suture (Fig. 1). The collision that formed the former suture occurred about 140 Ma ago between the Lhasa block and the Qiangtang Terrane (Allègre et al., 1984). The most recent collision between the Indian and the Asian blocks formed the Indus–Zangpo suture. The Indian block has continued to move northward resulting in a shortened and thickened crust. During the Quaternary east–west extension in Tibet formed a large number of north–south trending normal faults (Molnar and Tapponnier, 1978; Tapponnier et al., 1981; Armijo and Tapponnier, 1986). Such faults are most numerous in the Yandong–Gulu graben which has suffered an extension of about 600 km. Many shallow earthquakes occur in the Tibetan Plateau with epicenters clustering along the graben. Numerous hot springs are distributed along the normal faults, which often act as channels for geothermal-fluids movement.

The Yangbajain geothermal field is located in a NE–SW elongated basin bound by the Nyainqentanglha Mountains on the north and the Tanshan Mountains on the south. The floor of the basin is covered by Tertiary moraines and recent alluvial sediments (Hochstein and Yang, 1994). Tertiary granitoids of the Gangdise batholiths related to Tethys subduction comprise the basement in the southeastern part of the area (Kidd et al., 1988). The volcanic and plutonic products have been dated at about 50 Ma (Xu et al., 1985). Inherited lead from zircon in the granitoid and high initial ^{87}Sr/^{86}Sr ratios of the volcanic and plutonic products indicate a crustal contribution to the magma source of the Tertiary magmatism. The Nyainqentanglha Mountains are composed of a granite–gneiss complex with a greater crustal component than the Gangdise plutonic rocks (Harris et al., 1988).
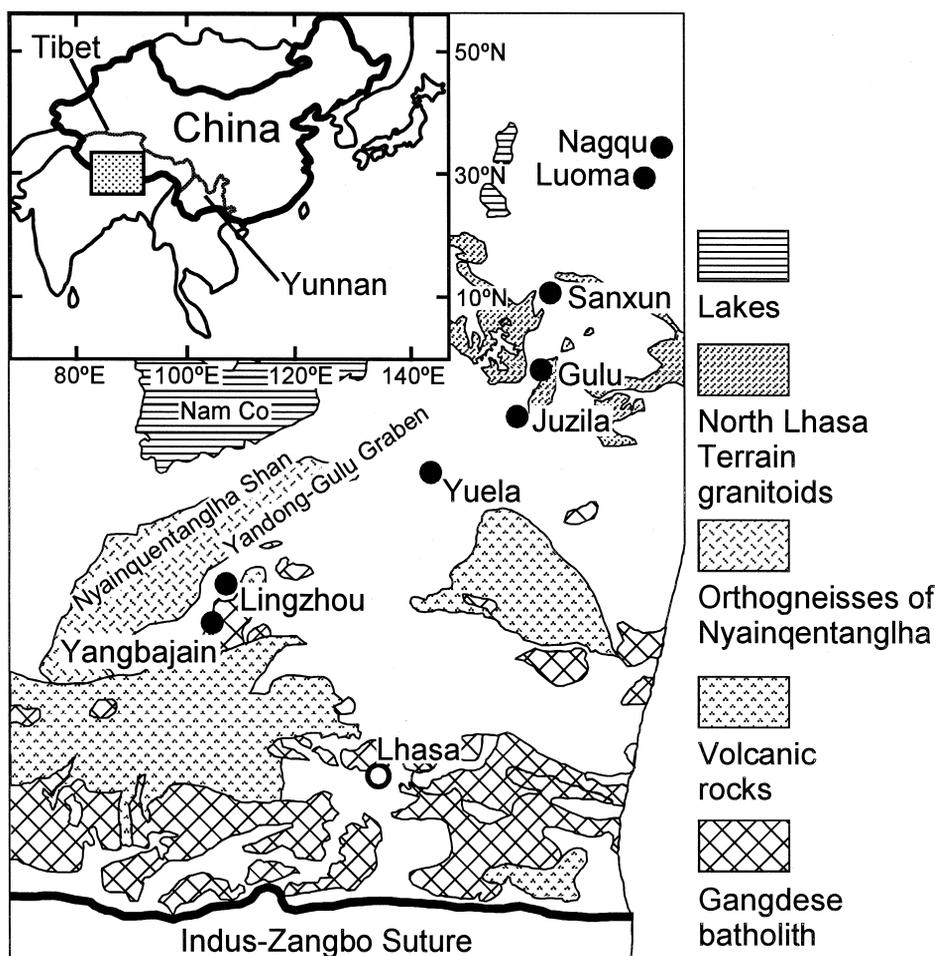
Fig. 1. Location of hot-spring sampling sites (solid circles) and igneous rocks in the Tibetan plateau (after Kidd et al., 1988). The hot springs belong to one of the north–south graben systems formed by extensional stress.

In the northern Lhasa Terrane, where our northernmost sampling sites are located, mid-Cretaceous anatectic granitoids have intruded early Cretaceous to late Jurassic green arenites (Allègre et al., 1984; Kidd et al., 1988).

3. Geochemistry of the hot spring water

Zhang et al. (1981) and Grimaud et al. (1985) reported that hot spring waters in Tibet are generally enriched in boron, arsenic, lithium, rubidium, cesium and fluorine, suggesting an interaction with granitic rocks. The hot spring waters from our sampling sites are rich in these cations as well as in chloride and bicarbonate and have pH values of 7.0 to 8.8, as commonly observed in Tibet (Ministry of Geology and the Comprehensive Scientific Expedition to the Qinghai–Xizang Plateau, 1981). Waters rich in boron and cesium are observed in Yangbajain and Gulu, but not in Yuela, Nagqu and Luoma.

By using the sodium–potassium (T_{NaK}) and magnesium–potassium geothermometers (T_{MgK}) proposed by Giggenbach (1986) and the abundance values of sodium, potassium and magnesium reported by the Ministry of Geology and the Comprehensive Scientific Expedition to the Qinghai–Xizang

Plateau (1981), we found T_{NaK} and T_{MgK} values ranging between 190–290°C and 110–120°C, respectively. These values are comparable to values of 240°C and 180°C reported by Hochstein and Yang (1994) for Yangbajain. According to Hochstein and Yang (1994), the T_{NaK} values reflect fluid temperatures at depths of > 5 km whereas the T_{MgK} values reflect temperatures at shallow depths (< 1 km) in an up flow zone.

4. Analytical methods

Fig. 1 shows sampling sites as well as the distribution of igneous rocks in the Tibetan Plateau (after Kidd et al., 1988). All gas samples were collected in 1991 from hot springs in the central section of a graben system that extends from Yandong to Gulu. A 50-cm^3 lead–glass container equipped with vacuum stopcocks at both ends was used for sampling. To collect a sample the whole sampling system including the container was pre-filled with water, which was then replaced by the gas bubbles.

4.1. Helium isotope measurement

Helium isotopes were measured with a high-precision mass spectrometer connected to an ultra-high vacuum purification line. The basic procedure of $^3He/^4He$ ratio measurements is described by Sano and Wakita (1988) and is outlined below: The sample container was connected to the inlet part of the purification line, into which 0.5 cm^3 of sample gas at STP was introduced. Helium and neon in the sample were extracted from other major components such as nitrogen, carbon dioxide, water vapor, and hydrocarbons by using three charcoal traps cooled at 76 K by liquid nitrogen and two titanium–zirconium getters held at 550°C. After the purification, the $^4He/^{20}Ne$ of the sample was measured by a quadrupole mass spectrometer (QMG112, Balzers), which was calibrated with standard air gas. In some cases, the abundance of helium was also measured with the quadrupole mass spectrometer. To prevent interference, helium was separated from neon by using another charcoal trap held at 40 K with a cryogenic refrigerator. The $^3He/^4He$ ratio of the separated gas was measured with a high-precision static gas mass spectrometer (VG5400, VG Isotope). The $^3He^+$ and $^4He^+$ beams were detected simultaneously with a double collector system. The $^3He/^4He$ ratio of the sample was calibrated against that of the standard air. The uncertainties of $^3He/^4He$ ratio (R/R_{atm}), $^4He/^{20}Ne$ ratio, and helium abundance are 1%, 10% and 10%, respectively.

4.2. Carbon isotope measurement

Carbon isotope compositions were analyzed with a combined gas chromatography–combustion–isotope ratio mass spectrometer (delta S, Finnigan MAT). Components in a sample gas were separated by using a capillary column (Chrompack Pora PLOT Q, 0.32 mm $\times$ 25 m), and then led into a flame ionization detector (FID) and a combustion furnace. The separated carbon-containing compounds were burnt at 850°C in the combustion furnace, which is composed of an electrically heated quartz tube packed with copper oxide particles. The H_2O produced by combustion was removed, while the carbon dioxide was led through the capillary into the ion source of the mass spectrometer. Carbon dioxide of known isotope composition was introduced intermittently into the ion source through another capillary as a reference during intervals between analysis of the separated components. The carbon isotope ratio of a sample is expressed relative to PDB (Pee Dee Belemnite from South Carolina, USA, $R_{PDB} = 0.0112372 \pm 0.0000090$), using the delta notation. The measurement errors for $\delta^{13}C(CO_2)$ and carbon dioxide abundance are 0.24‰ and 3%, respectively.

5. Results and discussion

5.1. Existence of mantle helium

$^3He/^4He$ and $^4He/^{20}Ne$ ratios of 22 samples were analyzed. The results are listed in Table 1 in the order of the sampling sites from south to north, together with 1σ errors of $^3He/^4He$ ratios. Contribution of air helium in each sample was estimated from the $^4He/^{20}Ne$ ratio by assuming that all the neon in the sample was derived from air. Helium concentration was measured in some samples, and

Table 1
Measured chemical parameters of hot spring gases in Tibet

Site	^{3}He/ ^{4}He (R_{atm})	^{4}He/ ^{20}Ne	He_{air} * (%)	He (ppm)	$\delta\,^{13}$C(CO_2) (‰)	CO_2 (%)	CO_2/ ^{3}He ($\times 10^{11}$)
Yangbajain 1	0.135 ± 0.008	57.8	0.6				
Yangbajain 2	0.119 ± 0.004	670	0.0	56	-7.35	102	1.1
Yangbajain 3	0.122 ± 0.004	584	0.1	40	-7.33	100	1.5
Yangbajain 4	0.121 ± 0.003	813	0.0	53	-7.15	93	1.1
Yangbajain 5	0.125 ± 0.002	127	0.3	52	-7.50	84	0.9
Yangbajain 6	0.157 ± 0.005	5.37	5.9		-6.34	39	
Yangbajain 7	0.565 ± 0.009	0.866	37				
Yangbajain 8	0.120 ± 0.005	48.1	0.7		-6.71	97	
Yangbajain 9	0.648 ± 0.006	0.587	54				
Yangbajain 10	0.126 ± 0.003	65.8	0.5		-7.19	92	
Yangbajain 11	0.131 ± 0.005	138	0.2	334	-9.05	69	0.1
Yangbajain 12	0.107 ± 0.005	154	0.2	30	-6.79	95	2.1
Lingzhou	1.08 ± 0.02	0.704	45				
Yuela	0.256 ± 0.005	154	0.2	67	-2.89	97	0.4
Juzila	0.194 ± 0.007	131	0.2	1.7	-4.09	95	21
Gulu 1	0.248 ± 0.003	114	0.3	127	-1.04	90	0.2
Gulu 2	0.252 ± 0.006	104	0.3	17	-2.03	96	1.7
Sanxun	0.170 ± 0.003	32.2	1.0				
Luoma	0.217 ± 0.006	166	0.2	35	-4.33	90	0.9
Nagqu 1	0.380 ± 0.006	2.40	13		-1.99	99	
Nagqu 2	0.240 ± 0.004	30.7	1.0				
Nagqu 3	0.240 ± 0.004	201	0.2	9.5	-2.35	101	3.2
Air	1	0.318					
Error				10%	0.24‰	3%	

$*\,He_{air}$ means contribution of air helium calculated from ^{4}He/^{20}Ne ratio, assuming all the neon was derived from air.

the results are also given in Table 1. Fig. 2 shows the relationship between the measured ^{3}He/^{4}He and ^{4}He/^{20}Ne ratios. Since four samples (marked by cross in Fig. 2) were found to be significantly contaminated by air, they are not further considered in the following discussion. By fitting the ratios with a mixing line between the air component and an underground component which has a ^{4}He/^{20}Ne ratio of infinity, we obtain an estimated ^{3}He/^{4}He ratio for the underground component of 0.12 R_{atm} for Yangbajain and 0.22 R_{atm} for the northern sites.

The above-estimated values are much higher than the generally accepted ^{3}He/^{4}He ratio of about 0.02 R_{atm} for stable continental crust (Lupton, 1983, Mamyrin and Tolstikhin, 1984). They are also higher than the ^{3}He/^{4}He ratios of 0.01 to 0.02 R_{atm} measured for natural gases sampled from over 100 sites in the middle or northwest region of China, where no young volcanism exists (Xu et al., 1995). Thus the underground components of the two sets of samples must contain helium with ^{3}He/^{4}He ratio higher than

typical radiogenic helium ($> 0.22\ R_{atm}$). We discuss below four possible sources for such a high ^{3}He/^{4}He ratio, namely, radiogenic ^{3}He produced by the decay of ^{6}Li, helium in Tertiary basement granite, helium produced by the decay of tritium (^{3}H), and helium from the mantle.

5.1.1. Decay of ^{6}Li

Morrison and Pine (1955) showed that the ^{3}He/^{4}He ratio of radiogenic helium in a rock depends on its lithium content because ^{6}Li can produce ^{3}He by the decay reaction ^{6}Li$(n,\alpha)^3$H$(\beta^-)^3$He. We do not know the lithium contents in the basement rocks in the studied area, but the Li content in various igneous and sedimentary rocks compiled by Moriguti et al. (1993) are < 100 ppm. According to the formula of Gorshkov et al. (1966), the ^{3}He/^{4}He ratio of radiogenic helium in a rock with a lithium content of 100 ppm cannot exceed 0.1 R_{atm}. Thus, it is unlikely that ^{6}Li decay is the source of the underground helium component.
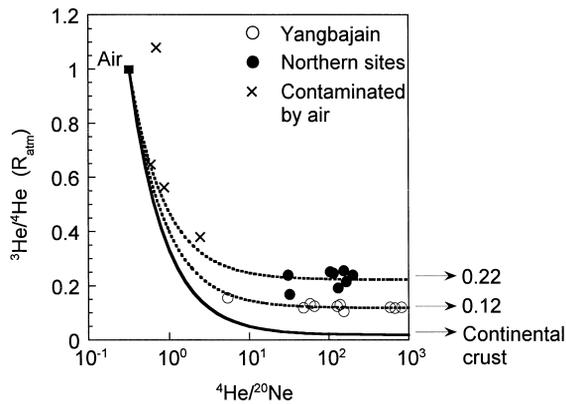
Fig. 2. Relationship between ^{3}He/^{4}He and ^{4}He/^{20}Ne ratios of hot spring gases in Tibet. Open circles are the data of Yangbajain, solid circles are those of the northern sites, whereas the solid square indicates the air component. The two dotted curves depict mixing lines between the air component and an underground component that best fits the data from each region. The solid curve depicts a mixing line between the air component and stable continental crustal component having ^{3}He/^{4}He and ^{4}He/^{20}Ne ratios of 0.02 R_{atm} and infinity, respectively, as defined by Lupton (1983) and Mamyrin and Tolstikhin (1984). Crosses represent samples which have been significantly contaminated by air as judged by their high air helium contributions (> 10%).

5.1.2. Tertiary granite

The Gandise granitoid belt formed by subduction-related plutonism in the Tertiary extends along the southern margin of the Lhasa terrain. Patches of the subduction-related granite distributed near Yangbajain and Paleogene ignimbrite scattered along the Yandong–Gulu graben (Fig. 1) are possible sources of elevated ^{3}He/^{4}He ratios near the studied area. However, since the isotopic features of these rocks indicate a crustal origin (Xu et al., 1985; Harris et al., 1988), it is unlikely that they supplied mantle helium to the hot-spring gas we analyzed. Xu et al. (1994) reported that zircons of the Yangbajain granite and the ignimbrite contain an inherited older Pb component, and concluded that a significant portion of its magmatic protolith was derived from the continental crust. They also analyzed samples from the northern part of the Yandong–Gulu graben, and reported that zircons from the Gulu pluton yielded ages older than those obtained from the Yangbajain granite. Moreover, these zircons also contained an inherited Pb component. Although few Nd and Sr isotopic data are published for samples from the

Lhasa terrain, two samples of the Nyainqentanglha granites show high ^{87}Sr/^{86}Sr of 0.7092 and 0.7158 and negative initial ε_{Nd} of -6.9 and -6.2, indicating an anatectic origin (Harris et al., 1988). Thus the Pb, Nd and Sr isotopic data indicate that the igneous rocks found near the studied area are of crustal origin. In addition, post-crystallization in the rocks must have accumulation of radiogenic ^{4}He produced by the decay of U and Th, which further reduced their ^{3}He/^{4}He ratios, making them even more unsuitable sources of high ^{3}He/^{4}He ratios for the gas. As for the sedimentary rocks, a ^{143}Nd/^{144}Nd ratio of 0.51185 (initial $\varepsilon_{Nd} = -12.2$) was reported for a siltstone from Damxung (Harris et al., 1988) which also precludes the presence of juvenile mantle-derived material in the area. All this evidence makes it unlikely that the granites and sediments contain helium with higher ^{3}He/^{4}He ratio than typical crustal rocks.

5.1.3. Tritium

Another possible source of ^{3}He is the decay of tritium. Man-made tritium due to hydrogen bomb tests reached a peak in 1963. Although we have no data of tritium concentration in Tibetan precipitation in 1963, we can estimate the maximum value from the tritium concentration in hot spring waters, which was found to be lower than our detection limit (< 1 T.U.; a ratio of ^{3}H/H $= 10^{-18}$ is defined as 1 T.U.) in October of 1995. Thus the upper limit of tritium concentration in 1963 is estimated to be less than 3 T.U. If all ^{3}He decayed from the tritium is preserved in ground water without any loss, the ground water should have had a radiogenic ^{3}He concentration of 1.2×10^5 atoms ^{3}He/cm^3 H$_2$O in 1991 when the hot spring gases were collected. Assuming that helium in the gas samples was in equilibrium with hot spring water, the corresponding helium content in waters can be calculated using Henry's Law and the ^{3}He/^{4}He ratio and helium concentration in the gas sample. At the sampling site atmospheric pressure of ~ 0.6 atm, the calculated ^{3}He content is $> 10^6$ atoms ^{3}He/cm^3 H$_2$O, much higher than the maximum tritiogenic helium content of 1.2×10^5 atoms ^{3}He/cm^3 H$_2$O. Thus it is unlikely that tritiogenic helium can account for the observed high ^{3}He/^{4}He ratios.

5.1.4. Mantle-derived helium

From the above discussion, we can conclude that mantle-derived helium is required to explain our data. There are some geophysical data suggesting the intrusion of magma in the thickened Tibetan crust. For example, some Chinese seismograms indicated that the energy of Lg waves passing through the Tibetan Plateau is very low compared with Lg waves not passing through the Tibetan Plateau (Liao, 1981; Wei et al., 1981). This was ascribed to the strong absorption of Lg waves by molten or partially molten material such as igneous rocks intruding the crust which underlies the Tibetan Plateau. Francheteau et al. (1984) reported high heat flow (146 mWm^{-2}), comparable to values found in volcanic areas, in two lakes in the Tibetan Plateau south of the Indus–Zangpo suture. They inferred the existence of a heat anomaly at depths no greater than 25 km, which they attributed to the recent emplacement of plutons. Another heat flow measurement in Nagqu also showed a high value of 319 mWm^{-2} (Shen et al., 1994). In addition, magnettelluric studies by Pham et al. (1986) suggested the presence of some shallow conductive hot zones on both sides of the Tsangpo suture, and estimated the depth of the hot zone at 20–30 km in Yangbajain. These four geophysical observations support the presence of intruded magma in the shallow crust in the studied area.

Existing models which seek to explain the geothermal activities in the area, in terms of heat produced by decay of radioactive elements in the anomalously thickened crust (Molnar et al., 1983) or low thermal conductivity at surface (Jaupart and Provost, 1985), cannot explain the observed high ^{3}He/^{4}He ratios of the hot spring gases. Our results require the injection of helium from the mantle. Thus, we propose that the magma which transports heat in the crust, and whose existence is suggested by the geophysical data, was generated by partial melting at the boundary between the mantle and the lower crust. The magma trapped mantle-helium and carried it along as it rose into the crust along fissures. Due to the thickened nature of the crust, the magma could not, however reach the surface but was instead ponded at relatively shallow depth. The mantle-derived helium, contaminated by radiogenic helium produced in the crust, was released together with other magmatic volatiles and incorporated in the hot spring fluids which transported into the surface.

5.2. Regional differences in helium isotopes

The difference in the mean end-member ^{3}He/^{4}He ratios of the underground components between the Yangbajain and the northern sites (Fig. 2) indicates a difference in the origin of the helium in these two areas. As discussed above, it is likely that intruded magma exists in shallow parts of the crust under the Tibetan Plateau. Helium in these magmas is considered to have high ^{3}He/^{4}He ratio relative to the surrounding crust owing to the existence of the mantle component. The magmas supply volatile components, including helium, to the studied hydrothermal systems. Considering the long distance (200 km) from Yangbajain to Nagqu, it is unlikely that a single magma body supplies heat and mantle-derived helium to the hot springs. Thus the regional difference may result from two or more magma bodies which have different helium isotope ratios owing to differential assimilation of radiogenic helium of crustal origin. Any such differences could have been further enhanced as the hydrothermal fluids containing volatile components from the magma interacted with different basement rocks in the two areas. The basement rocks in Yangbajain are Lower Tertiary granite (Hochstein and Yang, 1994) whereas those in the northern part of Yangbajain, are Middle to Upper Jurassic flysh, limestone, and slates (Allègre et al., 1984; Kidd et al., 1988). The lower ^{3}He/^{4}He ratios at Yangbajain could result from addition of more radiogenic ^{4}He there by interaction with the granites enriched in uranium and thorium. As discussed below such regional difference is also found in carbon isotope ratios.

5.3. Carbon isotope ratios of carbon dioxide

Table 1 shows the measured abundances and carbon isotope compositions of carbon dioxide as well as the corresponding CO_2/^{3}He ratios in 16 samples. As in the helium isotope ratios, a regional difference can be recognized in the carbon isotope compositions. The samples from the Yangbajain area contain lighter carbon than those from the northern sites. The $\delta^{13}C$ values of the carbon dioxide are comparable with mantle values, which range from -5 to -7‰ (Hoefs, 1978). However, the measured values of

$CO_2/^3He$ (more than 10^{10}) are higher than those of MORB (about 2×10^9, Marty and Jambon, 1987), suggesting an insignificant carbon contribution from the mantle. Carbonate minerals formed in the ocean have $\delta^{13}C$ values close to zero. In contrast, organic matter in recent sediment contain light carbon with $\delta^{13}C$ values ranging from -10 to -30‰. Thus our measured $\delta^{13}C$ values can be explained by a combination of groundwater dissolution of marine carbonate minerals and oxidation of organic matter. Sano and Marty (1995) discussed the origin of carbon in fumaroles and hot spring gases in island arcs and showed that the gas composition can be explained by mixing of three components consisting of organic carbon in sediment, marine limestone and MORB. Using Eqs. (1) and (2) of Sano and Marty (1995), we can show that the carbon in Yangbajain samples is a mixture of 30% organic carbon and 70% marine carbonate with a negligible contribution from MORB. In contrast, more than 80% of the carbon in hot spring gases from the northern sites is derived from marine carbonate minerals, with the rest being organic carbon without any MORB contribution. These results are consistent with the observed lithological differences between the Yangbajain and northern sites, for the basement rocks at the northern sites are early Cretaceous to late Jurassic green arenites (Kidd et al., 1988) containing marine carbonate minerals, whereas the Yangbajain area is covered with fluvial sediments (Hochstein and Yang, 1994).

Mook et al. (1974) reported that isotope fractionation of carbon between dissolved CO_2 and gaseous CO_2, and between dissolved CO_2 and HCO_3^- depend on fluid temperature. Although the former fractionation is within 0.8‰ at temperatures higher than 100°C, the latter is strongly affected not only by temperature but also the pH value of the fluid owing to the equilibrium between dissolved CO_2 and HCO_3^-. However, using the ambient fluid temperature and pH values at our sampling sites, the calculated fractionation is < 1.6‰ implying isotope fractionation does not affect our data.

6. Concluding remarks

Helium and carbon isotope compositions of hot spring gases in the Tibetan Plateau were measured to constrain the origin of the hot spring gases. The helium in the gases indicates mixing of air and underground components. The estimated $^3He/^4He$ ratios of the underground components are higher than typical stable continental crustal values indicating a contribution from the mantle.

Both the $^3He/^4He$ ratio and $\delta^{13}C(CO_2)$ data show regional differences, which are attributed to the interaction of surface water with basement rocks which have different bulk compositions. In the case of $^3He/^4He$ ratios, however, it is possible that the regional difference was caused by the differential contamination of mantle-derived magma with radiogenic ^4He derived from different country rocks. The source of carbon dioxide of the hot spring gases may be marine carbonate minerals contained in sedimentary rocks in the northern sites, but is probably largely organic in the sedimentary rocks of Yangbajain.

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