DOI:10.7524/j.issn.0254-6108.2017.05.2016090604
周晓成, 陈超, 吕超甲,等.首都圈西北部主要活动断裂土壤气中氢气(H_2)地球化学特征[J].环境化学,2017,36(5):977-983.
ZHOU Xiaocheng, CHEN Chao, LYV Chaojia, et al. Gas geochemistry of H_2 in soil gas from the main faults of northwest area of the capital region, China[J].Environmental Chemistry,2017,36(5):977-983.

首都圈西北部主要活动断裂土壤气中氢气(H_2)地球化学特征*

周晓成[1**]　陈　超[2]　吕超甲[1]　孙凤霞[1]　陈　志[1]　仵柯田[1]
黄　丹[1]　张冠亚[1]　张瑞鑫[1]　刘　红[1]　崔月菊[1]

(1. 中国地震局地震预测重点实验室,中国地震局地震预测研究所, 北京, 100036;
2. 四川省地震局康定地震台, 康定, 626000)

摘　要　在首都圈西北部 9 条活动断裂上布置了 17 个土壤气氢气(H_2)测区,土壤气 H_2浓度分别在 2012 年 5 月和 2013 年 5 月测量两次,测点共 1105 个.测量数据结果表明:(1)9 条活动断裂上土壤气 H_2的浓度在断裂附近明显高于非断裂区域;(2)9 条活动断裂上土壤气 H_2的浓度从西向东呈增大的趋势.首都圈西北部活动断裂带土壤气 H_2的释放会引起大气电离层的扰动,有关活动断裂带土壤气 H_2释放的进一步研究对大气环境变化研究有重要的意义.

关键词　氢气, 断裂, 土壤气, 地球化学, 首都圈.

Gas geochemistry of H_2 in soil gas from the main faults of northwest area of the capital region, China

ZHOU Xiaocheng[1**]　*CHEN Chao*[2]　*LYV Chaojia*[1]　*SUN Fengxia*[1]　*CHEN Zhi*[1]
WU Ketian[1]　*HUANG Dan*[1]　*ZHANG Guanya*[1]　*ZHANG Ruixin*[1]　*LIU Hong*[1]　*CUI Yueju*[1]

(1. CEA Key Laboratory of Earthquake Prediction (Institute of Earthquake Science), China Earthquake Administration, Beijing, 100036, China; 2. Kangding Seismic Station, Sichuan Earthquake Administration, Kangding, 626000, China)

Abstract: H_2 in soil gas was measured twice in seventeen sites in the nine faults in the northwest area of the capital region, China, in May 2012 and May 2013. The results indicated that the H_2 concentrations in the soil gas from the nine faults had obvious anomalies. The H_2 concentrations in soil gas increased from west to east in the nine faults in northwest of capital region. The release of H_2 from faults would impact the ionosphere. It is very significant to carry on further study on the release of H_2 from faults and its impact on atmospheric environment.

Keywords: hydrogen, fault, soil gas, geochemistry, capital region.

氢在自然界中分布很广,水便是氢的“仓库”——氢在水中的质量分数为 11%,泥土中约有 1.5%的氢,石油、天然气、动植物体也含氢.在空气中,氢气倒不多,约占总体积的一千万分之五.在整个宇宙中,

2016 年 9 月 6 日收稿(Received: September 6, 2016).

* 中国地震局地震预测研究所基本科研业务费(2014IES010202,2014IES0402,2012IES0408,2016IES010103)和国家自然科学基金(41673106)资助

Supported by the National Science and Technology Support Program CEA Key Laboratory of Earthquake Prediction (2014IES010202, 2014IES0402,2012IES0408,2016IES010103) and the National Natural Science Foundation of China (41673106)

* * 通讯联系人, E-mail:zhouxiaocheng188@163.com

Corresponding author, E-mail:zhouxiaocheng188@163.com

按原子百分数来说,氢却是最多的元素.据研究,在太阳的大气中,按原子百分数计算,氢占 81.75%.在宇宙空间中,氢原子的数目比其他所有元素原子的总和约大 100 倍[1-2].

地球内部炽热高温与固态地表之间存在巨大的热力梯度,地球内部各种物理化学场的变化,板块块体之间的相互作用都不断驱使地下气体从各种通道逸散.地壳大部分地区,地球的脱气是以小规摸,低速度的形式进行的,而在地壳的某些薄弱部位,如洋脊、火山、活动断裂带等[3-5],脱气是非常强烈的.目前,基本一致地认为活动断裂带深部脱气过程含有大量的二氧化碳、水蒸气及少量的烃类气体、氮气、氢气和稀有气体等.环境灾害效应是当代大陆动力学研究的重要课题之一,其中地球排气作用的研究已经为人们所关注[6-10].

H_2浓度变化与断裂的活动性有密切的关系[11-13].在加拿大一个喷气口 H_2的释放通量是 42 $\mu g \cdot m^{-2} \cdot h^{-1}$[14].在汶川地震后,延汶川地震破裂带释放大量的氢气[15-17].我国对地球排气作用, 特别是对氢气逸出与自然灾害关系的研究还处于初始阶段,特别是地震活动断裂带的脱气[17].

本文通过研究活动断裂带内 H_2的浓度时空变化特征,探讨地球内部向大气释放 H_2影响因素和环境效应.

1 实验部分(Experimental section)

1.1 地质概况

研究区处于北西向的张家口-蓬莱活动构造带西部和北东向山西断陷带北端.张家口-蓬莱断裂带是我国华北地块一条规模巨大的 NWW 向活动断裂带[18-20].该断裂带西起张家口附近,向东南经北京、天津、渤海、山东半岛北缘,过威海到达黄海海域,总长度达 700 km 以上[21-22].研究区内发育多组断裂,主要有 NNE、NE、NNW、NW 和近 EW 向断裂.NE 向活动断裂是区内最活动的主干断裂,其规模较大,一般长度都在几十至百余千米;其次是与之近于正交的 NW 向活动断裂,其断续分布,地表出露规模比 NE 及 NNE 向断裂小;近 EW 向断裂发育规模不大.区内 NW 向断层与 NNE、NE 向主干断裂相互错切,控制了延矾、怀涿、蔚广、阳原、灵丘、怀安、张家口等多个活动断陷盆地的形成[23-32].这些盆地呈斜列式展布,走向 NEE,多数为单地堑盆地,盆地之间均以隆起相隔.经过长期的构造发展演化,这些盆地与多组不同规模的断裂系统构成了区内特有的盆岭构造特征.盆地平原区海拔 480—1000 m 不等,周围山地海拔 1000—2870 m[33].

1.2 测点布置

在首都圈西北部 9 条活动断裂上布置了 17 个土壤气 H_2测区,土壤气 H_2浓度分别在 2012 年 5 月和 2013 年 5 月测量两次,测点共 1105 个.17 个土壤气 H_2测量剖面被划分为 2 个区域,分别是山西地震带北端和张-渤地震带西段.山西地震带北段内的土壤气 H_2剖面编号顺序按从南向北顺序排列,张-渤地震带西部内土壤气 H_2剖面编号按从西向东的顺序排列(图 1、表 1).

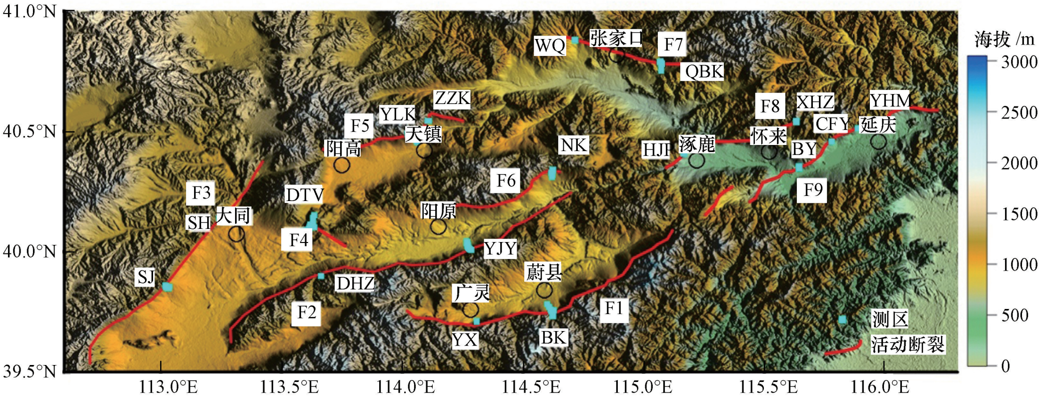

图 1 首都圈西北部主要活动断裂带土壤气 H_2浓度测区分布

Fig.1 Distribution of the testing sites for the Hydrogen concentration in soil gas from the main faults in the northwest area of capital region

表 1　首都圈西北部主要断裂带土壤气 H_2 测区位置和采样时间

Table 1　Location and sampling time of H_2 concentration in soil gas from the main faults in the northwest area of capital region

测区号 Number	经度(度) Longitude	纬度(度) Latitude	采样区名称 Surveyed area	点编号 No.	断裂名称 Fault name	断裂号 Fault number	采样时间和点数 2012 年	2013 年
1	114.30946	39.71033	宜兴庄	YX	蔚县广灵断裂	F1	32	32
2	114.62463	39.73928	北口	BK	蔚县广灵断裂	F1	43	32
3	113.66411	39.89839	东后子口	DHZ	六棱山断裂	F2	32	32
4	114.28321	40.00822	阎家窑	YJY	六棱山断裂	F2	46	32
5	113.01900	39.85852	石井村	SJ	口泉断裂	F3	39	32
6	113.24270	40.13674	上皇庄	SH	口泉断裂	F3	32	32
7	113.62041	40.10783	大同火山	DTV	大同火山断裂	F4	48	32
8	114.01864	40.48906	榆林口	YLK	阳高天镇断裂	F5	39	32
9	114.10827	40.54350	张仲口	ZZK	阳高天镇断裂	F5	32	32
10	114.62183	40.34035	南口	NK	阳原盆地北缘断裂	F6	32	32
11	114.71552	40.87952	万全	WQ	张家口断裂	F7	32	32
12	115.06876	40.78824	青边口	QBK	张家口断裂	F7	40	32
13	115.63497	40.53806	西洪站	XHZ	怀来涿鹿断裂	F8	35	37
14	115.16601	40.40770	郝家坡	HJP	怀来涿鹿断裂	F8	32	32
15	115.88783	40.51389	玉皇庙	YHM	延庆矾山断裂	F9	32	32
16	115.72476	40.41039	蚕房营	CFY	延庆矾山断裂	F9		37
17	115.65576	40.35878	八营	BY	延庆矾山断裂	F9	36	

2012 年 5 月和 2013 年 5 月的两次测量,每一个测区布置 4 条测线,每条测线垂直断裂陡坎走向,每条测线 8 个测点,测线间距 10 m,测点间距 20 m[17].为了获得每条断裂的背景浓度,在每条断裂上布置一条加长测线,测线的测点间距随着离开断裂位置不断加大(图 2).

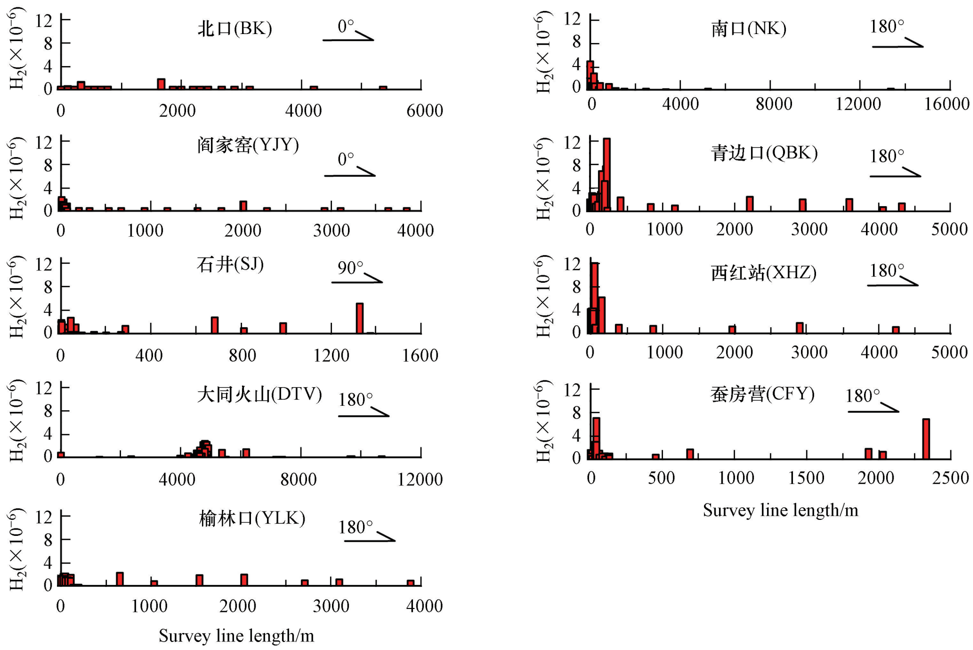

图 2　首都圈西北部主要活动断裂带以及附近区域的土壤气 H_2 浓度空间变化

Fig.2　Spatial variation of H_2 concentration from soil gas from the main faults and nearby regions in northwest of capital region

1.3　测量方法

野外现场测量断裂带土壤气中的 H_2 浓度.野外采样是在测点处打孔,深度约 80 cm,将取样器置于孔内,封住孔口,然后,用抽气泵抽气,用 250 mL 取样针管扎进硅胶管路,现场取样,取样针孔是侧针孔.

现场使用便携式 Agilent Mrco 3000 气相色谱测量 H_2的浓度,使用进样针现场直接进样测量.H_2的检测限是 1 mg·L^{-1},误差小于 5%[16].

2 结果与讨论(Results and discussion)

2.1 断裂带土壤气 H_2浓度异常的主要影响因素

在 2012 年 5 月和 2013 年 5 月,两次测量总共获得 1105 个土壤气中 H_2浓度数据(表 1),土壤气中 H_2的浓度值范围是 0.5×10^{-6}—68×10^{-6},平均值是 1.8×10^{-6}(表 2).空气中 H_2的浓度一般在 0.5×10^{-6}左右[1],土壤气中大部分 H_2的浓度高于空气的浓度.利用 Q-Q 图法划定土壤气中 H_2的异常[34],H_2的浓度异常界定为 4×10^{-6}(图 3).

表 2 土壤气中氢气统计

Table 2 Statistics of H_2 concentration in soil gas

采样时间(年/月)	测点数/个	平均值($\times10^{-6}$)	均方差($\times10^{-6}$)	最小值($\times10^{-6}$)	最大值($\times10^{-6}$)
2012/5	582	1.5	4.6	0.5	68.0
2013/5	523	2.4	4.2	0.5	67.4
总体数据	1105	1.8	4.4	0.5	68.0

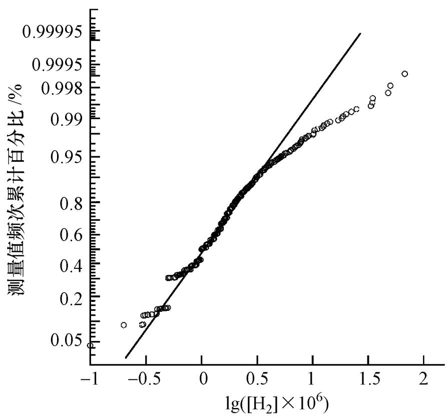

图 3 土壤气 H_2浓度异常界划定

Fig.3 Abnormal threshold of H_2 concentration

从首都圈主要断裂的土壤气 H_2的浓度长剖面(图 2)可以看出土壤气 H_2的浓度异常主要集中在断裂带附近;从首都圈主要断裂的 17 个测区土壤气 H_2的异常浓度分布图可以看出,土壤气 H_2的浓度异常主要集中在断裂附近 50 m 范围内(图 4).首都圈西北部主要断裂的土壤气 H_2的浓度异常特征与活动断裂内部构造和裂隙发育程度有密切关系.活动断裂带内孔隙度发育,离活动断裂带越远,孔隙度越低[35].断裂带的氢气主要有以下几个来源,H_2作为深源气体,地球在形成时,地球内部就储存有大量的 H_2,这些 H_2会延着地球的薄弱地带逸散到大气中[36].在岩石中 U 和 Th 元素在放射性衰减过程中与水产生高浓度氢气[37].橄榄石蛇纹石化过程中产生大量氢气[38];断裂破裂新鲜岩石面产生氢气[39-40].活动断裂带活动性越强,断裂带内硅酸岩新鲜破裂面越发育,产生的 H_2越多[40-42].土壤有机质在厌氧细菌发酵过程中产生氢气[43].

首都圈西北部主要断裂的土壤气 H_2的每个测区浓度从西向东有增大的趋势,每个测区的土壤气浓度平均值和最大值从西向东有增大的趋势(图 5).2012 年和 2013 年测量都有这些特征.这与区域断裂活动强度有很大的联系.华北地区地壳运动速率的整体分布呈现由东向西逐渐减小、自北向南逐渐增大的特点[44].

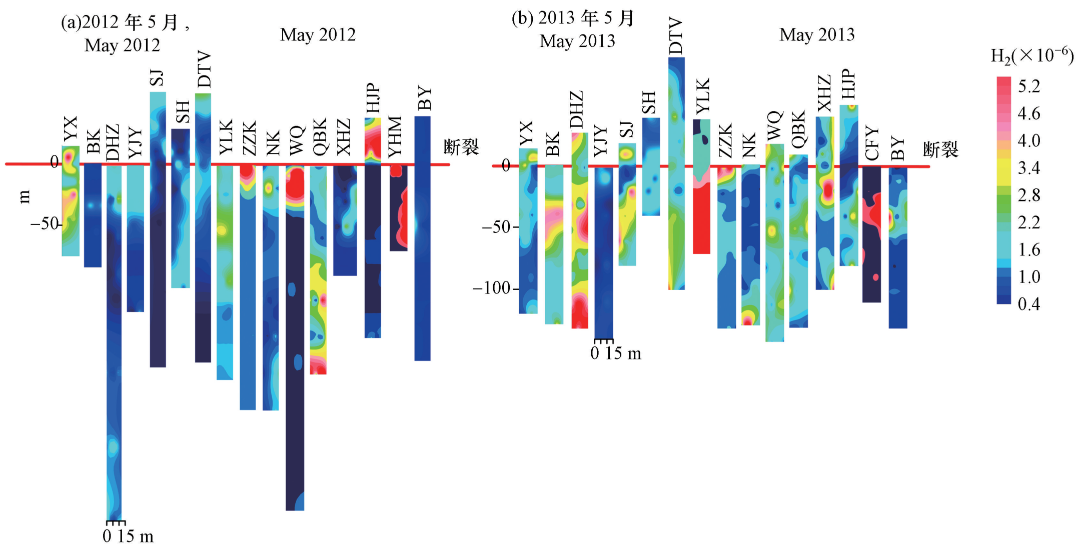

图 4　首都圈西北部主要活动断裂带土壤气 H_2浓度空间变化

Fig.4　Spatial distribution of H_2 concentration in soil gas in soil gas in the main faults in northwest of capital region

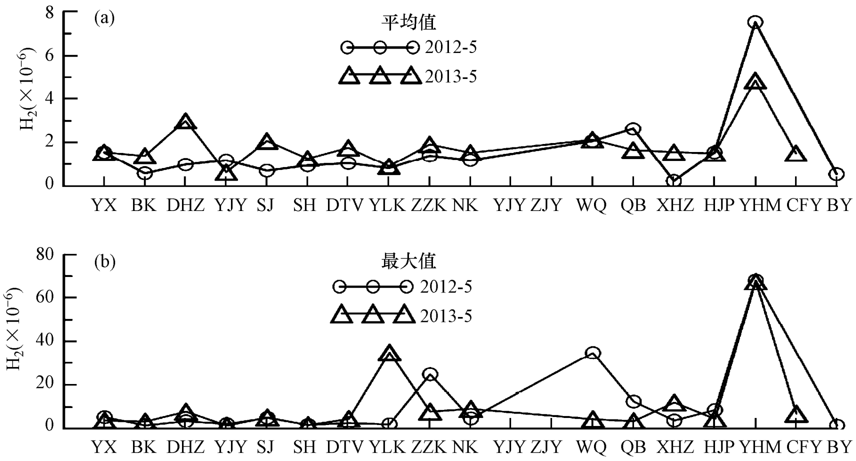

图 5　土壤气 H_2浓度平均值和最大值空间分布

Fig.5　Average and Maximum concentration of H_2 in soil gas

2.2　断裂带土壤气中 H_2释放的环境效应

氢气虽然不是温室气体,但是,氢气能破坏大气臭氧层,所以,被认为是间接温室气体[45-47].大地震后,活动断裂短时间内会以很高的强度释放 H_2,在汶川 *Ms* 8.0 地震后,地震破裂带内,土壤气浓度最高达到 279.4×10^{-6}[16].断裂带土壤气中 H_2释放后能在较大空间范围内扩散,大量消耗大气电离层的电子,形成一定尺度的电离层“空洞”;释放化学物质的量越多,电子密度的扰动幅度越大;相同量的 H_2在电离层峰值高度处释放后,白天电子密度的扰动幅度要大于夜间的扰动幅度.H_2在不同高度处释放对电子数密度的影响是不同的,一般释放中心处的电子密度相对变化率最大,而最大的相对变化率并不是在峰值处释放时出现的,但电离层临界频率的最大相对变化率是在电子密度峰值高度处释放时出现的[48-49].在许多大地震发生前都发现震中大区域范围内电磁场和大气电离层异常变化,这些现象与氢气的产生的机理和释放过程有重要的联系[50].

3　结论(Conclusion)

(1)首都圈西北部 9 条活动断裂上土壤气 H_2的浓度在断裂附近明显高于非断裂区域.

(2)首都圈西北部9条活动断裂上土壤气 H_2的浓度从西向东呈增大的趋势.

首都圈西北部活动断裂活动断裂带土壤气 H_2的释放会引起大气电离层的扰动,活动断裂带土壤气 H_2的释放进一步的研究对大气环境变化研究有重要的意义.

参考文献(References)

[1] NOVELLI P C, LANG P M, MASARIE K A, et al. Molecular hydrogen in the troposphere: Global distribution and budget[J]. Journal of Geophysical Research, 1999, 104:30427-30444.

[2] LIBERT M, BILDSTEIN O, ESNAULT L, et al. Molecular hydrogen: An abundant energy source for bacterial activity in nuclear waste repositories [J]. Physics and Chemistry of the Earth, 2011, 36:1616-1623.

[3] WARE R H, ROECKEN C, WYSS M. The detection and interpretation of hydrogen in fault gases[J]. Pure and Applied Geophysics, 1984,122(2):392-402.

[4] SHANGGUAN Z, HUO W. δD values of escaped H_2 from hot springs at the Tengchong Rehai geothermal area and its origin [J]. Chinese Science Bulletin, 2002, 47(2):148-150.

[5] MAYHEW L E, ELLISON E T, MCCOLLOM T M, et al. Hydrogen generation from low-temperature water-rock reactions[J]. Nature geoscience, 2013, 6: 577-584.

[6] 杜乐天.地球排气作用的重大意义及研究进展[J].地质论评, 2005,51(2):174-180.
DU L. Significance of Earth Degassing and Its Research Progress [J]. Geological Review, 2005, 51(2):174-180 (in Chinese).

[7] 车用太,刘耀炜,何鑷.断层带土壤气中 H_2观测-探索地震短临预报的新途径[J].地震,2015,35(4):1-10.
CHE Y T, LIU Y W, HE L. Hydrogen monitoring in fault zone soil gas-A new approach to short/immediate earthquake prediction[J]. Earthquake, 2015, 35(4):1-10 (in Chinese).

[8] 周晓成,王传远,柴炽章,等. 海原断裂带东南段土壤气体地球化学特征研究[J]. 地震地质, 2011,33(1):123-132.
ZHOU X, WANG C, CHAI Z, et al. The geochemical characteristics of soil gas in the southeastern part of Haiyuan fault[J]. Seismology and Geology, 2011, 33(1):123-132 (in Chinese).

[9] 周晓成,柴炽章,雷启云,等.银川隐伏断层带土壤气中 H_2地球化学特征[J].物探与化探,2013, 37(1):147-149.
ZHOU X, CHAI C, LEI Q, et al. Geochemical characteristics of H_2 in soil gas of Yinchuan buried fault belt [J]. Geophysical and Geochemical Exploration, 2013, 37(1):147-149 (in Chinese).

[10] WIERBERG T, ERZINGER J. On the origin and spatial distribution of gas at seismogenic depths of the San Andreas Fault from drill mud gas analysis [J]. Applied Geochemistry, 2008, 23:1675-1690.

[11] WAKITA H, NAKAMURA Y, KITA I, et al. Hydrogen release: New indicator of fault activity [J]. Science, 1980, 210:188-190.

[12] SUGISAKI R, IDO M, TAKEDA H, et al. Origin of hydrogen and carbon dioxide in fault gases and its relation to fault activity[J]. Journal of Geology, 1983,91(3):239-258.

[13] 邵济安, 赵谊, 张福松, 等.黑龙江省中西部地球排气与地震活动的探讨[J].岩石学报, 2010, 26(12): 3651-3656.
SHAO J A, ZHAO Y, ZHANG F S, et al. Discussions on earth degassing and seismic activities in central west Heilongjiang Province[J]. Acta Petrologica Sinica, 2010, 26(12):3651-3656 (in Chinese).

[14] POISSANT L,CONSTANT P, PLOTE M, et al. The ebullition of hydrogen, carbon monoxide, methane, carbon dioxide and total gaseous mercury from the Cornwall Area of Concern [J]. Science of the Total Environment, 2007,381:256-262.

[15] 周晓成,杜建国,陈志,等.地震地球化学研究进展[J]. 矿物岩石地球化学通报, 2012,31(4):15-18.
ZHOU X, DU J, CHEN Z, et al. Advance review of seismic geochemistry[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2012, 31(4):340-346 (in Chinese).

[16] ZHOU X, DU J, CHEN Z, et al. Geochemistry of soil gas in the seismic fault zone produced by the Wenchuan *Ms* 8.0 earthquake, southwestern China [J]. Geochemical Transactions,2010,11:5. doi:10.1186/1467-4866-11-5.

[17] ZHOU X, CHEN Z, CUI Y. Environmental impact of CO_2, Rn, Hg degassing from the rupture zones produced by Wenchuan *Ms* 8.0 earthquake in western Sichuan, China[J]. Environmental Geochemistry and Health, 2016, 38:1067-1082.

[18] FU Z, LIU J, LIU G. On the long-term seismic hazard analysis in the Zhangjiakou-Penglai seismotectonic zone, China [J]. Tectonophysics, 2004,390:75-83.

[19] GUO L, LI S, SUO Y, et al. Experimental study and active tectonics on the Zhangjiakou-Penglai fault zone across North China [J]. Journal of Asian Earth Sciences, 2015,114:18-27.

[20] SHI W, CEN M, CHEN L, et al. Evolution of the late Cenozoic tectonic stress regime in the Shanxi Rift, central North China Plate inferred from new fault kinematic analysis [J]. Journal of Asian Earth Sciences, 2015,114:54-72.

[21] 李西双,刘保华,华清峰,等.张家口-蓬莱断裂带渤海段晚第四纪活动特征[J].海洋科学进展,2009,27(3).332-347.
Li S X, LIU B H,HUA Q F, et al. Characters of the Zhangjiakou-Penglai Fault Zone Activity in the Bohai Sea Since Late Quaternary[J]. Advances in Marine Science, 2009, 27(3):332-347 (in Chinese).

[22] 徐杰,马宗晋,陈国光,等.中国大陆东部新构造期北西向断裂带的初步探讨[J].地学前缘,2003,10(Z1):193-198.
XU J, MA Z J, CHEN G G, et al. NW Trending active fault zones of the eastern Chinese continent in neo tectonic time[J]. Earth Science Fronties (China University of Geosciences, Beijing), 2003, 10(Z1):193-198 (in Chinese).

[23] 程绍平,杨桂枝,杨喆.延庆盆地北缘断裂带蚕房营段晚更新世晚期断层作用[J].地震地质, 1994,16(4):346-354.
CHENG S P, YANG G Z, YANG Z. The latest Pleistocene faulting along the Canfangying segment of the fault zone along the northern margin of Yanqing Basin[J]. Seismolgy and Geology, 1994,16(4):346-354 (in Chinese).

[24] 段瑞涛,方仲景.六棱山北麓断裂新活动特征[J].地震地质,1995,17(3):207-213.
DUAN R, FANG Z. Neotectonic Characteristics of the northern piedmont fault of the Liuleng mountain[J]. Seismolgy and Geology, 1995, 17(3):207-213 (in Chinese).

[25] 冉勇康.我国几个典型地点的古地震细研究和大地震重复行为探讨[D].北京:中国地震局地质研究所学位论文,1997.

RAN K. Detailed research of paleoearthquakes at several typical regions in China and exploration of recurrence behavior of large earthquakes [D]. Beijing:Institute of Geology, China Earthquake Administration, 1997 (in Chinese).

[26] LI Y L, YANG J C, XIA Z K, et al. Tectonic geomorphology in the Shanxi Graben System, northern China[J]. Geomorphology, 1998, 23:77-89.

[27] PAVLIDES S B, ZOUROS N C, FANG Z J, et al. Geometry, kinematics and morphotectonics of the Yanqing-Huailai active faults (Northern China) [J]. Tectonophysics, 1999, 308:99-118.

[28] 徐锡伟,吴卫民,张先康,等.首都圈地区地壳最新构造变动与地震[M].北京:科学出版社.2002.
XU X W,WU W M,ZHANG X K,et al. Neotectonic Movements and Seismology in the Crust of the Capital Region[M]. Beijing, Science Press, 2002 (in Chinese).

[29] 谢富仁,张红艳,崔效锋,等.延怀盆地活动断裂运动与现代构造应力场[J].地震地质,2007,29(4):693-305.
XIE F R, ZHANG H Y, CUI X F, et al. Active fault movement and recent tectonic stress field in Yanhuai basin[J]. Seismolgy and Geology, 2007,29(4):693-305 (in Chinese).

[30] 周月玲,尤惠川.张家口断裂第四纪构造变形与活动性研究[J].震灾防御技术, 2010,5(2):157-166.
Zhou Y L, YOU H C. Research on Quaternary Deformation and Activities of Zhangjiakou Fault, Hebei Province[J]. Technology for Earthquake Disaster Prevention, 2010,5(2):157-166 (in Chinese).

[31] 徐伟,刘旭东,张世民.口泉断裂中段晚第四纪以来断错地貌及滑动速率确定[J]. 地震地质, 2011, 33(2):335-346.
XU W, LIU X D, ZHANG S M. Late quaternary faulted landforms and determination of slip rates of the middle part of Kouquan fault[J]. Seismolgy and Geology, 2011, 33(2):335-346 (in Chinese).

[32] 王林, 田勤俭, 李德文, 等. 京西北蔚县-广灵半地堑盆地南缘断裂带的断层生长研究[J]. 地震地质, 2011, 33(4): 828-838.
WANG L, TIAN Q J, LI D W, et al. the growth of the south margin fault of the Yuxuan-Guangling basin in Northwest Beijing area[J]. Seismolgy and Geology, 2011, 33(4): 828-838 (in Chinese).

[33] 索艳慧,李三忠,刘鑫,等.中国东部 NWW 向活动断裂带构造特征:以张家口-蓬莱断裂带为例[J].岩石学报, 2013, 29(3): 953-966.
SUO Y H, LI S Z, LIU X, et al. Structural characteristics of NWW-trending active fault zones in East China: A case study of the Zhangjiakou-Penglai Fault Zone[J]. Acta Petrologica Sinica, 2013, 29(3):953-966 (in Chinese).

[34] CIOTOLI G, LOMBARDI S, ANNUNIATELLIS A. Geostatistical analysis of soil gas data in a high seismic intermontane basin: Fucino Plain, Central Italy [J]. Journal of Geophysical Research, 2007,112:B05407.

[35] EVANS J P, FORSTER C B, GODDARD J V. Permeability of fault-related rocks, and implication for hydraulic structure of fault zones [J]. Journal of Structural Geology, 1997,19:1393-1404.

[36] HERNÁNDEZ P, PÉREZ N, SALAZAR J, et al. Soil gas CO_2, CH_4 and H_2 distribution in and around Las Cañadas caldera, Tenerife, Canary Islands, Spain[J]. Journal of Volcanology and Geothermal Research, 2000,103:425-438.

[37] LIN L, HALL J, LIPPMANN-PIPKE J, et al. Radiolytic H_2 in continental crust: Nuclear power for deep subsurface microbial communities [J]. Geochemistry Geophysics Geosystems, 2005, 6(7): 1-13.

[38] KATAYAMA I, KUROSAKI I, HIRAUCHI K. Low silica activity for hydrogen generation during serpentinization: An example of natural serpentinites in the Mineoka ophiolite complex, central Japan [J]. Earth and Planetary Science Letters, 2010, 298:199-204.

[39] KAMEDA J, SARUWATARI K, TANAKA H. H_2 generation in wet grinding of granite and single-crystal powders and implications for H_2 concentration on active faults [J]. Geophysical Research Letters, 2003, 30(20):2063.

[40] KAMEDA J, SARUWATARI K, TANAKA H. H_2 generation by dry grinding of kaolinite [J]. Journal of Colloid and Interface Science, 2004, 275:225-228.

[41] KITA I, MATSUO S, WAKITA H. H_2 generation by reaction between H_2O and crushed rock: An experimental study on H_2 degassing from the active fault zone [J]. Journal of Geophysical Research, 1982, 87(B13): 10789-10795.

[42] KITA I, MATSUO S, WAKITA H, et al. D/H ratios of H_2 in soil gases as an indicator of fault movements [J]. Geochemical Journal, 1980,14: 317-320.

[43] LIBERT M, BILDSTEIN O, ESNAULT L, et al. Molecular hydrogen: An abundant energy source for bacterial activity in nuclear waste repositories [J]. Physics and Chemistry of the Earth, 2011, 36:1616-1623.

[44] 胡勐乾,邓志辉,陆远忠,等.三维数值模拟在华北地区现今构造变形分析中的应用[J]. 地震地质, 2014, 36(1): 148-165.
HU M Q, DENG Z H, LU Y Z, et al. Contemporary tectonic deformation in north China by using three-dimensional simulation[J]. Seismolgy and Geology, 2014, 36(1): 148-165 (in Chinese).

[45] EHHALT D H. Gas phase chemistry of the troposphere, in Global Aspects of Atmospheric Chemistry, edited by R. Sellner [M]. New York, Springer, 1999, 21-109.

[46] HAUGLUSTAINE D A, EHHALT D H. A three-dimensional model of molecular hydrogen in the troposphere [J]. Journal of Geophysical Research, 2002,107:(D17):ACH4-1—ACH4-16.

[47] WARWICK N J, BEKKI S, NISBET E G, et al. Impact of a hydrogen economy on the stratosphere and troposphere studied in a 2-D model [J]. Geophysical Research Letters, 2004,31(5):325-341.

[48] 汪四成,方涵先,杨升高,等.H_2释放扰动电离层的数值模拟[J].大气科学学报,2013,36(4):499-503.
Wang S C, FANG H X, YANG S G, et al. Numerical simulation of ionoshperic modification by release[J].Transactions of Atmospheric Sciences, 2013,36(4):499-503 (in Chinese).

[49] 闫雨龙,温彦平,冯新宇,等.太原市城区臭氧变化特征及影响因素[J].环境化学,2016,35(11):2261-2268.
YAN Y L,WEN Y P,FENG X Y,et al. Variation and the influence factors of ozone in urban area in Taiyuan[J].Environmental Chemistry, 2016,35(11):2261-2268(in Chinese).

[50] FREUND F. Pre-earthquake signals: Underlying physical processes[J]. Journal of Asian Earth Sciences, 2011, 41:383-400.