Analysis of Chemical and Environmental Isotopic Characteristics and Formation Age of Geothermal Fluids in Gansu Province (Postprint)

Authors: Zhang Lingpeng

Date: 2021-02-13T15:38:12+00:00

Abstract

Using extensive test data on the chemical composition and environmental isotopes (δD, $ $18O, 14C) of geothermal fluids, this study conducted an in-depth analysis of the chemical characteristics and distribution patterns of geothermal fluids in uplifted mountain tectonic convection-type and subsidence basin conduction-type systems. Subsequently, the distribution characteristics of environmental isotopes and formation ages of geothermal fluids were systematically summarized, yielding clear conclusions. The results indicate that geothermal fluids in uplifted mountain tectonic convection-type geothermal fields primarily discharge as fault ascending springs distributed in the West Qinling-Qilian orogenic belt. Their recharge source is local and surrounding atmospheric precipitation infiltration, with formation ages generally ranging from 5,000 to 30,000 years. These fluids exhibit good water quality and belong to an "open-type" geothermal system. The lithology of the reservoir, fault scale, and the mode and depth of hydrothermal circulation significantly control the chemical type, environmental isotope characteristics, and formation age of geothermal fluids. In subsidence basin conduction-type geothermal fields, geothermal fluids are mainly extracted through well drilling. For geothermal wells with reservoir burial depths less than 1,600 m, the geothermal fluid recharge source is local and surrounding atmospheric precipitation infiltration, with formation ages generally ranging from 5,000 to 30,000 years. These fluids have relatively good water quality and belong to a "semi-open to semi-closed" geothermal system. For geothermal extraction wells with reservoir burial depths between 1,600 and 2,600 m, the fluids are primarily "paleo-water" formed gradually during geological history, exhibiting complex hydrochemical types and poorer water quality. The formation ages of these geothermal fluids range from 30,000 to 50,000 years, belonging to a "closed-type" geothermal system. The lithology of the reservoir,

burial depth, groundwater residence time in rock strata, and circulation depth significantly control the chemical type, degree of environmental isotope enrichment, and formation age of geothermal fluids.

Full Text

Hydrochemistry and Environmental Isotopic Characteristics and Formation Age Analysis of Geothermal Fluids in Gansu Province

ZHANG Ling-peng[1], **DING Hong-wei**[2], **ZHANG Jia-feng**[2],[3], **WANG Yu-xi**[4], **TIAN Liao-xi**[5]

([1] The Second Institute of Geology and Minerals Exploration, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou 730020, Gansu, China; [2] Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou 730000, Gansu, China; [3] The First Institute of Geology and Minerals Exploration, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Tianshui 741020, Gansu, China; [4] The Third Institute of Geology and Minerals Exploration, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou 730050, Gansu, China; [5] Institute of Hydrogeology and Engineering Geology, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Zhangye 734000, Gansu, China)

Abstract

Based on extensive test data of geothermal fluid chemical composition and environmental isotopes (δD, δ^{18}O, and ^{14}C), this study provides a comprehensive analysis of the hydrochemical characteristics and distribution patterns of convective geothermal fluids in uplifted mountainous regions and conductive geothermal fluids in subsidence basins within Gansu Province. The environmental isotope distribution features and formation ages of these geothermal fluids are systematically summarized, yielding clear conclusions. The results demonstrate that convective geothermal fields in uplifted mountainous areas primarily discharge as fracture-controlled ascending springs, distributed across the West Qinling and Qilian orogenic belts, with recharge derived from local and regional atmospheric precipitation infiltration. These geothermal fluids generally have formation ages of 5,000–30,000 years and good water quality, constituting an "open-type" geothermal system. The lithology of thermal reservoirs, fracture scales, and hydrothermal circulation patterns and depths significantly control the hydrochemical types, isotopic characteristics, and formation ages of these fluids. Conductive geothermal fields in subsidence basins mainly exploit fluids through production wells. Wells with reservoir burial depths less than 1,600 m receive recharge from local and regional atmospheric precipitation, with formation ages generally less than 30,000 years and relatively good water quality, representing a "semi-open" geothermal system. Wells with reservoir depths of 1,600–2,600 m primarily contain "paleowater" formed gradually during geological history, exhibiting complex hydrochemical types and poor water quality, with formation ages of 30,000–50,000 years, belonging to a "closed-type" geothermal system. Overall, the lithology, burial depth, groundwater residence time, and circulation depth in rock layers distinctly control the hydrochemical types, environmental isotope enrichment, and formation ages of geothermal fluids.

Keywords: thermal fluid; hydrochemistry; environmental isotope; formation age; geothermal system

Introduction

Geothermal energy refers to the heat stored within the Earth's interior, generally forming a relatively independent system for thermal energy storage, migration, and conversion. Based on geological genesis and energy transfer mechanisms, geothermal fields can be classified into two types: uplifted mountain tectonic convection type and subsidence basin conduction type. Gansu Province, located at the intersection of five major geological plates in China, features complete stratigraphic sequences across all geological eras, intense neotectonic movement, multi-phase alternating magmatic intrusion and eruption, and coexisting volcanic, sedimentary, and metamorphic rocks. The region exhibits complex structural activity with well-developed folds and faults within and between tectonic units. Combined with relatively abundant precipitation in mountainous areas, "ancient sealed water" formed during geological history, and water-conducting structures connecting mountains and basins, the hydrothermal geothermal resources are prominently endowed, resulting in abundant geothermal resources. Geological exploration has confirmed that Gansu possesses complete geothermal types with wide distribution, relatively shallow burial, and convenient development characteristics, making it a province rich in geothermal resources with promising development prospects and a major province for new and renewable energy in China. Preliminary assessments indicate that the exploitable hydrothermal geothermal resources in Gansu reach 1.41×10^{12} tons of standard coal equivalent, which could provide heating for 1.58×10^{9} m^2 upon full development, demonstrating enormous potential.

Since the 1980s, researchers have conducted fruitful investigations into the geological conditions, distribution characteristics, genetic types, storage and enrichment patterns, and development approaches for geothermal resources in Gansu or specific regions. Studies by Li Baixiang et al. and An Yongkang et al. qualitatively discussed the control of Gansu's basin-mountain structural pattern on the geothermal field and resource types, outlining distribution characteristics and development prospects. Zheng Ximin et al., Bai Fu et al., and Zhang Zixiang et al. conducted in-depth analyses of geothermal geological conditions in the Lanzhou-Minhe fault basin and proposed conceptual thermal storage models. Ding Hongwei et al., Wang Caixia et al., and Gao Zhenrong et al. examined environmental isotope content characteristics in different water bodies to investigate recharge sources and causes of deep geothermal anomalies. These research findings have undoubtedly accelerated geothermal exploration and development in Gansu. However, studies examining the formation mechanisms, recharge sources, and ages of geothermal fluids from hydrochemical and environmental isotope perspectives remain rarely reported, making this study the first of its kind for Gansu Province.

1 Regional Geothermal Geological Background Conditions

1.1.1 Uplifted Mountain Orogenic Belt

Based on statistical analysis of heat flow values across different tectonic units in the province, a strong correlation exists between terrestrial heat flow, tectonic activity, and geological age. The basement in tectonically active zones generally conceals high heat flow from deep crustal or upper mantle sources, which in turn increases the intensity of shallow crustal activity. In Gansu' s tectonically active Qilian Mountains and Altun Mountains, terrestrial heat flow values generally exceed 70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$. The West Qinling and Beishan regions exhibit values between 60-70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$, while the Liupanshan tectonic belt shows values around 60 $\mathrm{mW} \cdot \mathrm{m}^{-2}$. The Hexi Corridor basin group displays heat flow values of 60-70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$, with an overall pattern of decreasing values from south to north and from mountainous areas to basins. The Longxi Loess Plateau generally shows values of 60-70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$, locally exceeding 70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$. The Longdong Loess Plateau exhibits values of 60-70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$, gradually increasing eastward, with values exceeding 70 $\mathrm{mW} \cdot \mathrm{m}^{-2}$ in the Ziwuling area to the east. Research indicates that the Huahai Basin in the Hexi Corridor and the Lanzhou-Yuzhong Basin in the Longxi Loess Plateau have relatively high heat flow values. Both the Dunhuang-Guazhou Basin and the adjacent Dunhuang Basin are located in ancient blocks with Precambrian basement, which generally exhibit lower heat flow values, while rift extensional stages typically show very high heat flow values. The Lanzhou-Yuzhong Basin, situated between the north marginal fault of the West Qinling orogenic belt and the south marginal fault of the Qilian orogenic belt, belongs to a Cenozoic pull-apart basin. The high-temperature field in the Yaojie Coal Mine area at the basin margin in Honggu District shows an average heat flow value of 81.4 $\mathrm{mW} \cdot \mathrm{m}^{-2}$, the highest in Gansu Province, primarily caused by underground temperature increases due to coal seam spontaneous combustion forming baked rocks. Additionally, the free CO_2 content in the Yaojie mining area is relatively high, resulting from carbonate rock decarbonation during deep groundwater circulation, where CO_2 dissolves in water at high temperatures and coexists with thermal water. Thermal anomaly wells in the Tiangou Bridge Tianging International New City area of Lanzhou and the Qilihe District western section also show high temperatures.

1.2 Regional Geothermal Field Characteristics

Gansu Province's geothermal gradient generally ranges between 2.0-3.5°C $\cdot$ (100 m)$^{-1}$, with a maximum of 4.0°C $\cdot$ (100 m)$^{-1}$, showing an increasing trend from north to south and from west to east. The Beishan area has the lowest gradient, generally less than 2.0°C·(100 m)$^{-1}$. The Qilian-Altun Mountains and West Qinling show gradients of 2.5-3.5°C·(100 m)$^{-1}$, with an average of 3.0°C·(100 m)$^{-1}$ on the northern slope of West Qinling. The Hexi Corridor basin group generally exhibits gradients of 2.5-3.5°C·(100 m)$^{-1}$, locally reaching 4.0°C·(100 m)$^{-1}$ in the western Dunhuang-Guazhou, Jiuquan East, and Zhangye-Minle basins. The Longxi Loess Plateau shows gradients of 2.0-3.0°C·(100 m)$^{-1}$, with higher values in the Lanzhou-Yuzhong, Jingyuan-Huining basins reaching 2.5-3.0°C·(100 m)$^{-1}$, locally exceeding 3.5°C·(100 m)$^{-1}$ at margins. The Longdong Loess Plateau exhibits gradients of 2.5-3.5°C·(100 m)$^{-1}$, gradually increasing eastward, with values of 2.5-3.0°C·(100 m)$^{-1}$ in the western margin thrust-fold belt west of the Qingyang-Pingliang fault, 3.0-3.5°C·(100 m)$^{-1}$ in the Cretaceous basin to the east, and exceeding 3.5°C·(100 m)$^{-1}$ east of Ziwuling. Evidently, Gansu' s regional geothermal field correlates with terrestrial heat flow, where high heat flow zones correspond to high geothermal gradients and low heat flow zones correspond to low gradients. Geothermal gradients in uplifted mountain orogenic belts are generally 0.5-1.0°C·(100 m)$^{-1}$ higher than in subsidence basin areas.

1.3 Geothermal Anomaly Points and Distribution Characteristics

According to the latest statistics, Gansu Province had 116 geothermal anomaly points (including springs and geothermal wells) as of December 2018. Among these, 36 are springs (accounting for 31.0% of the total) and 80 are geothermal wells (69.0%). Based on temperature classification, there are 81 low-temperature anomalies (<40°C), 21 medium-temperature anomalies (40-60°C), and 14 high-temperature anomalies (>60°C). The low-temperature anomalies are distributed across the Qilian-Altun strike-slip fault zone terminus, Beishan, and West Qinling, with water temperatures below 25°C, representing 69.3% of all geothermal points. Medium-temperature anomalies occur in the Qilian Mountains, Altun Mountains, Beishan, West Qinling, Hexi Corridor basin group, and Longxi Loess Plateau, with wellhead temperatures generally ranging 25-40°C. High-temperature anomalies are concentrated in the West Qinling and its northern foothills, including Diebu Kalagou, Wushan County, and Tianshui Wenjiaxia, as well as in the Lanzhou-Yuzhong Basin and Minle Basin, with wellhead temperatures of 40-60°C. Currently, 77 thermal fluid wells are distributed mainly in Lanzhou, Yuzhong, and Minle basins, including low-temperature thermal wells at 77.0°C in Xigu District of Lanzhou, 73.0°C in Anning District, and 75.0°C in Minle County' s Liuba Industrial Park.

2 Data Collection and Testing

The project collected and analyzed 116 sets of geothermal fluid chemical samples and 105 sets of environmental isotope samples. Among these, 36 chemical sample sets and 32 isotope sample sets were from uplifted mountain orogenic belts, while 80 chemical sample sets and 73 isotope sample sets were from subsidence basin areas, including 10 sets of atmospheric precipitation samples. Chemical composition analysis included 11 factors: total dissolved solids (TDS), total hardness, total alkalinity, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, $SO_4{}^{2-}$, $HCO_3{}^-$, and SiO_2 concentrations. Environmental isotope analysis comprised δD, δ^{18}O, and ^{14}C ages.

Chemical testing was completed by the Gansu Provincial Central Laboratory, Gansu Geological Engineering Laboratory, and Lanzhou Veolia Water Group Laboratory. Routine anions were measured using a Dionex DX-120 chromatograph, cations by ICP-DES (ICAP6300), and pH was determined on-site using a portable meter. Environmental isotope analyses were conducted by the Shijiazhuang Institute of Hydrogeology and Environmental Geology (China Geological Survey), and the Institute of Isotope Hydrology at Hohai University. δD and δ^{18}O isotopes were measured using a MAT253 gas stable isotope ratio mass spectrometer with an analytical precision of \$±\$0.5‰, following the Vienna Standard Mean Ocean Water (VSMOW) standard. ^{14}C content was determined using Accelerator Mass Spectrometry (AMS) combined with liquid scintillation technology, with a test precision of \$±\$0.5%. Comparative analysis of parallel samples confirmed all results to be authentic and valid.

3 Hydrochemical Characteristics of Geothermal Fluids

3.1 Convective Geothermal Fluids in Uplifted Mountain Tectonic Zones

Based on water quality analysis of convective geothermal fluids in uplifted mountain tectonic zones, TDS values range 0.50–8.99 $g \cdot L^{-1}$, averaging 2.87 $g \cdot L^{-1}$. Geothermal fluids mainly discharge as natural spring groups, with few geothermal wells (some artesian). Among these, 8 sample sets have TDS of 0.50–1.0 $g \cdot L^{-1}$, distributed in Tongwei Tangchigou, Qingshui Tangyugou, Maiji Zhongtan on the northern foothills of West Qinling, and Liangzhou Yaowangquan on the northern foothills of eastern Qilian Mountains, with hydrochemical types of $HCO_3 \cdot SO_4$-$Na \cdot Ca \cdot Mg$ and $SO_4 \cdot HCO_3$-$Ca \cdot Mg$. Only 2 sample sets have TDS of 1.0–2.0 $g \cdot L^{-1}$, found in Diebu Wangzang on West Qinling, as fault ascending springs with $HCO_3 \cdot SO_4$-$Na \cdot Mg$ type. A total of 26 sample sets show TDS of 2.0–8.99 $g \cdot L^{-1}$, concentrated in Diebu Kalagou, Wushan County, and Tianshui Wenjiaxia on West Qinling and its northern foothills, as fault ascending spring groups or production wells, with hydrochemical types dominated by $SO_4 \cdot Cl$-$Na \cdot Ca$ and $Cl \cdot SO_4$-Na. The δD values range from -82.3‰ to -59.4‰, averaging -68.7‰, with the maximum at Liangzhou Yaowangquan on the eastern Qilian Mountains northern foothills and the minimum at Tongwei Tangchigou on West Qinling northern foothills. δ^{18}O values range -11.8‰ to -8.6‰, averaging -10.1‰, with the maximum at Maiji Zhongtan, Tianshui (geothermal well, 1,500 m depth, artesian) and the minimum at Diebu Kalagou (self-flowing fault ascending spring). Both δD and δ^{18}O values show small variation amplitudes, with average contents close to local atmospheric precipitation background values (Tianshui station: δD average -62.8‰, δ^{18}O average -9.2‰). The δ^{18}O-δD relationship diagram shows most sample points near the global meteoric water line and northwest China meteoric water line, indicating atmospheric precipitation as the main recharge source, with some fluids affected by evaporation. The low hydrogen-oxygen isotope exchange probability with dissolved ions in thermal water results in small δ^{18}O drift, generally characterized as an "open-type" geothermal system.

3.2 Conductive Geothermal Fluids in Subsidence Basins

Based on water quality analysis of conductive geothermal fluids in subsidence basins, TDS values range 1.25–45.93 $\mathrm{g \cdot L^{-1}}$, averaging 15.81 $\mathrm{g \cdot L^{-1}}$, with significantly greater variation than uplifted mountain types. All fluids discharge through geothermal wells (some artesian). Only 2 sample sets have TDS of 1.0-3.0 $\mathrm{g \cdot L^{-1}}$, distributed near Dunhuang city in the Dunhuang-Guazhou Basin and northeast of Suzhou city in the Jiuquan East Basin, with reservoir depths of 1,400–1,600 m and hydrochemical type $\mathrm{HCO_3 \cdot SO_4}$-$\mathrm{Na \cdot Ca}$. A total of 26 sample sets show TDS of 3.0–10.0 $\mathrm{g \cdot L^{-1}}$, concentrated in the Longdong Cretaceous Basin and Dunhuang-Guazhou Basin. The Longdong Cretaceous Basin has reservoir depths of 1,600–2,200 m with hydrochemical types dominated by $\mathrm{SO_4 \cdot HCO_3}$-Na and $\mathrm{SO_4 \cdot Cl}$-$\mathrm{Na \cdot Ca}$, while the Dunhuang-Guazhou Basin has depths of 900–1,600 m with $\mathrm{SO_4 \cdot Cl}$-$\mathrm{Na \cdot Ca}$ type. Eight sample sets have TDS of 10.0–50.0 $\mathrm{g \cdot L^{-1}}$, distributed in the Jiuquan East Basin, Zhangye-Minle Basin, and locally in Lanzhou-Yuzhong Basin, with reservoir depths of 2,200–2,400 m and hydrochemical types of $\mathrm{Cl \cdot SO_4}$-Na and Cl-$\mathrm{Na \cdot Mg}$. Only 2 sample sets exceed 50.0 $\mathrm{g \cdot L^{-1}}$, found in the Lanzhou-Yuzhong Basin with reservoir depths of 2,450–2,600 m and Cl-Na type.

4 Environmental Isotopic Characteristics and Geothermal Systems

4.1 Convective Geothermal Fluids in Uplifted Mountain Zones

Based on environmental isotope test results (Table 1), convective geothermal fluids in uplifted mountain zones show δD values ranging -82.3‰ to -59.4‰, averaging -68.7‰, and δ^{18}O values ranging -11.8‰ to -8.6‰, averaging -10.1‰. The δ^{18}O-δD relationship diagram [Figure 2: see original paper] shows most sample points clustered near the global meteoric water line and northwest China meteoric water line, indicating atmospheric precipitation as the primary recharge source with minimal evaporation effects. The low hydrogen-oxygen isotope exchange probability results in small δ^{18}O drift, generally characterizing an "open-type" geothermal system. ^{14}C dating reveals formation ages of (0.36–3.26)$\times10^{4}$ years, averaging 1.23$\times10^{4}$ years. Samples with ages <10,000 years are mainly distributed in Diebu Kalagou, Wushan County, and Tianshui Wenjiaxia on West Qinling, as fault ascending springs with hydrochemical types $\mathrm{HCO_3 \cdot SO_4}$-Na and $\mathrm{SO_4 \cdot HCO_3}$-$\mathrm{Ca \cdot Mg}$. Samples aged 10,000–30,000 years occur in Maiji Zhongtan, Diebu Wangzang, Qingshui Tangyugou, Tongwei

Tangchigou on West Qinling northern foothills, and Liangzhou Yaowangquan on eastern Qilian Mountains northern foothills. Samples aged >30,000 years appear at Yongdeng Yaoshuigou and Qin' an Fuzigou in the Qilian orogenic belt.

4.2 Conductive Geothermal Fluids in Subsidence Basins

Conductive geothermal fluids in subsidence basins show δD values ranging -85.6‰ to -54.3‰, averaging -67.2‰, and δ^{18}O values ranging -11.9‰ to -7.2‰, averaging -9.8‰. Regionally, western Jiuquan East Basin, Minle Basin, and parts of eastern Longdong Cretaceous Basin exhibit significantly higher δD values (-67.2‰ to -54.3‰, average -60.8‰) and δ^{18}O values (-9.8‰ to -7.2‰, average -8.5‰). In contrast, central Lanzhou-Yuzhong Basin and eastern Longdong Cretaceous Basin show relatively lower δD values (-85.6‰ to -67.2‰, average -76.4‰) and δ^{18}O values (-11.9‰ to -9.8‰, average -10.8‰). Overall, western Hexi Corridor basin groups show δD and δ^{18}O values significantly higher than local atmospheric precipitation background values (Zhangye station: δD average -62.8‰, δ^{18}O average -9.2‰), while central-eastern Lanzhou-Yuzhong Basin and Longdong Cretaceous Basin values are lower than background values (Lanzhou station: δD average -64.5‰, δ^{18}O average -9.5‰). The δ^{18}O-δD diagram shows 15 sample points distant from the meteoric water line: 5 points above the line left side and 10 points below the line, indicating complex formation mechanisms and diverse circulation patterns for conductive geothermal fluids.

Samples near the meteoric water line are mainly distributed in western Dunhuang-Guazhou Basin, Jiuquan East Basin, and eastern Longdong Cretaceous Basin, with well depths of 1,600–2,400 m, reservoir depths of 900–2,200 m, and hydrochemical types $SO_4 \cdot HCO_3$-Ca $\cdot$ Mg and $SO_4 \cdot Cl \cdot HCO_3$-Na $\cdot$ Ca. These have TDS of 0.5–3.0 $g \cdot L^{-1}$, ^{14}C ages of <15,000 years, and represent relatively new geothermal fluids. Samples distant from the meteoric water line occur in western Jiuquan East Basin, Zhangye-Minle Basin, central Lanzhou-Yuzhong Basin, and eastern Longdong Cretaceous Basin, with well depths of 2,200–2,600 m, reservoir depths of 2,200–2,600 m, and hydrochemical types $Cl \cdot SO_4$-Na and Cl-Na. These have TDS of 10.0–50.0 $g \cdot L^{-1}$, ^{14}C ages of 30,000–50,000 years, and represent old geothermal fluids in a "closed-type" system, similar to groundwater occurrence features in the Guanzhong Basin, Shaanxi Province.

4.3 Formation Age Analysis

4.3.1 Convective Geothermal Fluids in Uplifted Mountain Zones ^{14}C dating of convective geothermal fluids in uplifted mountain zones yields ages of (0.36–3.26)\$×10^{4}\$ years, averaging 1.23\$×10^{4}\$ years. By hydrochemical type, fluids with TDS <0.5 $g \cdot L^{-1}$ (average 0.50 $g \cdot L^{-1}$) and $HCO_3 \cdot SO_4$-Na or HCO_3-Ca $\cdot$ Mg types, dominated by bicarbonate, show ^{14}C ages of (0.36–0.76)\$×10^{4}\$ years (average 0.53\$×10^{4}\$ years), representing new geothermal fluids <10,000 years old. Fluids with TDS of 0.5–3.0 $g \cdot L^{-1}$ (average 1.39

$g \cdot L^{-1}$) and $SO_4 \cdot HCO_3$-Na or $SO_4 \cdot$ Cl-Na $\cdot$ Ca types, dominated by sulfate, show ages of (0.76–2.65)$×10^{4}$ years (average 1.81$×10^{4}$ years), representing relatively old fluids of 10,000–30,000 years. Fluids with TDS of 3.0–10.0 $g \cdot L^{-1}$ (average 5.81 $g \cdot L^{-1}$) and $Cl \cdot SO_4$-Na or Cl-Na $\cdot$ Mg types, dominated by chloride and sulfate, show ages of (2.65–3.51)$×10^{4}$ years (average 3.26$×10^{4}$ years), representing old fluids of 30,000–40,000 years. Fluids with TDS >10.0 $g \cdot L^{-1}$ (average 21.27 $g \cdot L^{-1}$) and Cl-Na type, dominated by chloride, show ages of (3.51–4.36)$×10^{4}$ years (average 4.36$×10^{4}$ years), representing ancient fluids of 40,000–50,000 years.

4.3.2 Conductive Geothermal Fluids in Subsidence Basins ^{14}C dating of conductive geothermal fluids yields ages of (0.76–4.36)$×10^{4}$ years, averaging 2.49$×10^{4}$ years. Samples <10,000 years old are mainly distributed in the western Dunhuang-Guazhou Basin and Jiuquan East Basin at depths <1,600 m. Samples aged 10,000–30,000 years occur in the Dunhuang-Guazhou Basin, Jiuquan East Basin, and Longdong Cretaceous Basin at depths of 1,600–2,400 m. Samples aged 30,000–50,000 years are found in the Zhangye-Minle Basin and Lanzhou-Yuzhong Basin at depths of 2,400–2,600 m. This clearly demonstrates that formation age increases progressively with well depth. Fluids in deep, closed geological conditions have minimal hydraulic connection with overlying loose rock pore water and other water bodies, representing "paleowater" formed during geological history. With weak or no recharge, these fluids rely mainly on heat conduction from deep crustal and upper mantle sources. The long residence time and strong water-rock interaction result in greater hydrogen-oxygen isotope exchange probability, significant $\delta^{18}O$ drift, and easy enrichment, producing complex hydrochemical types and poor water quality in this "closed-type" system. Overall, conductive geothermal fluids in subsidence basins have relatively old formation ages, following the pattern that deeper reservoir burial, more closed geological conditions, greater δD and $\delta^{18}O$ enrichment, and older fluid ages.

4.3.3 Factors Controlling Geothermal Fluid Formation Age For uplifted mountain convection-type geothermal fields, fluids mainly discharge as fracture ascending springs. Thermal reservoir lithology, fracture scale, and hydrothermal circulation mode and depth significantly control hydrochemical types and formation ages. Recharge sources are local and regional atmospheric precipitation infiltration, with fluids circulating and heating primarily along fracture zones at shallow depths with rapid alternation, resulting in short residence times, weak water-rock interaction, low hydrogen-oxygen isotope exchange probability, small $\delta^{18}O$ drift, and low enrichment. These fluids generally have formation ages <30,000 years and represent "open-type" systems with relatively new ages.

For subsidence basin conduction-type geothermal fields, fluids occur in deep basin sections and discharge through production wells (some artesian). Thermal reservoir lithology, burial depth, recharge sources, and circulation depth significantly control hydrochemical types and formation ages. Wells with reservoir burial depths <1,600 m have thin cap rocks with relatively insufficient lithological density, maintaining some hydraulic connection with overlying loose rock pore water (recharged by local atmospheric precipitation and surface water infiltration) and other water bodies, though with weak recharge intensity. These fluids have relatively shallow circulation depths, moderate residence times, weak water-rock interaction, low hydrogen-oxygen isotope exchange probability, small δ^{18}O drift, and low enrichment, yielding formation ages generally <30,000 years and representing "semi-open"systems. Wells with reservoir depths of 1,600–2,600 m have massive, dense cap rocks of Paleogene mudstone and sandy mudstone over 1,000 m thick, essentially eliminating hydraulic connection with overlying water bodies. These fluids represent "paleowater" formed during geological history, with large δ^{18}O drift and easy enrichment, representing "closed-type" systems with formation ages of 30,000–50,000 years.

5 Conclusions

(1) For uplifted mountain convection-type geothermal fields, fluids mainly discharge as fracture ascending springs. Thermal reservoir lithology, fracture scale, and hydrothermal circulation mode and depth significantly control hydrochemical types and formation ages. Recharge from local and regional atmospheric precipitation infiltration circulates along fracture zones at shallow depths with rapid alternation, resulting in short residence times, weak water-rock interaction, low hydrogen-oxygen isotope exchange probability, small δ^{18}O drift, and low δ^{18}O content. These fluids have relatively good water quality with formation ages generally <30,000 years, representing "open-type" systems with relatively new ages.

(2) For subsidence basin conduction-type geothermal fields, fluids occur in deep basin sections and discharge through production wells (some artesian). Thermal reservoir lithology, burial depth, groundwater recharge sources, and circulation depth significantly control hydrochemical types and formation ages. Wells with reservoir burial depths <1,600 m have thin cap rocks with relatively insufficient density, maintaining hydraulic connection with overlying loose rock pore water (recharged by local atmospheric precipitation and surface water infiltration) and other water bodies, though with weak recharge intensity. These fluids have relatively shallow circulation depths, moderate residence times, weak water-rock interaction, low hydrogen-oxygen isotope exchange probability, small δ^{18}O drift, and low δ^{18}O content, yielding relatively good water quality with formation ages generally <30,000 years, representing "semi-open" systems. Wells with reservoir depths of 1,600–2,600 m have massive, dense cap rocks, essentially eliminating hydraulic connection with overlying water bodies. These fluids represent "paleowater" formed during geological history, with long residence times, strong water-rock interaction, large hydrogen-oxygen isotope exchange probability, significant δ^{18}O drift, and high δ^{18}O content,

resulting in complex hydrochemical types and poor water quality with formation ages of 30,000–50,000 years, representing "closed-type" systems.

(3) This study reveals that uplifted mountain convection-type geothermal fluids in Gansu generally have relatively good water quality and younger formation ages. Some samples with TDS $<0.5\ \mathrm{g \cdot L^{-1}}$ and strontium content of $1.29\ \mathrm{mg \cdot L^{-1}}$ meet the standards for strontium-type natural mineral drinking water, warranting further exploration and development. In contrast, subsidence basin conduction-type geothermal fluids generally have poor water quality and older formation ages, with most samples dominated by chloride or chloride-sulfate, TDS $>10.0\ \mathrm{g \cdot L^{-1}}$, and wellhead temperatures of 40–77°C. Such high-salinity, high-temperature fluids with abundant H_2S overflow are harmful to human health and highly corrosive to pipelines, pumps, and heating facilities, requiring careful attention during development.

(4) Due to the lack of isotopic test data for atmospheric precipitation, glacial meltwater, and permanent snow meltwater at different altitudes in the study area, quantitative analysis of hydraulic connections, transformation characteristics, recharge elevations, water temperatures, and water-conducting channels for geothermal fluids, particularly conductive-type fluids in subsidence basins, could not be performed using deuterium excess parameters. This limitation should be addressed in future research.

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Note: Figure translations are in progress. See original paper for figures.