Helium Isotopic Compositions in Quaternary Volcanic Geothermal Area near Indo-Eurasian Collisional Margin at Tengchong, China

Sheng Xu1, Shun’ichi Nakai1, Hiroshi Wakita1, Xianbin Wang2, and Jianfa Chen2

1Laboratory for Earthquake Chemistry, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan
2Lanzhou Institute of Geology, Academia Sinica, Lanzhou, Gansu 730000, China

Abstract. The helium isotope compositions have been determined for gas samples from a Quaternary volcanic geothermal area near the Indo-Eurasian collisional margin at Tengchong, China. The $^{3}$He/$^{4}$He ratios in the range from 0.208 to 5.16 times atmosphere indicate the presence of mantle-derived helium in all the samples. The high $^{3}$He/$^{4}$He ratios were observed to concentrate within a circular structure in the central Tengchong. Hot spring gases away from central part contain mostly radiogenic helium. This distribution pattern of $^{3}$He/$^{4}$He ratios suggests the presence of a magma supplying mantle volatiles beneath the circular structure, which is consistent with a seismic reflection profile study and micro-earthquake observations.

1. Introduction

The Himalayan geothermal belt extends from the southwestern region of Tibet to the western region of Yunnan along the Indo-Eurasian suture zone (Fig. 1). The Tengchong area in western Yunnan is an only geothermal area accompanied by Quaternary volcanism. This area is characterized by topographic features of circular structures clearly apparent in aerial photographs. The structures are considered to be surface manifestations of hidden magma bodies at depth (Liao and Guo, 1986). The most active geothermal areas are distributed around the largest circular structure located to the south of Tengchong town (Fig. 2). Geophysical studies implied that a molten body exists beneath the circular structure (Liao and Guo, 1986; Tong and Zhang, 1989).

In order to reveal the heat source of the geothermal activity, we analyzed helium isotopic composition in hot spring gas. Helium isotopic signature of this area will be briefly compared with other convergent margins such as continent collision and subduction zones.

2. Outline of Geology

The tectonic structures of Tengchong and neighboring area developed in
response to the collision between India and Asia which occurred about 40 m.y. ago (MÖLNAR and TAPPONNIER, 1975). Western Yunnan is the corner where the Indian-Eurasian convergent zone shifts its direction from E-W to N-S. Mountains and tensional faults are ranging in a N-S direction. Many volcanoes and hydrothermal systems are distributed along the main alignment. TAPPONNIER et al. (1982), based on model experiments, have suggested that Indochina and southwestern China have rotated clockwise and have been extruded eastwards (Fig. 1). Prior to collision, a north-dipping subduction zone presumably existed to the south of the crustal segment now carrying the Tengchong volcanics.

The Tengchong area is regionally characterized by large granitic batholiths of Jurassic age (160–180 m.y.), which are host for the volcanic rocks. Rocks older than Jurassic are rare. They include the carboniferous Menghong group, and a small outcrop of Triassic limestone. The total crustal thickness in the Tengchong area is 40–50 km. Volcanism began in Tengchong in the Pliocene (ca. 7 m.y.) when extensional stresses resulted in the formation of downfaulted NS trending basins. The volcanic suite covers an area of about 1000 km² with varied composition such as basalt, dacite, andesite, olivine-basalt, andesite-basalt and pyroxene-basalt, with most lavas being rich in LIL-element, light REE and radiogenic Sr (MU et al., 1987; ZHU et al., 1983). The main series (most voluminous) lava were derived by partial melting of a metasomatized and heterogeneous mantle source, with crustal and possibly seawater components probably related to prior subduction beneath Asia. An
Fig. 2. Map showing the general characteristics of the Tengchong volcanic geothermal area and the distributions of air-corrected $^3\text{He}/^4\text{He}$ ratios of hot spring gases.

andesite-dacite series with similarities to Tibetan calc-alkaline lavas shows clear indications of assimilated crust and crystal fractionation. No evidence for the presence of a strongly depleted subcontinental mantle was observed in Tengchong area (ZHÚ et al., 1983).
Table 1. He results for gas samples from Tengchong volcanic geothermal area, China.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sampling site</th>
<th>Temperature (°C)</th>
<th>$^{3}$He/$^{4}$He (R/Ra)**</th>
<th>$^{4}$He/$^{20}$Ne (R/Ra) **</th>
<th>$^{3}$He/$^{4}$He (R/Ra) **</th>
<th>He (ppm)</th>
<th>M (%)</th>
<th>C (%)</th>
<th>A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hot Sea-1</td>
<td>92.5</td>
<td>2.62±0.03</td>
<td>0.67</td>
<td>4.10</td>
<td>4.3</td>
<td>27</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>Hot Sea-2</td>
<td>76</td>
<td>3.69±0.05</td>
<td>2.0</td>
<td>4.19</td>
<td>3.7</td>
<td>44</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>Hot Sea-3</td>
<td>94</td>
<td>4.17±0.05</td>
<td>21</td>
<td>4.22</td>
<td>67</td>
<td>52</td>
<td>46</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Hot Sea-4</td>
<td>20.9</td>
<td>4.06±0.05</td>
<td>42</td>
<td>4.08</td>
<td>80</td>
<td>51</td>
<td>48</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Hot Sea-5</td>
<td>62.5</td>
<td>4.11±0.05</td>
<td>290</td>
<td>4.11</td>
<td>45</td>
<td>51</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Hot Sea-6</td>
<td>52.4</td>
<td>4.10±0.05</td>
<td>83</td>
<td>4.11</td>
<td>54</td>
<td>51</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Qushi</td>
<td>27.5</td>
<td>2.82±0.09</td>
<td>0.90</td>
<td>3.81</td>
<td>0.30</td>
<td>31</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>Shiqiang-2</td>
<td>19.4</td>
<td>0.454±0.006</td>
<td>46</td>
<td>0.450</td>
<td>67</td>
<td>5</td>
<td>94</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Ruidian-1</td>
<td>90.7</td>
<td>0.772±0.059</td>
<td>0.57</td>
<td>0.484</td>
<td>0.50</td>
<td>3</td>
<td>41</td>
<td>56</td>
</tr>
<tr>
<td>10</td>
<td>Ruidian-2</td>
<td>81.5</td>
<td>0.457±0.007</td>
<td>450</td>
<td>0.456</td>
<td>75</td>
<td>6</td>
<td>94</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>Ruidian-3</td>
<td>54</td>
<td>0.452±0.007</td>
<td>760</td>
<td>0.452</td>
<td>420</td>
<td>5</td>
<td>95</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>Danza</td>
<td>50.5</td>
<td>0.208±0.003</td>
<td>20</td>
<td>0.194</td>
<td>250</td>
<td>2</td>
<td>96</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Sujiang</td>
<td>36.5</td>
<td>0.448±0.006</td>
<td>85</td>
<td>0.446</td>
<td>49</td>
<td>5</td>
<td>95</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>Xiaoshuiba</td>
<td>34</td>
<td>0.340±0.005</td>
<td>160</td>
<td>0.338</td>
<td>1080</td>
<td>4</td>
<td>96</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>Qingkou</td>
<td>44.5</td>
<td>0.485±0.007</td>
<td>26</td>
<td>0.378</td>
<td>350</td>
<td>4</td>
<td>95</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Xiaolaisong</td>
<td>80.3</td>
<td>0.237±0.004</td>
<td>16</td>
<td>0.221</td>
<td>220</td>
<td>2</td>
<td>96</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>Dieshuihe</td>
<td>20.5</td>
<td>5.05±0.06</td>
<td>200</td>
<td>5.05</td>
<td>64</td>
<td>63</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>Heshun</td>
<td>26</td>
<td>5.16±0.05</td>
<td>250</td>
<td>5.17</td>
<td>79</td>
<td>64</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>Longwozhai</td>
<td>80</td>
<td>1.39±0.02</td>
<td>27</td>
<td>1.40</td>
<td>320</td>
<td>17</td>
<td>82</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>Langpu</td>
<td>84.5</td>
<td>3.04±0.04</td>
<td>16</td>
<td>3.08</td>
<td>1.9</td>
<td>38</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>Wubenqiao</td>
<td>29.1</td>
<td>1.73±0.02</td>
<td>3.4</td>
<td>1.81</td>
<td>52</td>
<td>20</td>
<td>71</td>
<td>9</td>
</tr>
<tr>
<td>22</td>
<td>Yongle</td>
<td>36.2</td>
<td>1.18±0.01</td>
<td>4.6</td>
<td>1.19</td>
<td>72</td>
<td>14</td>
<td>79</td>
<td>7</td>
</tr>
<tr>
<td>23</td>
<td>Menglian</td>
<td>44.5</td>
<td>1.31±0.02</td>
<td>2.3</td>
<td>1.36</td>
<td>41</td>
<td>14</td>
<td>72</td>
<td>14</td>
</tr>
<tr>
<td>24</td>
<td>Banglazhang-1</td>
<td>76.4</td>
<td>0.878±0.012</td>
<td>12</td>
<td>0.875</td>
<td>60</td>
<td>9</td>
<td>88</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>Banglazhang-2</td>
<td>94</td>
<td>0.888±0.012</td>
<td>42</td>
<td>0.887</td>
<td>47</td>
<td>11</td>
<td>88</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>Banglazhang-3</td>
<td>26.7</td>
<td>0.872±0.012</td>
<td>50</td>
<td>0.872</td>
<td>140</td>
<td>11</td>
<td>88</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>1</td>
<td>0.32</td>
<td>0.32</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* M, C and A denote percent mantle, crustal and atmospheric helium, respectively, calculated from the model presented by Sano and Wakita (1985).
** R is the $^{3}$He/$^{4}$He ratio of the sample and Ra is the $^{3}$He/$^{4}$He of the atmosphere (1.4×10⁻⁶). Measured values of R/Ra are corrected for atmospheric contamination by assuming that the neon is of atmospheric origin, according to the expression given by Craig et al. (1978): \((\text{R/Ra})_{\text{corr}} = (\text{R/Ra})_{\text{meas}} \times (X - 1) / (X - 1)\), where \(X = (^{4}\text{He}/^{20}\text{Ne})_{\text{sample}} / (^{4}\text{He}/^{20}\text{Ne})_{\text{air}}\).
3. Experiments

Samples were collected in November 1992 and analysed within two months. All samples are gaseous and were collected as bubbles in water pools. Kennedy et al. (1988) pointed out the problem that gas bubbles entering at the bottom of a pool can strip the atmospheric-derived pool gases from the surrounding water while en route to the surface. However, all water pools where the samples were collected for this study were less than 50 cm in depth and samples were collected at the bottom. Thus the mixing problem is negligible. Lead glass containers (50 cm$^3$) with vacuum valves on each end were used. The bubbling gas was introduced into the glass container by the water replacement method. The sampling sites are shown in Fig. 2 and the names and temperatures of waters are listed in Table 1.

The detailed procedure of the helium isotopic ratio measurement has been described by Sano and Wakita (1988). Briefly, the procedure is as follows: a pipette of about 0.5 cm$^3$ STP gas was admitted to a purification line. Helium and neon were purified from other major components such as water, carbon dioxide and nitrogen, using three charcoal traps held at liquid nitrogen temperature and two titanium-zirconium getters held at 550°C. The $^{4}$He/$^{20}$Ne ratio and the helium concentration were measured with a quadrupole mass spectrometer (QMG 112, Balzers), calibrated with air standards. Helium was then separated from neon using another charcoal trap held at 40 K by a cryogenic refrigerator. Helium (with purification checked on the QMS) was introduced into a high-precision mass spectrometer (VG5400, VG Isotopes). The resolving power was about 550 at 5% peak height in order to get a complete separation of the $^{3}$He$^+$ beam from the $^{3}$H$^+$ and HD$^+$ beams. The $^{3}$He and $^{4}$He ion beams were detected simultaneously on a double collector system. Twenty-five measurements of the $^{3}$He/$^{4}$He ratio were conducted for each run, and the ratios were extrapolated to the time of the sample introduction into the mass spectrometer. The $^{3}$He/$^{4}$He ratio was calibrated with the air standard. The uncertainty on the ratio measurement is about 1%, considering statistical error (1-sigma) and reproducibility. Errors for $^{4}$He/$^{20}$Ne ratio and helium concentrations are estimated to be about 10%.

4. Results and Discussions

The observed $^{3}$He/$^{4}$He ($R/Ra$, where $Ra$ denotes atmospheric $^{3}$He/$^{4}$He ratio of $1.4 \times 10^{-6}$) and $^{4}$He/$^{20}$Ne ratios together with the He concentration of the 26 gas samples are listed in Table 1. The $^{3}$He/$^{4}$He and $^{4}$He/$^{20}$Ne ratios of samples range from 0.208$Ra$ to 5.16$Ra$ and from 0.57 to 760, respectively. A wide variation of helium concentrations from 0.30 ppm to 1080 ppm volume was also observed.

The observed $^{3}$He/$^{4}$He ratios of the gas samples are plotted against $^{4}$He/$^{20}$Ne ratios in Fig. 3. There is no simple correlation between $^{3}$He/$^{4}$He and $^{4}$He/$^{20}$Ne ratios. The distribution of all data in this diagram can be generally explained by a three component mixing: mantle-derived He, radiogenic He and atmospheric He. Based on a simple mixing equation presented by Sano and Wakita (1985), it is possible
Fig. 3. Relation between $^3$He/$^4$He (R/Ra) and $^4$He/$^{20}$Ne ratios in Tengchong volcanic geothermal area. A “normal” upper mantle magmatic helium with $^3$He/$^4$He (R/Ra) = 8 and $^4$He/$^{20}$Ne ≥ 1000, and average crustal radiogenic $^3$He/$^4$He (R/Ra) = 0.02 and $^4$He/$^{20}$Ne ≥ 1000 are plotted by following the discussion by Sano and Wakita (1985).

to calculate the fractions of mantle-derived He, radiogenic He and atmospheric He components in each sample. The calculated values are listed in Table 1 and indicate that all samples contain mantle-derived helium from 2% to 64%. Samples near the youngest volcanic areas in the central Tengchong (such as Nos. 1–6, 17 and 18) contain more than 50% mantle-derived helium, whereas others from outside the central Tengchong, independent of surface rock types, are mostly composed of radiogenic helium. It should be pointed out that samples in geothermal fields from Ruidian in the north, with volcanics of similar age and type, present significantly differences in mantle-derived helium.

Based on the assumption that the Ne is of atmospheric origin, measured values of $^3$He/$^4$He ratio can be corrected for atmospheric contamination (Craig et al., 1978) and listed in Table 1. The error of the corrected $^3$He/$^4$He ratios was not significantly different from that of the measured $^3$He/$^4$He ratios except a few samples (Nos. 1, 7 and 9) with $^4$He/$^{20}$Ne < 1. The distribution of air-corrected $^3$He/$^4$He ratios are shown in Fig. 2. The samples with high $^3$He/$^4$He ratio (4.1–5.2Ra) concentrate within the circular structure in the central Tengchong while the samples in geothermal fields away from the central part generally contain helium with low isotopic ratio except one sample in Qushi (No. 7). The corrected $^3$He/$^4$He ratios significantly decrease outside of the central circular structure. The corrected $^3$He/$^4$He ratios of nine samples within 30 km from the site 18, where a sample with the highest $^3$He/$^4$He ratio was collected, decrease with distance following a single trend. Three samples from
granite basement rocks are plotted below the trend (not shown). Such a trend suggests that mantle \(^3\)He leakage through hydrothermal degassing at Tengchong is greater in the central part than towards the margin. The same \(^3\)He/\(^4\)He distribution pattern was observed in many volcanoes, for example, Ontake, Nevado Del Ruiz, Kusatsu-Shirane and Hakone (MARTY et al., 1989; SAKAMOTO et al., 1992; SANO et al., 1984, 1990; WILLIAMS et al., 1987), and magma-based high temperature hydrothermal systems such as Long Valley (WELHAN et al., 1988b). The observed \(^3\)He/\(^4\)He distribution patterns reflect the occurrence of a single source of mantle-derived helium, and the lateral extent of mantle-derived helium seems to be related to the topographies of the volcano. Similarly, the spatial \(^3\)He/\(^4\)He distribution pattern in the Tengchong appears to imply an existence of a single source of mantle helium beneath the circular structure and thus indicates that the geothermal activity in the Tengchong district is a surface manifestation of a hidden magma chamber at depth of the central circular structure. Our helium isotopic results are consistent with the geophysical observation of the presence of a seismic-free zone in the circular structure (LIAO and GUO, 1986). Occurrence of a molten body by a seismic reflection profiling study (TONG and ZHANG, 1989) suggests that a shallow (ca. 7 km) magma chamber exists within the circular structure.

Although the mantle-derived helium component within the central circular structure was mainly derived by direct outgassing of an active magma chamber, rock leaching may represent an important source of mantle-derived helium outside of the circular structure. The sample from Qushi (No. 7) with the corrected \(^3\)He/\(^4\)He ratio of 3.8Ra contains significant mantle component (30%) in spite of its distance from the central circular structure. This spring is located at the rim of the lava flow from a monogenetic volcano, Mt. Heikongshan, one of the youngest craters in this district erupted about 10 ka ago (NAKAI et al., 1993). The high \(^3\)He/\(^4\)He ratio may result from leaching of mantle derived helium trapped in young volcanic rocks. The \(^3\)He/\(^4\)He ratios observed in Banglazhang in southeast where the geothermal fields occur near young volcanic rocks also have been augmented by the fluid-rock interaction.

The \(^3\)He/\(^4\)He ratios of the samples from Dieshuihe (No. 17, 5.05Ra) and Heshun (No. 18, 5.16Ra) within the circular structure, are the highest values (mantle component up to 65%) among the samples from mainland China reported so far. As the sampling in this study covered most of representative geothermal fields, the \(^3\)He/\(^4\)He ratios from this two sites can be considered as the highest value in Tengchong. These ratios are consistent with low values of range (R/Ra = 5–8) for the typical convergent plate margin such as subduction type volcanism (CRAIG et al., 1978; POREDA and CRAIG, 1989; SANO and WAKITA, 1985) and other high-temperature hydrothermal systems in continental plate boundaries (NAGAO et al., 1989; WELHAN et al., 1988a, 1988b), but significantly lower than that of the source for MORB (R/Ra = 8 ± 1, LUPTON, 1983; MAMYRIN and TOLSTIKHIN, 1984).

The observed data from Tengchong can be compared with those from other areas. Helium isotopic study has been carried out for a continent-continent collisional Quaternary volcanic zone in Turkey (NAGAO et al., 1989). The \(^3\)He/\(^4\)He ratio (7.6Ra) as high as that generally found in subduction volcanic areas was observed for a geothermal gas in the Nermut volcano. Basalts which experienced relatively small
extent of the assimilation process from the collision volcanism in East Anatolia have
\(^{143}\text{Nd}/^{144}\text{Nd}\) of more radiogenic than 0.5128 and \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of less radiogenic
than 0.704. The Nd and Sr isotopic signatures of the volcanic rocks indicate the
existence of mantle source similar to that beneath the subduction zone in the isotopic
compositions (PEARCE et al., 1990). In Tengchong area, however, in the course of
the volcanism from the Pliocene, volcanic rocks show a range of Sr and Nd isotopic
ratios (\(^{87}\text{Sr}/^{86}\text{Sr}\) ratios from 0.7059 to 0.7134 and \(^{143}\text{Nd}/^{144}\text{Nd}\) from 0.5120 to 0.5126,
respectively, MU et al., 1987; ZHU et al., 1983). Thus, there is no isotopic evidence
of the existence of the depleted mantle beneath this area. It is probable that the helium
ratios lower than typical subduction volcanic products reflect the difference in
mantle chemistry between the two collisional belts.

5. Concluding Remarks

High \(^{3}\text{He}/^{4}\text{He}\) ratios of the Tengchong volcanic geothermal gases indicate that
maggmatic volatile components dominate within the circular structure in the central
part. In contrast, \(^{3}\text{He}/^{4}\text{He}\) ratios decrease with the distance away from the circular
structure. This distribution pattern of \(^{3}\text{He}/^{4}\text{He}\) ratios reflects the occurrence of a
magma body beneath the circular structure in the central part.

Acknowledgements. We are grateful to Drs. N. Fujii of Nagoya University, X. Xue of
Geological Institute of Yunnan Province, Z. Liao and S. Liu of Peking University and Z. Pang
of Institute of Geology, Academia Sinica for their kind help during field work. We are also
grateful to Drs. K. Notsu, G. Igarashi, J. Ishibashi and T. Tohjima of University of Tokyo for
their useful advice to our study. We also thank an anonymous reviewer for his valuable
comments. This study is supported by a Grant in Aid for International Scientific Research
Program No. 05041053 by the Ministry of Education, Science and Culture, Japan and also
partially by National Natural Science Foundation of China.

REFERENCES

volcanic gases: Hakone, the Marianas, and Mt. Lassen. In Terrestrial Rare Gases (eds. E. C. ALEXANDER Jr.
LIAO Z. and GUO G. (1986) Geology of the Tengchong geothermal field and surrounding area, west
Geol. 76, 25–40.
MOLNAR P. and TAPPONNIER P. (1975) Cenozoic tectonics of Asia: effects of a continental collision.
Science 189, 419–426.
the Tengchong volcanic rocks, west Yunnan province, China. Geothermics 16, 283–297.


