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Helium and carbon isotopic compositions of thermal springs in the earthquake zone of Sichuan, Southwestern China

Jianguo Du[a,b,*], Wanzhen Cheng[c], Youlian Zhang[d], Chunlin Jie[b], Zhijun Guan[c], Wei Liu[b], Liping Bai[b]

[a]*Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China*
[b]*Institute of Earthquake Science, CEA, 63# Fuxing Road, Beijing 100036, China*
[c]*Sichuan Bureau of Seismology, Chendu 610041, China*
[d]*Seismological Press, CEA, Beijing 100081, China*

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Abstract

The origins of gases from hot springs and earthquake activity in the western part of Sichuan Province, Southwestern China, are discussed in terms of helium and carbon isotopes and energy released by earthquakes. $\delta^{13}C$ values of CO_2 in free and dissolved gases range from -3.34 to -17.09‰, and $^3He/^4He$ ratios vary from 1.5×10^{-8} to 3.63×10^{-6}. The isotopic compositions indicate that carbon dioxide from the hot springs is a mixture of crustal and mantle CO_2, and helium is derived from the crust, mantle and atmosphere. The thermal springs in different earthquake and/or fault zones, as well as in different parts of the same zone, have different values of $\delta^{13}C$ and $^3He/^4He$. The more tectonically active the district is, the larger the $\delta^{13}C$ and $^3He/^4He$ values and the greater the frequency of earthquakes. This means that more heat energy is derived from the deep earth with upward migration of anatectic fluids in the active-tectonic district, such as in the Kangding district. Therefore, hot spring gases (He, CO_2 etc.) may be important geochemical markers for determination of seismological and tectonic activity.

Keywords: Helium and carbon isotopes; Earthquake; Active fault; Isotope geochemistry; Hot-spring

1. Introduction

Isotope geochemistry is a major technique for tracing the origins of gases, rocks and geothermal energy. The geochemical behavior of gases depends upon their chemical properties. Inert gases hardly react with other materials during migration, so these gases derived from the deep-earth can provide important information about movement of the crust and mantle. Helium is a sensitive tracer for both fluid migration and gas origins. $^3He/^4He$ ratios in Earth's materials have a range from about 10^{-9} to 10^{-5} (Lupton, 1983). It has been shown that gases of the different origins have different isotopic compositions (Ozima and Podosek, 1983; Mamyrin and Tolstikhin, 1984; Du, 1994; Xu et al., 1998). Most of terrestrial $^3He/^4He$ ratios can be explained in terms of mixing among three end-members: atmospheric helium with a $^3He/^4He$ ratio (R_A) of 1.4×10^{-6}, radiogenic helium (0.01 R_A) and upper mantle helium (8 R_A) (Mamyrin and Tolstikhin, 1984; Kaneoka and Takaoka, 1985; Du, 1989; Ozima, 1994). The characteristics of gases derived from the various tectonic regions are geochemically different (Lupton, 1983; Du et al., 1998).

Helium isotopic ratios are directly correlated with heat flow, because heat flow sources are mainly the crust and mantle. Helium in spring gases is also derived from the crust and mantle (Ozima and Podosek, 1983; Polyak et al., 1985; Du et al., 1998). Therefore, heat flow has a close relationship with active tectonics and earthquakes related to both active faults and geothermal anomalies. For example, heat flow values are lower in tectonic areas that formed in pre-Mesozoic times and are presently not active,

* Corresponding author. Address: 63# Fuxing Road Beijing 100036, China. Tel.: +86 010 88015649; fax: +86 010 68218604.
E-mail addresses: djg001@163.net (J. Du), jianguodu@hotmail.com (J. Du).

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whereas higher heat flow values are measured in presently active tectonic regions in China (Cheng and Gao, 1990); most of the earthquake epicenters occur in geothermal zones worldwide. Many thermal springs and earthquakes of magnitude larger than 6.0 occur in three earthquake zones that extend alongside of three fault zones in the western part of Sichuan Province, Southwestern China (Tang and Han, 1993).

The hot springs are surface expressions of thermal fluids in the lithosphere, and the thermal fluids hold much information about the deep earth. Furthermore, earthquakes are generated in the crust and mantle, and release a lot of energy. It is believed that anatectic fluids play an important role in earthquake generation by reducing friction between the fault blocks and transporting upper mantle energy (Du et al., 1997; Miller et al., 1999; Du, 2000). The geochemical anomalies occur before, during and after earthquakes (Rikitake, 1982; Zhang et al., 1988; Igarashi and Wakita, 1990; Steinitz et al., 1999). Therefore, there must be an intrinsic relationship among the variations of helium and carbon isotopic compositions and temperatures of the hot springs and earthquakes. Consequently, it is possible for us not only to recognize the origins of these gases, but also to look into earthquake activities based on the isotopic geochemistry of helium and carbon. The goal of this paper is to discuss the origins of gases from hot springs in association with seismological and tectonic activity in the western part of Sichuan Province, Southwestern China, in terms of the isotope geochemistry of carbon and helium.

2. Geological setting

There are three large fault zones consisting of many active, deep faults in the Western Sichuan, along which there are three earthquake zones (Fig. 1) and many hot springs representing obvious thermal anomalies. One is called the Lunmengshan fault zone (LFZ) which penetrating the Moho and has a northeast–southwest strike (Tang and Han, 1993). Strata in the fault zone are predominantly Palaeozoic and Lower Mesozoic flysch and carbonate, with some intermediate layers of volcanic rocks. The hot springs are distributed mainly at the northwestern side of the fault zone.

The second fault zone is the Xieshuihe fault zone (XFZ) that can be divided into two parts. The northwestern part is called the Louhuo-Dengke-Qianning fault-zone with a strike of 300–310° in which strata are predominately Triassic metamorphic rocks, granite and some Quaternary sediments in the intermountainous basins. The southeastern part is called the Kangding-Shimian fault-zone, of which the strike turns to 10–30°and rocks are mainly Proterozoic granite, Palaeozoic strata and some Quaternary sediments in the intermountainous basins. The XFZ is characterized as a left-lateral strike-slip thrust with an inclination of 55–80° (Tang and Han, 1993; Li, 1993) and presently experiences strong earthquake activity. There are many hot springs along the fault zone. Its origin can be traced back to the Hercynian (250–405 Ma) with some ultrabasic-basic intrusive bodies along the fault. This fault developed during the Indosinian (205–250 Ma) with intrusive alkali-granite and has been continuously active since then.

The third one is the Anninghe fault zone (AFZ), with a nearly north-south strike, that formed in the Jingninnian (850–1000 Ma) along with large scale intrusion of intermediate-acidic magmas (Tang and Han, 1993). This fault evolved into the fault trough in Hersynian associated with Emei Mountain basalt derived from the upper mantle. The fault was controlled by tensile stresses during the Indosinian and compressional stresses in the Yanshannian (66–205 Ma) when it was associated with granite intrusions. The fault acted intensively to form a graben during the Himalayan tectonic period (<66 Ma), and continues to be active now with intrusion of granitic magma. The AFZ is divided into two branches at the south part (Fig. 1). The eastern branch is called as Zhemuhe fault zone from Xichang to Qiaojia with a length of 140 km (Li, 1993).

3. Sample collection and analysis

Twenty-five samples of spring water and gas were collected from the western part of Sichuan Province in January and October of 2000, and analyzed for isotope compositions of carbon and helium. The sample containers are the 500 ml glass bottles. The spring temperatures range from 14 to 88 °C (Table 1), and the altitudes of the springs are between 600 and 3500 m above sea level. The carbon isotope compositions of carbon dioxide in the samples was measured with a MAT 251 mass spectrograph at the Research Institute of Petroleum Exploration and Development, CSPC in March and December of 2000. The procedure for determining δ^{13}C values involves degassing on a vacuum line, separating and collecting carbon dioxide from the degassed gases by a freezing method, then measuring carbon isotope compositions with the MS. ^{3}He/^{4}He ratios were analyzed with VG5400 MS at the Laboratory Center of the Research Institute of Petroleum Exploration and Development, using an online technique. The sample bottles were connected to the vacuum line through a needle inserted into a rubber stopper in the bottle mouth so as to avoid air contamination. The results of δ^{13}C (PDB) and ^{3}He/^{4}He measurements have errors of 0.1‰ and $<7\%$, respectively.

4. Results and discussion

4.1. He/ ^{4}He and δ^{13}C in springs from the fault zones

Helium isotopic compositions of hot springs in the different fault zones in West Sichuan reveal obvious

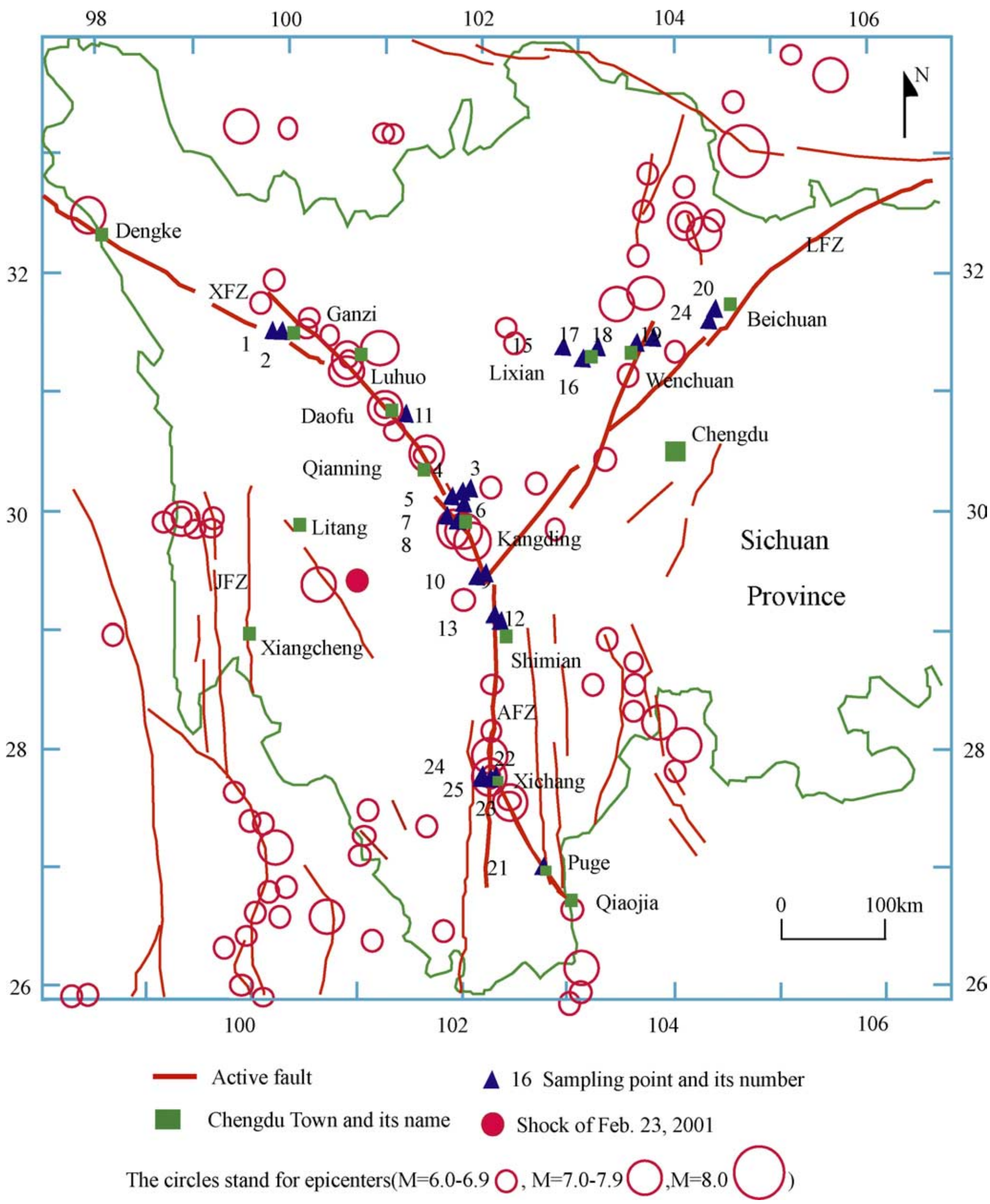

Fig. 1. Diagram of active faults, earthquakes and sample locations in the western part of Sichuan Province.

differences (Table 1). $^3He/^4He$ ratios of thermal springs in three zones of the Xianshuihe (XFZ), Lunmenshan (LFZ) and Anninghe (AFZ) faults range from 0.48 to 2.6R_A, 0.22 to 1.07R_A and 0.01 to 0.82R_A, respectively. Most helium isotopic ratios (up to 2.6R_A) in the Kangding district (XFZ) are larger than those in other areas. The $^3He/^4He$ ratios tend to vary from lower at Ganzi to higher at Kangding, and then lower at Puge along XFZ and AFZ (Fig. 1). It seems that there is no relationship between spring-water temperature and helium isotopic ratios with a correlative factor (γ) of 0.17 due to many factors, such as the supplying volume of surface water, the circling depth of spring water, and the heat supply of the geothermal reservoir. However, the carbon isotopic ratios show a weak positive correlation with temperature ($\gamma = 0.46$). Fig. 2 shows the relationship between helium isotopic ratios and the carbon isotopic composition of CO_2 ($n = 13$, $\gamma = 0.46$), which suggests that both helium and carbon dioxide may have been originally related. The helium isotopic ratios evidently differentiate in the different fault zones and in different parts of the same tectonic zone. The similar phenomena have also been reported in Tibet, China (Zhu, 1993). It was shown that helium in subsurface fluids in different tectonic regions of China's mainland is different. For example, helium in subsurface fluids in the stable tectonic region is predominantly derived from the crust, whereas in active regions it is derived from the mantle (Du et al., 1998; Xu et al., 1998).

The Ganzi-Daofu-Kangding-Shimian fault zone is the main part of XFZ where many large earthquakes have occurred (Fig. 1). There are also many hot springs, a few of

Table 1
Isotope compositions of carbon and helium in spring water and gas from western Sichuan, Southwestern China

Sample			Temp. of water (°C)	$\delta^{13}C_{CO2}$ ‰(PDB)	$^3He/^4He$	
No.	Position	Type			$R(\times 10^{-6})$	R/R_A
Xieshuihe earthquake zone						
1	Radon Observatory, Ganzi	Water	23.5	–	0.84 (6.13)	0.6
2	Well No15, Ganzi	Water	86.6	–	1.35(1.21)	0.96
3	Erdaoqiao, Kangding	Gas	34.8	−4.13	3.63(0.61)	2.59
4	Xingfuqiao, Kangding	Water	29.4	−3.97	1.81(1.63)	1.29
5	Zeduotang, Kangding	Water	60.0	–	1.18(0.56)	0.84
6	Luntougou, Kangding	Gas	72.0	−4.44	2.00(0.67)	1.43
7	Spinnery, Kangding	Water	>50	−6.38	1.33(0.89)	0.95
8	Guanding, Kangding	Water	88	−7.42	1.52(0.70)	1.09
9	Gonghe Moxi, Luding	Water	66.0	−9.95	0.94(1.59)	0.67
10	Erhaoyingdi, Luding	Gas	72.0	−3.34	1.94(0.56)	1.39
11	Lunpugou, Daofu	Water	37.9	−5.69	1.37(1.54)	0.98
12	Cuan-2 Well, Shimian	Water	34.7	–	0.67(0.93)	0.48
13	Lianghekou, Shimian	Water	58.0	−3.54	1.37(0.84)	0.98
Longmengshan earthquake zone						
14	Radon Observatory, Anxian	Water	19.0	–	0.32(2.67)	0.23
15	Guergou, Lixian	Water	62.0	–	0.57(1.38)	0.41
16	Jiasikou, Lixian	Water	42.0	–	1.31(4.44)	0.94
17	Reshuitang, Lixian	Water	31.0	−11.39	0.78(0.97)	0.56
18	Seismostation, Wenchuan	Water	14.0	−17.09	1.50(5.80)	1.07
19	Jiyu, Maoxian	Water	32.8	−8.63	0.05(3.55)	0.04
20	Seismostation, Beichuan	Water	19.0	–	1.17(3.65)	0.84
Anninghe earthquake zone						
21	Puge Hot Spring	Water	44.3	−9.80	0.02(6.40)	0.01
22	Chuanxing, Xichang	Water	41.5	–	0.02(6.53)	0.01
23	Satellite Hotel, Xichang	Water	42.0	–	0.02(6.97)	0.01
24	Taihe-well, Xichang	Water	21.5	–	1.11(0.87)	0.79
25	Z-ZK1-well, Xichang	Water	23.5	–	0.48(1.76)	0.34

– stands for no data because concentration of CO_2 is too low to measure; *n*, unmeasured; the numbers in brackets are errors of $^3He/^4He$ ratios in percent.

which are still active. Three gas and 10 water samples (No. 1–13) were collected in the region (Fig. 1 and Table 1). Temperatures of the hot-springs are generally higher than those in other areas, varying from 23 to 88 °C. The hot springs in the Luhuo-Qianning fault-zone between Ganzi and Kangding have a basement of intrusive granite; most of the springs occur in Proterzoic granite in the Kangding-Shimian fault-zone, but Erdaoqiao (No. 3) and Xinfuqiao (No. 4) springs occur in Paleozoic sedimentary rocks. Carbon dioxide in both dissolved and free gases of the hot springs is enriched in ^{13}C, with $\delta^{13}C$ values of −3.34 to −9.95‰; $^3He/^4He$ ratios are in the range of $(0.67–3.63)\times 10^{-6}$, five of which are higher than the atmospheric value of 1.4×10^{-6} (Table 1). Samples (No. 3–8) of hot springs in the vicinity of Kangding have higher helium isotopic ratios. Water sample No. 12 collected from an artesian well has a lower helium isotope ratio (0.67×10^{-6}) because the aquifer of Proterzoic granite produces helium enriched in ^4He. The carbon dioxide concentration in water sample No. 12 is so low that $\delta^{13}C$ could not be measured.

The collection sites of five water samples (No. 21–25) in Xichang and Puge Counties are located in the AFZ (Fig. 1). The water temperatures range from 21.5 to 44.3 °C. The outcrop in the Xichang-Puge district is predominately Jurassic–Cretaceous strata and Quaternary sediments. Four water samples were collected from wells in the Xichang district, and another from a hot spring in Puge. The concentrations of carbon dioxide in the well waters are too low to analyze for carbon isotopic compositions. The water sample (No. 21) of the hot spring in Puge has a $\delta^{13}C$ value of −9.8‰. $^3He/^4He$ ratios for five samples are in the range from 0.02×10^{-6} to 1.11×10^{-6}, four of which are much less than the atmospheric value, but similar to the crust

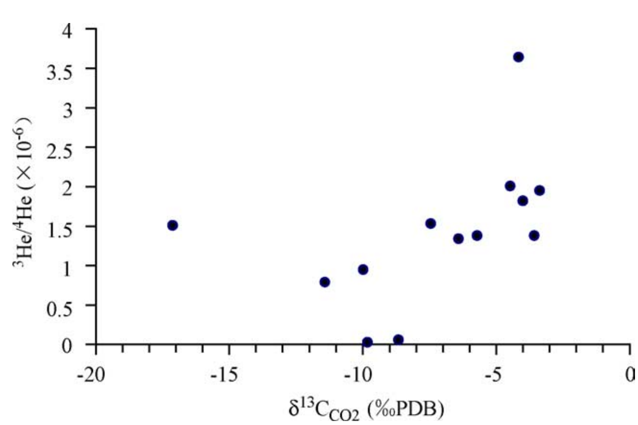

Fig. 2. Correlation diagram for $^3He/^4He$ versus $\delta^{13}C_{CO2}$ in Western Sichuan.

value (Table 1). This indicates that helium in the groundwater is hardly contaminated by atmospheric helium even though the well waters originated from precipitation. The lower water temperatures and helium isotope ratios resulted from the contribution of gases derived from widely distributed granite intruded during the Cenozoic (Li, 1993) and lack gases and heat from the mantle.

Seven water samples (No. 14–20) of springs were collected from the northwestern side of the LFZ where the outcrops are mainly composed of Paleozoic clastic rocks and carbonate rock. Temperatures of the spring are between 14 and 62 °C (Table 1). Carbon in three measured samples is isotopically lighter than those in other districts, with $\delta^{13}C$ values ranging from −17.09 to −8.63‰. $^3He/^4He$ ratios range from 0.05×10^{-6} to 1.50×10^{-6}, one exceeding the atmospheric value.

4.2. Sources of heat and gases in the fault zones

It is widely considered that two kinds of natural helium isotopes (^3He and ^4He) in underground fluids originated from three sources: atmosphere, crust and mantle (Mamyrin and Toltikhin, 1984; Du, 1989). Helium concentrations of free gases in the lithosphere are usually larger than those in the troposphere because helium in the latter escapes into space, resulting in helium concentrations decreasing with altitude. Helium is supplied by degassing of the solid part of the Earth. In addition, the solubility of helium is low. Therefore, helium in deep-earth fluids would not be severely contaminated by atmospheric helium in most cases, but helium in shallower groundwater recharged by meteoric water is partially derived from the atmosphere.

The helium isotopic ratios (0.84–2.59 R_A) in the Kangding district (No. 3–10) that belongs to the southern part of the Xianshuihe fault zone (XFR) are concordant with those (1.05–3.2 R_A) of springs in the Wudalianchi volcanic area of Heilongjiang Province, Northeastern China (Du et al., 1999), and lower than those (2.22–5.12 R_A) in the volcanic active region of Tengchong, Yunnan Province, Sorthwestern China. However, the helium isotopic ratios are higher than those (0.48∼0.67 R_A) in non-volcanic region of Tengchong (Zhu, 1993). It is reported that helium in springs in the volcanic areas of Wudalianchi and Tengchong is partially derived from the upper mantle (Du et al., 1999; Zhu, 1993), while helium in natural gases in the Sichuan basin neighboring the LFZ to west mainly originated from the crust with $^3He/^4He$ ratios about 2×10^{-8} (Xu, 1994). The helium isotopic ratios demonstrate that helium from springs in the Kangding district, where country rock is predominantly Protozoic granite, is partially derived from the mantle and mixed with crustal and atmospheric helium. Abundant thermal springs, deep faults and lack of Cenozoic volcanoes in the XFZ indicate that much of mantle heat is carried to the upper crust by anatectic fluids.

Helium isotopic ratios from springs in Lixian-Beichuan (No. 14–20) in the LFZ, Ganzi in the northwestern part of XFZ (No. 1, 2), Luding (No. 9) and Shimian (No. 12, 13) at the south end of the XFZ, Xichang (No. 22–25) and Puge (No. 21) in the AFZ exhibit helium ratios lower than the atmospheric value with the exception of sample No. 18 in the LFZ (Fig. 1, Table 1). This indicates helium has multiple origins. Helium in spring waters in those regions is predominately derived from the crust and mixes with mantle and atmosphere helium to a small degree. Heat in the thermal field may largely come from the crust also. Sample No. 18, however, has a slightly higher helium ratio (1.07 R_A) because of contributions of atmospheric and mantle helium since the sample was collected from a large, possible active fracture zone in the LFZ.

$\delta^{13}C$ values of CO_2 derived from the deep-earth or magma usually range from −5 to −8‰. CO_2 derived from organic matter has a typical $\delta^{13}C$ value more negative than −20‰ (Hoefs, 1980). Carbon isotopic compositions of carbon dioxide in the gas samples are more positive than in water samples. The distribution of $\delta^{13}C$ values for carbon dioxide in springs are analogous to helium isotopic ratios, i.e. CO_2 in the different tectonic zones has different carbon isotopic ratios (Table 1). $\delta^{13}C$ values of CO_2 in thermal springs along the XFZ are less negative than −7.42‰ with the exception of sample No. 9 (−9.95‰), but CO_2 in hot springs along the LFZ appear more negative (−8.63 to −17.09‰). The $\delta^{13}C$ values of CO_2 in thermal springs along the XFZ are similar to carbon dioxide from the mantle in the Wudalianchi volcanic area (−9.6 to −4.2‰, Du et al., 1998), volcanic carbon dioxide (−7.1 to −3.8‰) in Pantelleria island, Italy, derived from magmatic volatiles (Parello et al., 2000). Griesshaber et al. (1992) reported that carbon dioxide in water at East Eifel, West Eifel, and volcanic regions of Vogelsberg and Kaiserstuhl in Germany has a wider range of $\delta^{13}C$ values (−10 to −4‰), and is derived from the mantle. It can be considered, therefore, that carbon dioxide in springs distributed in the areas of XFZ and AFZ is derived from the upper mantle.

Furthermore, $\delta^{13}C$ values of carbon dioxide in the Kangding district, XFZ, vary from −9.95 to −3.34‰ with a difference of 6.6‰ that might be caused by isotope exchange among CO_2, CO_3^{2-} and CHO_3^- during ground water migration and deposition of carbonate and travertine. Spring waters in the Kangding district chemically belong to the types Na-HCO_3 or CaNa-HCO_3Cl; their PH values have a narrower range of 6.32–7.2, a higher partial pressure of carbon dioxide (Table 2), and $\delta^{13}C$ values of carbonate (3‰) and travertine (0.9–6.9‰) (Liu et al., 2000). The carbon isotopes fractionate between the pairs of CO_2 and CO_3^{2-}, CHO_3^- and CO_2, CO_3^{2-} and CHO_3^- with values of 8.2, 5.5 and 2.6‰, respectively (Emrich et al., 1970).

The carbon isotopic ratios of carbon dioxide in three samples (No. 17, 18, 19) from LFZ vary from −8.63 to −17.09‰. Carbon dioxide in sample No. 17 with a $\delta^{13}C$ value of −11.39‰ would mainly be derived from the upper mantle with mixing of CO_2 from sedimentary organic matter. A water temperature of 31 °C shows that the spring

Table 2
Chemical compositions of some spring waters in Kangding, Sichuan (Liu et al., 2000)

Positions	T/°C	PH	Concentration (mg/L)							$P_{CO2}\times 10^4$ Pa	Chem. type
			K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-		
Guanding	88	7.2	39.8	210.1	198.4	10.3	174	57.6	976.3	1.6	HC
Luntougou	73	7.06	56.6	606.7	68.7	34.3	205	174.9	1521.6	2.6	HN
Zheduotang	60	7.20	66.6	615.9	26.7	5.5	325	25.5	1288.9	1.3	HC
Youyongchi	29	6.40	17.7	120.3	502.9	22.3	39	26.2	1613.3	5.8	H
Erdaoqiao	42	6.32	18.0	122.4	389.2	37.0	198	153.9	1387.6	7.2	H

Notation: HC: HCO_3Cl-CaNa; HN: HCO_3-Na; H: HCO_3-Ca.

water flows through shallower strata. CO_2 in spring water at the Wenchuan Seismostation (No. 18) has a $\delta^{13}C$ value of −17‰, which indicates that the carbon dioxide predominately originated from sedimentary organic matter. The lower temperature (14 °C) of the gravity spring water indicates that it migrates through rocks near the surface so that biogenic carbon dioxide mixes with the spring water. Carbon dioxide in sample No. 19, with a $\delta^{13}C$ value of −8.63‰, would be largely derived from sedimentary rocks because of the crustal signature of helium and distribution of limestone near the spring.

More than 2000 hot springs have been found in China, and most of them occur along fault zones (Huang et al., 1986). The isotopic data of hydrogen and oxygen suggest that most of the hot springs in China originate from meteoric water (Wang et al., 1990; Shangguan, 1995). The depths of the heat reservoirs of the geothermal fields in Southwest China are generally within a range of 3–5 km (Wang et al., 1990). The isotope geochemical data indicate that helium in the studied thermal springs is partially derived from the upper mantle while carbon dioxide originates from the upper mantle and crust. This means that heat for the hot springs are also derived from the deep-earth. Mantle heat can be carried to the upper crust by upward migration of anatectic fluids and then to the surface by spring water.

4.3. The relationship between earthquake activity and isotopic compositions of carbon and helium

At least 515 earthquakes with magnitudes (M) larger than 4.7 on the Richter scale have been recorded in the area of Fig. 1 since 186 BC. One hundred of them have $M\geq 6.0$ and 23 shocks indicate $M\geq 7.0$. At least 9 earthquakes with $M\geq 7.0$ occurred in the Xianshuihe earthquake zone. The zone has a width of 50 km, length of 350 km, and is characterized by the dense distribution of epicenters (Fig. 1). The largest earthquake with a value of $M=7$ 3/4 occurred between Kangding and Moxi, Luding on 1st June, 1786 (Tang and Han, 1993). The most active section of the XFZ with the highest density of epicenters extends from Ganzi to Kangding, along which obvious geothermal anomalies are found (Wang et al., 1990) and larger helium and carbon isotopic ratios are obtained. It is worth mentioning that both the high frequency of strong earthquakes ($M\geq 7.0$) and higher flux of anatectic fluids, characterized by larger $^3He/^4He$ and $\delta^{13}C$ values, are found in the Kangding district in XFZ. Therefore, the Kangding district seems the most probable area where large earthquakes are likely occur (meeting report). This is supported by the occurrence of an earthquake with a magnitude of 6.0 in Richter scale occurred in the Kangding district on February 23, 2001. The epicenter was located at N 29.4°and E101.1° (Fig. 1).

The Anninghe-Zhemuhe earthquake zone extending along the AFZ has a width of 50 km and length of 300 km. Three large earthquakes of $M\geq 7.0$ were recorded along this zone with the largest and most recent one with $M=7$ 1/2 occurring between Xichang and Puge in 1850 A.D. (Tang and Han, 1993). The temperatures (Table 1) of the hot springs and fluxes of helium and carbon dioxide derived from the mantle at Xichang and Puge are lower than those in XFZ, which suggests that earthquake activity in AFZ is not presently very active. The Lunmengshan earthquake zone is characterized by a dense distribution of epicenters at the northwestern side of LFZ (Fig. 1) and has a width of about 70 km and length of 400 km. Five earthquakes of $6.0\leq M\leq 6.5$ occurred along this zone, the largest one being the Wenchuan shock ($M=6$ 1/2) of 1657A.D. (Tang and Han, 1993; Fig. 1).

The earthquake energy is mainly derived from mantle heat, crustal heat and mechanical energy of plate tectonics. Released energy ($\sqrt{E}$) calculated from strain measurements in the XFZ is about 2.5 times ($150\times 10^{10}erg^{1/2}$) that in the AFZ and much larger than in the LFZ (Tang and Han, 1993). The isotopic data of helium and carbon indicate that energy derived from the mantle in the XFZ is more than that in the AFZ and LFZ. It can be considered that helium and carbon dioxide in subterranean fluids may be reliable indicators of earthquake activity in Western Sichuan because hot springs with higher values of $^3He/^4He$ and $\delta^{13}C$ are located in the more active parts of faults where energy released through earthquakes is greater.

5. Conclusions

The $\delta^{13}C$ values of carbon dioxide from hot springs in three earthquake zones of Xianshuihe, Anninghe and

Lunmengshan in Western Sichuan have a range of -3.34 to $-17.09‰$. The $^3He/^4He$ ratios exhibit a wide range from 1.5×10^{-8} to 3.63×10^{-6}. The different earthquake and/or fault zones show different isotopic features of helium and carbon, and different parts of the same zone also differ in terms of isotopic compositions. The $^3He/^4He$ values indicate that helium from hot springs in fault zones of Xianshuihe (XFZ) and Longmengshan (LFZ) is partially derived from the mantle with a mixture of crustal and atmospheric helium. However, helium in the Anninghe fault zone (AFZ) is derived mainly from the crust with mixing of mantle and atmospheric helium. The $\delta^{13}C$ values show that carbon dioxide is predominately derived from the upper mantle except for Wenchuan (No. 18). The hot springs situated along the more active part of faults have higher temperatures. The local geothermal anomalies formed by upward migration of anatectic fluids that, in turn, contribute to the energy released through earthquakes. Our results on helium and carbon isotopes suggest that He and CO_2 in hot springs may be important geochemical markers for seismological and tectonic activity.

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