

咸阳地区某典型地热井的地热水地球化学特征分析

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摘要: 地球化学方法是了解地热系统特点、变化及起源的重要手段, 合理开发利用地热资源的前提。基于咸阳地热田 XY1 地热井 1999 年与 2017 年两期水质资料、多年水温变化资料, 参考其他学者在研究区取得的研究成果, 综合分析了该热水井及区域地热流体地球化学因子的变化特征。根据地热水 δD 、 $\delta^{18}O$ 、 ^{14}C 同位素分析, 探讨了该地区地热水的起源及其同位素水文特征。结果表明: 该热水井水温变化不大, 水-岩平衡状态未改变, 大部分离子组分浓度呈上升趋势, 水质变差。水化学类型未改变, 为 Cl-Na 型, 其中多种水化学组分浓度达到一定标准, 可作为医疗热矿水开发利用。研究区热储层以消耗静态储量为主, 无现代降水补给。该井地下热水属于第四纪末次冰期北山山区海拔 1200 m 大气降水入渗成因, 为混入古溶滤水的残存沉积水。建议生产过程中应采取地热水回灌措施, 使地热资源开发具有可持续性。

关键词: 咸阳地热田; 地热水; 同位素; 水化学特征

Analysis of geochemical characteristics of the geothermal water in a typical geothermal well in Xianyang area

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Abstract: *Background, aim, and scope* Geothermal water resources are the products of the interaction between geothermal energy, groundwater and rocks and minerals, and can be used as a heat source, water source and mineral resources, which is a new type of green energy. Geothermal water resources have obvious advantages in relieving energy pressure, adjusting energy structure and improving environmental quality, but they are not inexhaustible. The distribution of geothermal wells in urban areas of Xianyang is dense, and the amount of geothermal water extraction is large, but the long-term extraction of geothermal heat has caused the supply of

收稿日期: 2020-03-04; 录用日期: 2020-05-20; 网络出版: 2020-06-02

Received Date: 2020-03-04; Accepted Date: 2020-05-20; Online first: 2020-06-02

基金项目: 黄土与第四纪地质国家重点实验室开放基金 (SKLLQG1933); 中央高校基本科研业务费资助项目 (自然科学类) (300102298203); 陕西省自然科学基金基础研究计划资助项目 (2017JM4018)

Foundation Item: Open Fund of the State Key Laboratory of Loess and Quaternary Geology (SKLLQG1933); Fundamental Research Funds for the Central Universities (Natural Sciences) (300102298203); Natural Science Basic Research Program of Shaanxi (2017JM4018)

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引用格式: 邓若兰, 杨银科, 李强, 等. 2020. 咸阳地区某典型地热井的地热水地球化学特征分析 [J]. 地球环境学报, 11(5): 546–553.

Citation: Deng R L, Yang Y K, Li Q, et al. 2020. Analysis of geochemical characteristics of the geothermal water in a typical geothermal well in Xianyang area [J]. Journal of Earth Environment, 11(5): 546–553.

groundwater with lower temperature or high-temperature thermal fluid at depth, thus causing changes in the chemical characteristics of geothermal fluid. The study of geothermal well hot water geothermal system changes and causal characteristics has become an inevitable requirement for the efficient and reasonable use of geothermal water resources in Xianyang region. **Materials and methods** In this paper, the sampling site was selected as 185 coalfield geological team (34°22'N, 180°44'E), Zhouling Township, Weicheng District, Xianyang City, Shaanxi Province. In 1999 and 2017, water chemistry samples were collected in the region to collect hot water samples. In this paper, the water quality data of 1999 and 2017 and the data of multi-year water temperature changes were integrated, and the research results of other scholars in the research area were taken into consideration to study the change trend of the chemical composition, water temperature and water-rock balance of geothermal water. In addition, the characteristics of geochemical factors of the hot water well and regional geothermal fluid were also comprehensively analyzed. According to the research and analysis of δD , $\delta^{18}O$, ^{14}C isotopes of geothermal water, the origin of geothermal water and its isotopic hydrological characteristics in this region are revealed and discussed. It is hoped that this paper will provide scientific basis for the efficient utilization, management and protection of geothermal resources in this region as well as the prospect of geothermal industry development. **Results** According to the stable hydrogen and oxygen isotopes, the geothermal water supply elevation was calculated to be 1200 m. From the ^{14}C test age of 20251 a, it can be seen that XY1 well geothermal water belongs to the cause of precipitation infiltration in Beishan Mountain Area in the last glacial period of the Quaternary. Well XY1 was mainly used to exploit the thermal reservoir of Bahe formation in Lantian, with no change in the chemical type of geothermal water and the dynamic of water-rock equilibrium, and little change in water temperature. There was no shallow low temperature water supply in the thermal reservoir, nor deep high temperature water supply. **Discussion** Based on the correlation between $\delta^{18}O$ and δD values in the geothermal water of the well and the chemical composition of the groundwater, it can be inferred that the thermal reservoir fluid is the residual sedimentary water mixed with the ancient lixiviation water. The analysis showed that the renewable capacity of groundwater hot water in this region is relatively poor. With the consumption of static reserves as the main factor, the water level in this area decreased greatly, forming a descending funnel, which leads to the depletion of underground hot water resources and the deterioration of water quality. Geothermal wells without treatment of direct discharge will inevitably produce more serious thermal pollution of the urban environment, and the harmful chemicals contained in underground hot water can also pollute the water environment, soil environment and air environment. Therefore, it is necessary to strengthen the protection of the environment and the safety of drinking water sources during its discharge. It can only be discharged after the treatment has reached the standard, and measures such as geothermal water recharge can be taken. **Conclusions** The thermal reservoir in the study area mainly consumes static reserves without modern precipitation supply. The geothermal water in the well belongs to the cause of 1200 m atmospheric precipitation infiltration in the Beishan Mountain Area during the late Quaternary glacial period, which is the residual sedimentary water mixed with the ancient lixiviation water. In order to promote the experimental study of geothermal recharge, measures of geothermal water recharge should be taken in the production process. **Recommendations and perspectives** (1) It is necessary to further strengthen resource exploration and evaluation, and constantly revise and improve plans for the development and utilization of geothermal resources. (2) It is recommended that research be carried out on the development of medical thermal mineral water and its medical, health care and wellness effects. (3) The dynamic automatic monitoring and control system of geothermal mining can be established and improved to strengthen the chemical monitoring of geothermal fluid to understand the changes of geothermal system and strengthen management to make the development of geothermal resources sustainable.

Key words: geothermal field of Xianyang City; geothermal water; isotopes; hydrochemical characteristics

地热水资源是地热能、地下水与岩石矿物相互作用的产物,可以作为热源、水源和矿物资源利用,是一种新型绿色能源 (Chen et al, 2016; 朱红玉等, 2018)。虽然地热水资源在缓解能源压力和改善环境质量等方面优势明显,但是地热水并不是取之不尽、用之不竭的。地热的长期开采会引起温度较低的地下水或深部高温地热流体的越流补给,从而使其化学特征发生变化。地球化学方法是了解地球壳层各带中地下水特点、变化、形成与起源的重要手段。马致远等 (2018) 基于关中盆地地质构造情况,应用同位素水文地球化学方法对该地区不同构造下的地热水中重氧同位素富集原因进行分析。Kouadra et al (2019) 将地球化学和统计方法相结合,对阿尔及利亚东北部康斯坦丁地区的地热水进行了水文地球化学研究。Guo et al (2019) 根据西藏南部地热水水化学数据,分析了西藏南部地热水中砷含量过高的原因。Apollaro et al (2019) 采用新的地质、水文地球化学和同位素数据的多学科方法研究了意大利加拉特罗和安东尼米纳地热区的热水和冷水的起源。林韵等 (2020) 分析了广东江门地区的地热水水文地球化学特征,并探讨了该地区的地热水循环过程。前人将地球化学方法与多学科、新技术相结合开展了一系列卓有成效的研究工作,使地球化学方法在研究地热水方面不断发展。

咸阳城区地热井分布密集,地热水开采量大,存在的环境问题较为突出。研究该地区地热资源开发利用现状及存在的典型环境问题具有一定的实践价值,是高效合理利用地热水资源的必然需求。因此,本文利用地球化学方法,基于咸阳地热田某地热井两期水质测试、同位素和多年水温变化资料研究了地热水的化学成分、水温、水-岩平衡的变化趋势,并分析了同位素特征,为该地区地热资源的合理开发和保护,以及地热相关产业发展的前景等方面提供科学依据。

1 材料与方法

1.1 咸阳地热田概况

咸阳地热田是关中盆地地热田的一部分,位于关中盆地中部。本区主要构造断裂是渭河断裂,属隐伏性深大断裂,呈近东西向展布,断面南倾,倾角 70° 左右。此断裂为热水的形成提供了重要的通道和热源条件,并将咸阳地热田分为两个次级构造单元,北为咸礼凸起,南为西安凹陷 (图 1)。热储主要蕴藏于新生界沉积层中,其岩性主要为砂

岩、砂砾岩与泥岩互层。其中黏土岩 (泥岩、砂质泥岩) 因其导热性差,可作为隔水层和隔热保温层;砂岩、砂砾岩单层厚度大,其中孔隙和裂隙发育,是地下热水储存和运移的最佳场所。地热田地层自上而下大致分为:秦川群、三门组、张家坡组、蓝田灞河组、高陵群组 (李婷, 2012)。咸阳地热田热源主要为上地幔热能传导,其次,放射性元素衰变、黏土矿物蒙脱石向伊利石转化、生物降解等过程产生也产生了一部分热能。

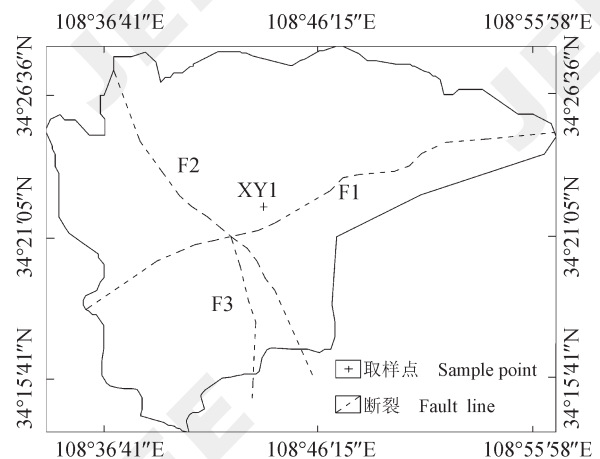


图 1 咸阳城区地质构造及井位图 (F1: 渭河断裂; F2: 长安—咸阳断裂; F3: 沔河西岸断裂)
Fig.1 Geological structure and well location map of Xianyang urban area (F1: Weihe River fault; F2: Chang'an—Xianyang fault; F3: west shore of Fenghe River fault)

根据咸阳市 1999 年开采的 XY1 地热井资料,该地热井位于咸礼凸起南部,地热井深度为 2000 m,开采地热水主要用于洗浴和冬季供暖,取水水源为蓝田灞河组热储层地热水。本井自上而下依次钻遇位于新生界的四个地层,其中蓝田灞河组未穿透,按照由新到老的顺序对本井地层特征分述如表 1。从表中可以看出,地温是随深度的增加而逐渐增高。

1.2 取样与测试

取样地点为咸阳市渭城区周陵乡陕西省 185 煤田地质队生活区内 ($34^\circ22'N$, $108^\circ44'E$),分别于 1999 年与 2017 年 12 月在区域内采集热水水样。所有水样采集于 500 mL 聚乙烯瓶中,在采样前,用蒸馏水清洗采样瓶 3 次,水样装满整个取样瓶,为防止瓶中有气泡产生,装样后要立即用蜡密封瓶口。水化学样品是在陕西省工程勘察研究院水土检测中心测试, $\delta^{18}O$ 、 δD 、 ^{14}C 及 2017 年

之前的水温数据引自其他学者在该地区的研究结果(穆根胥等, 2016; Ma et al, 2017)。

2 结果与分析

2.1 同位素特征

地下水中的 δD 与 $\delta^{18}O$ 值组成可以判断地下水的补给, 反映补给水的同位素特征, 作为地下水来源的判定依据(焦杏春, 2016)。图2中GMWL(Craig, 1961)为全球大气降水线($\delta D=8\delta^{18}O+10$), LMWL(王兴和李王成,

2018)为西安地区的降水线($\delta D=7.5\delta^{18}O+6.1$)。利用氕盈余 $d=\delta D-8\delta^{18}O$ 来表征热水点偏离大气降水线的程度(Dansgaard, 1964)。从图2可以看出, 该井同位素数据落在大气降水线右下方, 氕盈余 d 为34.1‰, 偏离程度较大, δD 较低, 氧漂移显著, 说明赋存环境较封闭, 水-岩反映强烈。同位素点接近沉积水范围线, 另外 δD 与 $\delta^{18}O$ 的特点符合古溶滤水或沉积成因的特征。根据 ^{14}C 测定结果 $^{14}C=20251$ a, 此时正值第四纪末次冰期, 气候寒冷。

表1 地层分层数据表
Tab.1 Stratum stratification data

地层层位 Stratigraphic position	底界深度 Bottom boundary depth/m	厚度 Thickness/m	平均地温梯度 Average geothermal gradient /($^{\circ}C \cdot (100 m)^{-1}$)	平均地温 Average ground temperature / $^{\circ}C$
三门组(Q_{1s}) Sanmen formation	710.8	256.3	2.96	44.0
张家坡组(N_{2z}) Zhangjiapo formation	1390.0	679.2	3.26	62.0
蓝田灞河组(N_{2l+b}) Lantian Bahe formation	2000.0	610.5	3.62	89.2

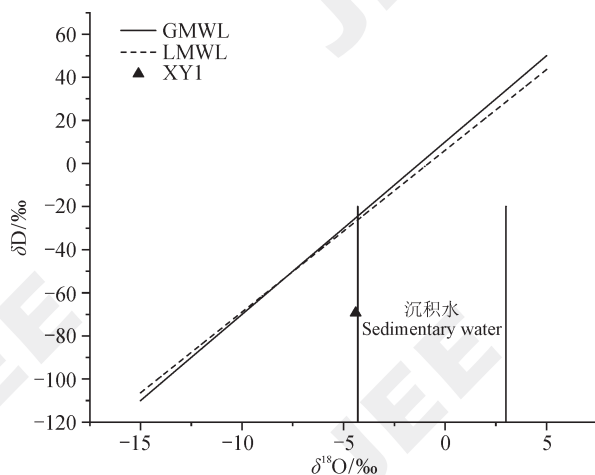


图2 研究区地下热水 $\delta D-\delta^{18}O$ 关系

Fig.2 Relationship between δD and $\delta^{18}O$ of geothermal water in the study area

降水中的 δD 与 $\delta^{18}O$ 受高程效应影响, 因此根据式(1)确定地下热水补给区的高程(Zhang et al, 2013; 李修成等, 2016):

$$H=h+(\delta G-\delta P)/K_H \quad (1)$$

式中: H 为补给区标高(m); h 为取样地区标高(m); δG 为热水中的 δD 值(‰); δP 为取样点附近大气降水的 δD 值(‰); K 为同位素高度

梯度($\text{‰} \cdot (100 m)^{-1}$)。

其中取样地标高约为400 m, δP 取关中地区大气降水 δD 平均值 -45‰ , δG 为 -69.3‰ , K 约为 $-2.5 \text{‰} \cdot (100 m)^{-1} - 2.0 \text{‰} \cdot (100 m)^{-1}$, 取 $-2.1 \text{‰} \cdot (100 m)^{-1}$, 经计算该地热井地下热水的补给高程约1200 m, 西北方向是咸阳城区地热水流动通畅方向及补水方向(李婷, 2012), 其西北方向为北山山系。结合 ^{14}C 测试年龄结果可以推断出研究区地下热水属于第四纪末次冰期北山山区海拔1200 m大气降水入渗成因。罗璐等(2019)与马致远等(2008)研究表明, 关中盆地地热水补给源是大气降水, 咸阳地热水补给来源为北山山区700 m以上高处, 西安地热水源自秦岭1510 m以上高处, 与本文同位素研究结果相符。

2.2 温度动态

温度是计算热储能和评价地热资源最重要的参数。图3为XY1地热井多年水温变化趋势, 自1999年成井以来, 19 a间水温有下降趋势, 降幅为 $4^{\circ}C$, 变化幅度为 $0.21^{\circ}C \cdot a^{-1}$, 变化幅度不大。说明地热流体所处的环境封闭, 盖层保温性能好, 未有现代大气降水补给。蓝田灞河组以下的热储层为高陵群组, 高陵群组平均温度 $86^{\circ}C$ (赵慧,

2009), 而该地热井热水温度并未有升高现象, 说明并未受到深部高温地热流体的补给。也进一步说明蓝田灞河组热储层地热水更新能力差, 地热水的开采以消耗静态储量为王。

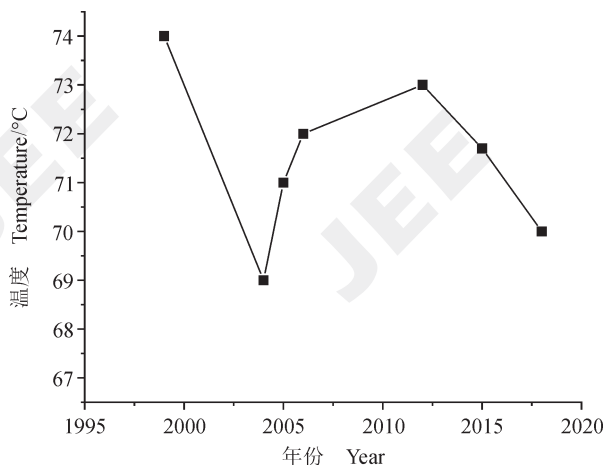


图 3 XY1 地热井多年水温变化

Fig.3 Water temperature change of XY1 geothermal well in many years

2.3 水化学动态

XY1 井 1999 年与 2017 年两期水质测试结果如表 2 所示, 可以看出地热水的大部分离子组分浓度都呈上升趋势。主要阳离子含量变化趋势不明显, 主要阴离子变化相对较大, 其中: HCO_3^- 减少了 $43.2 \text{ mg} \cdot \text{L}^{-1}$, Cl^- 增加 $301.4 \text{ mg} \cdot \text{L}^{-1}$, SO_4^{2-} 增加 $43.1 \text{ mg} \cdot \text{L}^{-1}$ 。TDS (矿化度) 增加 $680 \text{ mg} \cdot \text{L}^{-1}$ 。地热井经过长期开采, 且又未采取回灌措施, 水位降

低, 地下热水资源衰竭, 蓝田灞河组热储层段热水水位平均下降速率为 $16.6\text{—}27.1 \text{ m} \cdot \text{a}^{-1}$, 并以 XY1 地热井为中心形成降落漏斗 (赵慧, 2009)。地下水位大幅度下降, 使地下水水力坡度增加, 地下水的流速和对地下岩体的冲刷、溶蚀能力增加, 导致水中矿物质成分增加; 集中开采地段或开采井位密集地区局部已改变了地热水的流向, 地热水从四周汇集到降落漏斗区, 且矿化度在靠近断裂处较高 (刘文辉等, 1999), 还可能为周边同一储层高矿化度地热水迅速向漏斗中心流动, 导致地热水中 TDS 与 Na^+ 、 Cl^- 、 SO_4^{2-} 含量随之增加。水化学类型未改变, 两期都为 Cl-Na 型, 总硬度在 $450\text{—}700 \text{ mg} \cdot \text{L}^{-1}$, 属于高硬水; TDS 大于 $3000 \text{ mg} \cdot \text{L}^{-1}$, 为咸水; 依据 GB/T 11615—2010 《地热资源勘查规范》中医疗热矿水水质标准, 将水质测试结果与标准进行对比 (表 3), 发现氟、溴、偏硅酸达到医疗价值浓度, 碘、锶、偏硼酸达到医疗命名矿水浓度标准, 可作为医疗热矿水开发利用。且臭和味、色度、浑浊度等指标明显增大, 指示水质变差。pH 由 8.50 到 7.63, HCO_3^- 减小, 推断可能因为在碱性条件下发生以下反应: $\text{HCO}_3^- \rightleftharpoons \text{CO}_3^{2-} + \text{H}^+$, 使已形成的碱度受到中和, pH 变为 7.63, HCO_3^- 减小。根据 Wang et al (2013) 的研究, SiO_2 的含量与热水温度 T 呈正相关关系, 相关关系式为: $\text{SiO}_2 = 0.8686T - 9.7891$ ($R^2 = 0.842$)。本研究中, 地热井水温降低了 4°C , SiO_2 的含量降低了 $5.7 \text{ mg} \cdot \text{L}^{-1}$, 与根据 Wang et al (2013) 关系式计算出的 SiO_2 含量 ($6.3 \text{ mg} \cdot \text{L}^{-1}$) 相差不多。

表 2 XY1 地热井水质测试结果
Tab.2 Water quality test results of XY1 geothermal well

年份 Year	分析项目 Analysis item						
	K^+ $/(\text{mg} \cdot \text{L}^{-1})$	Na^+ $/(\text{mg} \cdot \text{L}^{-1})$	Ca^+ $/(\text{mg} \cdot \text{L}^{-1})$	Mg^{2+} $/(\text{mg} \cdot \text{L}^{-1})$	Cl^- $/(\text{mg} \cdot \text{L}^{-1})$	SO_4^{2-} $/(\text{mg} \cdot \text{L}^{-1})$	总硬度 Total hardness $/(\text{mg} \cdot \text{L}^{-1})$
1999	43.0	2650	132.3	34.6	3828.6	501.9	472.9
2017	39.1	2671	154.0	47.1	4130.0	545.0	580.0

年份 Year	分析项目 Analysis item						
	SiO_2 $/(\text{mg} \cdot \text{L}^{-1})$	TDS $/(\text{mg} \cdot \text{L}^{-1})$	HCO_3^- $/(\text{mg} \cdot \text{L}^{-1})$	Br^- $/(\text{mg} \cdot \text{L}^{-1})$	pH	色度 Chromaticity	臭和味 Smell and taste
1999	42.3	7536	250.2	18.65	8.50	15 度	咸味 Salty taste
2017	36.6	8216	207.0	22.70	7.63	>50 度	强咸味 Strong salty taste

表3 水质测试结果与医疗矿水水质标准对比
Tab.3 Comparison of water quality test results and medical mineral water quality standards

成分 Ingredient	有医疗价值 浓度 Medically valuable concentration /(mg·L ⁻¹)	命名矿水 浓度 Named mineral water concentration /(mg·L ⁻¹)	测试结果 Test results /(mg·L ⁻¹)	
			1999	2017
氟 F	1	2	1.95	1.99
溴 Br	5	25	18.65	22.70
碘 I	1	5	12.8	13.6
锶 Sr	10	10	37.2	36.2
偏硼酸 HBO ₂	1.2	50	160	188
偏硅酸 H ₂ SiO ₃	25	50	55.0	47.6

在地下水化学成分中,许多化学组分之间存在着某种相关关系,依据某些元素含量之间的这种固定关系(沈照理等,1999),可以进一步验证地下水的成因和所处环境。 $\gamma\text{Na}/\gamma\text{Cl}=0.64$, $\text{Cl}/\text{Br}=181.94$, $\text{Ca}/\text{Sr}=4.25$ 。 $\gamma\text{Na}/\gamma\text{Cl}$ 满足沉积水 <0.85 的特征,其他符合溶滤水特征。在汾渭盆地石油普查阶段成果报告(中国石化华北石油局第三普查勘探大队,1977)中也提及咸阳城区渭河断裂北部可能曾有海水入侵情况,张家坡组中部及渭河地区发现了通常被认为是海相生物的孔虫化石。因此热储流体可能包含残存海相沉积水,说明热储流体为混入古溶滤水的残存沉积水。

2.4 水-岩平衡动态

1988年Giggenbach首先提出了Na-K-Mg三角图解法,用来评价水岩平衡状态,在三角图中分为完全平衡、部分平衡和未成熟水三个区域(Giggenbach, 1988),分别对应图4中A、B、C三部分。在某一温度下, Na^+ 和 K^+ 达到饱和并保持相对稳定,此时地下水处于完全平衡状态。当受到冷水补给或上升过程与浅部冷水之间发生混合作用时,平衡状态被打破, Na^+ 和 K^+ 处于非饱和状态,地热流体处于部分平衡状态。从图4可以看出,XY1井两期水样均为完全平衡水,而马致远等(2019)对关中盆地腹部热水水-岩平衡动态的研究结果是各热水水样均为部分平衡,接近完全平衡。这可能是因为马致远等人的取样点主要为西安城区,咸阳城区比西安热水受压更大,热储环境更为封闭(李婷,2012),与现代水联系较差,在长期的热水开采过程中,地热水并未受到冷水的混合,热水与围岩矿物多处于水-岩平

衡状态。

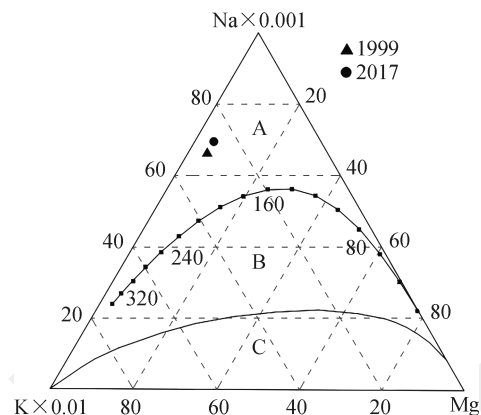


图4 Na-K-Mg三角图

Fig.4 Na-K-Mg triangular diagram of geothermal water

3 结论

依据氢氧稳定同位素计算了地热水补给高程为1200 m,结合 ^{14}C 测试年龄为20251 a,可知XY1井地下热水属于第四纪末次冰期北山山区海拔1200 m大气降水入渗成因。根据该井地热水中 $\delta^{18}\text{O}$ 与 δD 值特点,推断出热储流体为古溶滤水或沉积成因。分析表明该区域地下热水可再生能力较差。

XY1地热井多年水温变化不大,水-岩平衡动态未发生改变,说明地热流体所处的环境封闭,地热水补给微弱,盖层保温性能好,未有现代大气降水补给,且未受到深部高温地热流体的补给,地热水的开采以消耗静态储量为主体。

根据XY1井两期水质测试结果,XY1井水化学类型未改变,为Cl-Na型,属于高硬水、咸水。多种矿物含量达医疗标准,可作为医疗热矿水开发利用。以XY1地热井为中心形成降落漏斗,地下水水力坡度增加,地下水的流速和对地下岩体的冲刷、溶蚀能力增加,周边同一储层高矿化度地热水向漏斗中心流动,导致水中矿物质成分增加,水质变差。依据元素含量之间的固定关系 $\gamma\text{Na}/\gamma\text{Cl}=0.64$, $\text{Cl}/\text{Br}=181.94$, $\text{Ca}/\text{Sr}=4.25$,进一步验证了热储流体为混入古溶滤水的残存沉积水。

地热井尾水不加处理直接排放必然会对城市环境产生较为严重的热污染,而且地下热水中有害化学成分对水环境、土壤环境和空气环境也会产生污染。因此,必须加强地热井尾水排放时对

环境及饮用水源安全的保护, 经处理达标后才能排放, 可采取地热水回灌等措施。另外应加强地热水的化学监测, 深入了解地热系统变化, 使地热资源开发具有可持续性。

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