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Hydrogeochemical characteristics and the genesis of the No. Lu 32 well in the Jiaodong Peninsula, China

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The No. Lu 32 well is a seismic observation well situated on the easternmost tip of the Penglai–Weihai fault zone in the Jiaodong Peninsula. It is necessary to reveal the genetic mechanism of the water in this well for earthquake forecasting along the Penglai–Weihai fault zone. Water samples were collected from the No. Lu 32 well, neighboring wells, and seawater to measure the hydrochemical composition and main hydrogen and oxygen isotopic compositions. The water type of the No. Lu 32 well is Cl–Na, which may be due to the influence of seawater intrusion. Hydrogen and oxygen isotopes indicate that the No. Lu 32 well and adjacent wells are mainly influenced by meteoric water, that the high salinity in the water is mainly from the mixing of modern seawater, and that the proportion of seawater there is approximately 5%. Observation of water temperature data in the No. Lu 32 well over several years shows regular annual variations. This comprehensive study shows that the well is greatly affected by seawater backflow infiltration and shallow water. The results of this paper provide an important reference for exploring the hydrogeochemical characteristics and genesis of wells in other coastal zones.

KEYWORDS

No. Lu 32 well, hydrochemistry, genesis, seawater mixing, water temperature

1 Introduction

Geochemical methods have been widely used in studies of groundwater genesis and characteristics (Lai et al., 2021; Song et al., 2021; Su et al., 2021). The main research direction of geochemical methods for earthquake observations is focused on soil gas measurements near seismically active fault zones, ion concentrations in observation wells, and hydrogen and oxygen isotope compositions from water (Gao et al., 2015; Tiwari et al., 2020; Zhang et al., 2021). The most important hydrochemical method is related to water chemistry and hydrogen and oxygen isotope composition analysis (Pope et al., 2014; Sasaki et al., 2021), which are used for analyzing ions in groundwater and verifying groundwater anomalies (Liu et al., 2015).

The groundwater temperatures and levels in seismic observation wells are important tools in earthquake forecasting (Lai et al., 2016; Lai et al., 2021). Groundwater temperatures have both

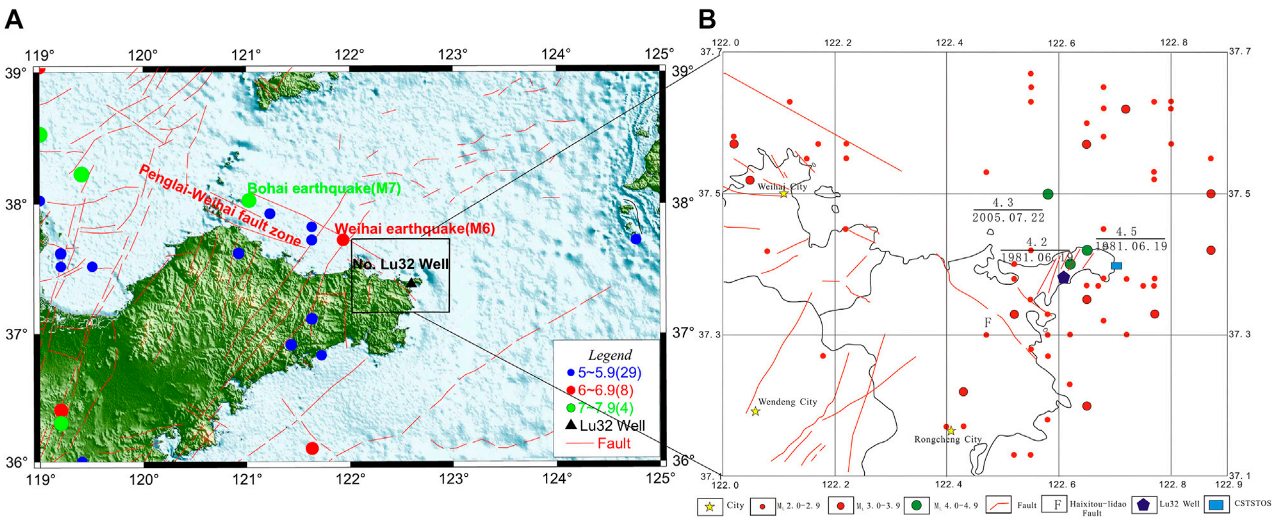

FIGURE 1
Seismotectonic settings of the No. Lu 32 well in the Jiaodong Peninsula, China. **(A)** Geological setting; **(B)** regional location [CSTSTOS is the Chengshantou seawater temperature observation station, and fault information and earthquake information are revised from (Chao et al., 1997)].

normal and abnormal changes. Previous studies have suggested that some strong earthquakes may cause abnormal variations in water levels and water temperatures, which are called the "coseismic" effects of water temperature (Ma et al., 2015). However, not all abnormalities are caused by earthquakes (Liu et al., 2015). Therefore, it is important to conduct a quantitative analysis when water temperature data exhibit abnormal variations, to quickly determine the cause of abnormal changes and to verify whether the changes are precursor abnormalities related to an earthquake or disturbances in earthquake monitoring and forecasting (Liu et al., 2015; Ma, 2016; Miyakoshi et al., 2020).

In this study, we take the No. Lu 32 well in the Jiaodong Peninsula as an example and use geochemical methods to constrain the causes of abnormal fluctuations in the groundwater temperature during an earthquake. Since this observation well is located on the easternmost tip of the Penglai–Weihai fault zone, its tectonic location has special significance for earthquake monitoring and forecasting. In this paper, we combine the regional geological and hydrogeological conditions and test the water chemistry and hydrogen–oxygen isotope compositions of the No. Lu 32 well and neighboring wells to comprehensively analyze the characteristics of the observation well, which will help to finally constrain the cause of abnormal groundwater temperatures during the earthquake process. At the same time, this analysis has some implications for groundwater temperatures in observation wells affected by seawater.

2 Geological settings

As the collision edge zone between the North China and Yangtze blocks, the Jiaodong Peninsula is characterized by a complicated crustal structure (Zhao et al., 2010; 2013; Gu et al., 2020; Qu et al., 2021). A great number of frequent moderate–strong earthquakes have occurred along the active fault zone in the Jiaodong Peninsula Penglai–Weihai fault zone, such as the Weihai M6.0 and Bohai M7.0 (Pan et al., 2015; Qu et al., 2021).

The No. Lu 32 well is located near the eastern side of the Haixitou–Lidao Fault, which is a fracture developed on land at the easternmost tip of the Penglai–Weihai fault zone (Figures 1, 2). The Yantai–Weihai section in the eastern part of the Penglai–Weihai fault zone is a Middle Pleistocene active tectonic section, and no Late Pleistocene stratigraphic discontinuity has been found there until now. The Penglai–Weihai fault zone has controlled the occurrence of historical earthquakes; the 1548 M7.0 earthquake occurred in the western part of the fault zone, and the 1948 M 6.0 earthquake occurred in its eastern part (Wang et al., 2006; Pan et al., 2015; Gu et al., 2020). The Haixitou–Lidao Fault is 27 km long, with a strike of 300°–320° and a tendency to the northeast. The middle of the fault has gentle dips of 50°–60°, while the northwest and southeast sections have larger dips of 75°–85°. The whole fault zone forms a gentle wave shape. The fault appears as a transitional zone of different colors from satellite images, with light gray–white areas on the northeast side and green, brown, and pink areas on the southwest side. The topography and landforms have obvious tonal contrasts along the fault, which indicates the controlling role of the fault on the landform. The fault experienced different activities from the Early to Middle Pleistocene, but these movements have ceased since the Late Pleistocene. According to its tectonic rock characteristics, overlying geological ages, and geomorphological features, the northwest section of the fault (Haixitou–Wangguanzhuang section) has manifested older activity, implying that it was active in the pre-Quaternary, while the southeast section (Chegu–Lidao section) was active in the Middle Pleistocene.

3 Data and methods

3.1 Hydrochemical characteristics and δD and $\delta^{18}O$ stable isotopes

To analyze the genesis of water temperature variations, water samples from the No. Lu 32 well were collected from March 2016 to April 2018. Chemical ion concentrations and δD and $\delta^{18}O$ stable isotope compositions

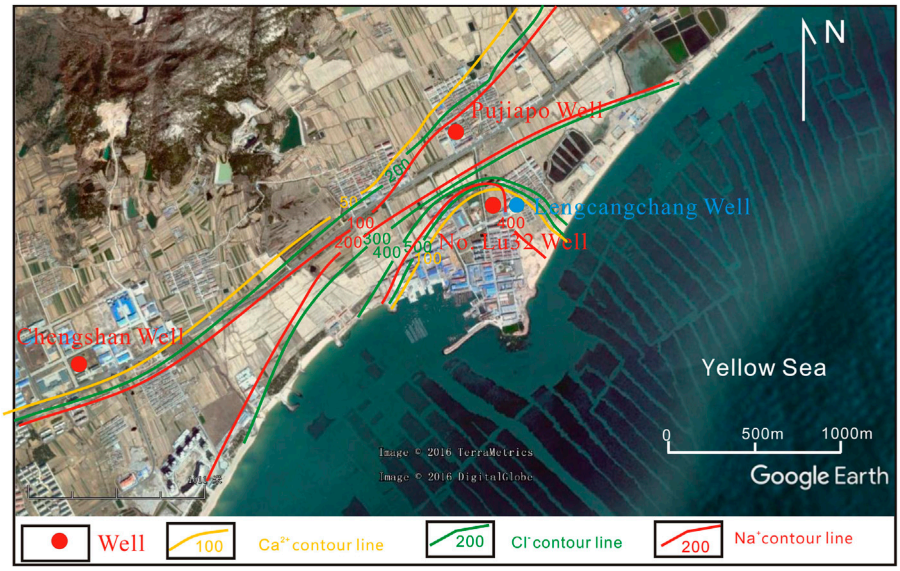

FIGURE 2
Location and distribution of the ion contours of the No. Lu 32 well and surrounding wells (sampling period: April 2017).

in water samples were measured. To analyze the spatial distribution characteristics of water chemistry, the ion contents and hydrogen and oxygen isotope compositions of the Lengcangchang, Pujiapo, and Chengshan wells in the vicinity were collected and tested in April 2017 (Figure 2). The Lengcangchang well is located approximately 50 m from the No. Lu 32 well, the Pujiapo well is approximately 600 m from it, and the Chengshan well is approximately 3.5 km from the No. Lu 32 well (Figure 2). The ion concentrations and δD and $\delta^{18}O$ stable isotope compositions were measured at the Key Laboratory of Crustal Dynamics, National Institute of Natural Hazards, Ministry of Emergency Management of China. Volumetric analysis methods and CIC-200 ion chromatograph were used for hydrochemistry analysis. δD and $\delta^{18}O$ stable isotopes were measured using a type of LGR 912-0008 Hydrogen-Oxygen Stable Isotope Analyzer.

3.2 Water temperature for long-term observations

The No. Lu 32 well is 94 m deep, and the observed aquifer is fracture water in granite. Digital underground water temperature and water level observations have been implemented since September 2007. The No. Lu 32 well uses an SZW-1A digital thermometer for geothermal observation, with a probe depth of 89 m, and an LN-3A digital water level meter for digital water level observations was used in the well with a probe depth of 7.1 m.

4 Results

The hydrochemical characteristics and δD and $\delta^{18}O$ stable isotope compositions are shown in Table 1. The ion contents and hydrogen and oxygen isotope compositions of the wells and seawater were collected in April 2017 and tested once, while the waters from No. Lu 32 well were collected five times from March 2016 to April 2018. It can be seen from Table 1 that the ion contents of seawater were higher than those of the wells.

4.1 Chemical type of the No. Lu 32 well water

Piper diagrams were drawn according to the Ca^{2+}, Mg^{2+}, and Na^+–K^+ concentrations and relative Cl^-, SO_4^{2-}, and HCO_3^-contents (Figure 3), which can directly indicate the general chemical characteristics of the samples and water types. The intersection point obtained from the upper diamond represents the milliequivalent contents of anions and cations in the waters, the triangle in the lower left corner represents the milliequivalent contents of cations, and the triangle in the lower right corner represents the milliequivalent contents of anions. Figure 3 shows that the Na^+, K^+, and Cl^- milliequivalent concentrations were relatively high, and the water chemistry type of the No. Lu 32 well was the Cl–Na type, indicating intermediate mineralization water of mixed origin and that the water may be related to seawater.

4.2 Water–rock reaction processes

The Na–K–Mg ternary diagram is mainly used to analyze the water–rock equilibrium state in groundwater (Su et al., 2021). According to the analysis of the Na–K–Mg ternary diagram, seawater is located near the mineral equilibrium line, and the Na–K–Mg water–rock interaction reaches the ionic equilibrium state (Figure 4). In contrast, the data of the No. Lu 32 well and nearby wells were basically distributed near the Mg end, which indicated unsaturated water, the water–rock interaction had not yet reached the ionic equilibrium state, and the water–rock interaction was still ongoing, indicating that the No. Lu 32 well possessed the characteristics of shallow water (Figure 4).

TABLE 1 Hydrochemical characteristics of the No. Lu 32 well and seawater in the Jiaodong Peninsula.

No.	Name	K^{+} (mgL^{-1})	Na^{+} (mgL^{-1})	Ca2+ (mgL^{-1})	Mg^{2+} (mgL^{-1})	F^{-} (mgL^{-1})	Cl^{-} (mgL^{-1})	SO_4^{2-} (mgL^{-1})	NO^{3-} (mgL^{-1})	HCO_3^{-} (mgL^{-1})	δD (‰)	δ^2O (‰)	Data
1	Lu32 well	54.91	288.91	28.95	54.32	1.96	531.29	162.17	94.65	N.D.	−51.48	−7.43	Mar 2016
2		50.04	299.28	111.36	21.52	0.84	578.98	133.19	71.80	154.08	−71.94	−10.43	Jun 2016
3		28.363	304.290	111.288	25.259	1.217	517.105	132.502	73.006	N.D.	−67.11	−9.33	Dec 2016
4		15.262	498.236	125.576	10.632	0.779	866.124	123.319	54.530	361.769	−54.95	−7.32	Apr 2017
5		33.92	480.07	131.69	27.23	0.92	926.13	109.87	47.66	227.98	−39.50	−4.90	Apr 2018
6	Seawater	442.72	9818.6	343.56	1241.94	3.06	17543.14	2411.94	82.52	158.156	−5.097	−0.538	Aug 2017
7	Lengcangchang well	2.010	323.774	141.328	19.768	0.375	715.009	152.728	65.583	244.312	−41.73	−5.94	Apr 2017
8	Chengshan well	5.385	67.521	26.392	4.708	0.331	131.082	31.669	6.033	155.044	−53.00	−7.615	Apr 2017
9	Pujiapo well	7.837	132.828	75.356	9.436	0.389	242.024	64.062	219.51	79.8712	−50.35	−7.06	Apr 2017

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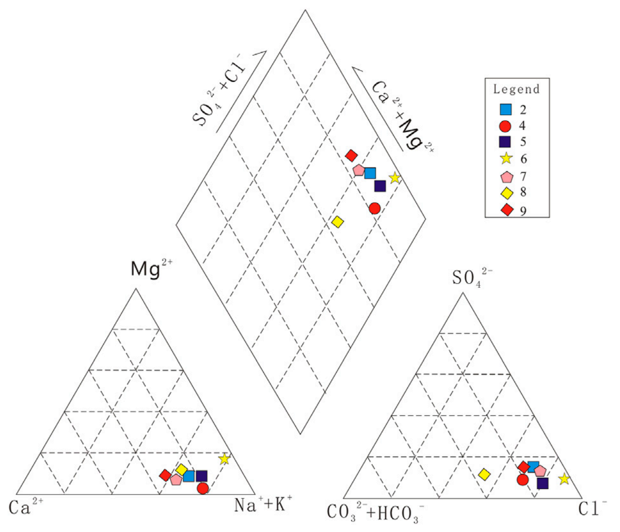

FIGURE 3
Piper diagram of the No. Lu 32 well.

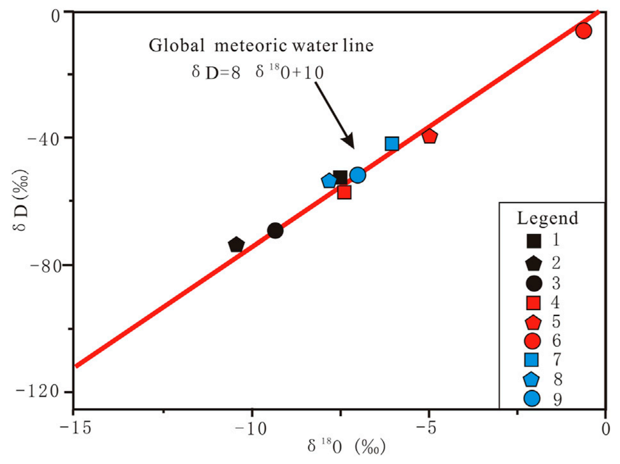

FIGURE 5
Relationships between the δD and $\delta^{18}O$ values of the No. Lu 32 well and the Global Meteoric Water Line (GMWL) [the number in the figure corresponds to that in Table 2, and the GMWL is from (Craig, 1961)].

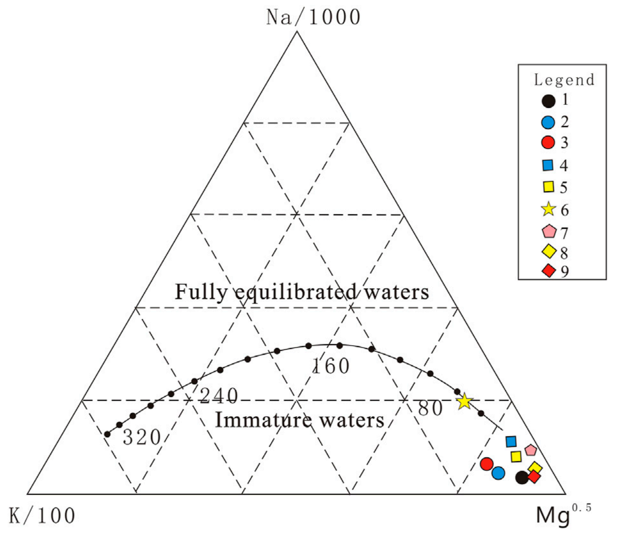

FIGURE 4
Na–K–Mg diagram of the No. Lu 32 well (the number in the figure corresponds to that in Table 1).

4.3 δD and $\delta^{18}O$ stable isotope characteristics

The isotope analysis method has been widely used in environmental hydrogeological research. The analysis of hydrogen and oxygen isotopes is an effective method for constraining the origin of groundwater (Tiwari et al., 2020; Sasaki et al., 2021; Duan et al., 2022). The Global Meteoric Water Line is the red line in Figure 5 (Craig, 1961; Li et al., 2011). The hydrogen and oxygen stable isotopes of nine samples were distributed near this line, and it is inferred that the study well and adjacent wells were influenced by meteoric water.

4.4 Annual variations in water temperature

The water temperature of the No. Lu 32 well has shown several fluctuations since January 2014, with a maximum variation of approximately 0.10°C.The water temperature exhibits a certain annual variation, and its variations from 2018 were used as an example. As shown in Figure 6, the water temperature in the observation well fluctuated several times between October and May of the following year, and the characteristics of the changes varied from year to year.

5 Discussion

Fluid geochemistry, such as the determination of hydrogeochemical characteristics and measurement of stable hydrogen and oxygen isotopes, is a promising and important method for determining the genesis of groundwater (Su et al., 2021; Du et al., 2023). Based on previous geological data of water chemistry and hydrogen–oxygen isotope compositions, water chemistry data were first used to analyze the water type and water–rock interactions of the No. Lu 32 well; the relationship between the No. Lu 32 well and meteoric water was then analyzed based on the hydrogen–oxygen isotope compositions.

5.1 Spatial distribution of ion contents in the No. Lu 32 well and neighboring wells

Coastal zones are the most sensitive regions on Earth, and have multiple groundwater quality types, such as fresh, brackish, and saline

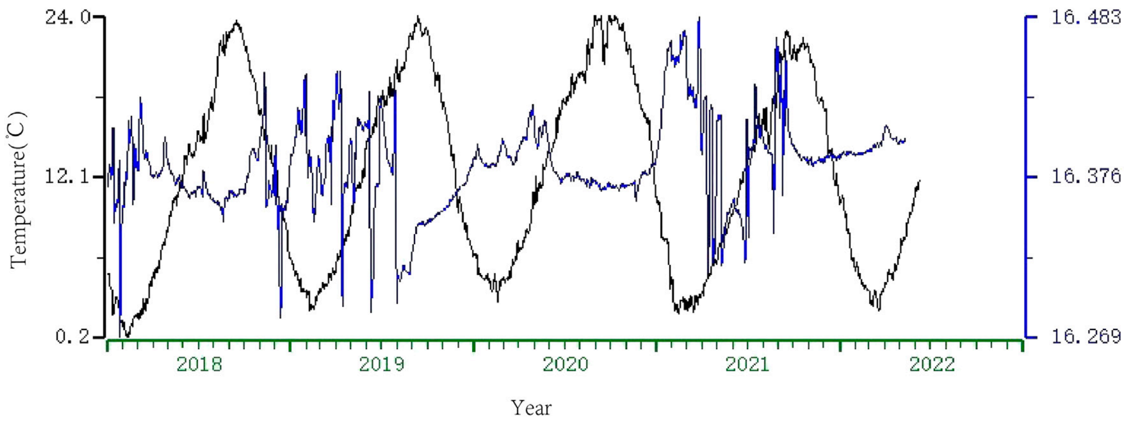

FIGURE 6
Comparison of temperature between CSTSTOS and the No. Lu 32 well from January 2018 to May 2022. The black line is the seawater temperature of CSTSTOS, and the blue line is the groundwater temperature of the No. Lu 32 well.

TABLE 2 Seawater and groundwater mixing at different ratios.

Name		K^+ (mgL⁻¹)	Na^+ (mgL⁻¹)	Ca^{2+} (mgL⁻¹)	Mg^{2+} (mgL⁻¹)	F^- (mgL⁻¹)	Cl^- (mgL⁻¹)	SO_4^{2-} (mgL⁻¹)	NO^{3-} (mgL⁻¹)	HCO_3^- (mgL⁻¹)
Seawater		442.72	9818.6	343.56	1241.94	3.06	17543.14	2411.94	82.52	158.156
Pujiapo well		7.837	132.828	75.356	9.436	0.389	242.024	64.062	219.51	79.8712
Seawater mixing ratio	5%	29.58	617.11	88.76	71.06	0.52	1107.08	181.45	212.66	83.78
	10%	51.32	1101.4	102.17	132.68	0.65	1972.13	298.84	205.81	87.69
Average value of the No. Lu 32 well		36.49	374.157	101.77	27.79	1.143	683.92	132.21	68.329	247.94

water (Sun et al., 2023). The results of the water chemistry analysis in April 2017 showed the contours of Na^+, Ca^{2+}, and Cl^- in the No. Lu 32, Chengshan, and Pujiapo wells (Figure 2). At the same time, with increasing distance from the sea, the ion content of seawater exhibited a decreasing trend from the No. Lu 32, Lengcangchang, and Chengshan wells to the Pujiapo well, suggesting that their sources may be seawater infiltration. This spatial distribution characteristic of the water chemistry compositions is consistent with previous research results in other coastal zones (Liu et al., 2017; Sun et al., 2023).

5.2 Seawater mixing effect

From the water chemistry data, we found that the No. Lu 32 well received a small amount of seawater recharge, and the mixing ratio of seawater was calculated using the water chemistry ratio method (Jaime, 1990; Wang, 2018) by the following equation:

$$M = x^*F + (1 - x)^*S \quad (1)$$

where x is the proportion of groundwater in the mixing water, F is the content of a certain ion in groundwater, (1−x) is the proportion of seawater in the mixing water, S is the content of a certain ion in seawater, the ion content in seawater is referred to as the global average ion contents (Wang, 2018), and M is the content of a certain ion in the mixing water. The calculation results are shown in Table 2. The mixing ratio of the No. Lu 32 well was approximately 5%.

5.3 Annual variations between well and seawater temperatures

To analyze the possible effects of seawater temperature changes on groundwater temperature in the No. Lu 32 well, we collected the ocean forecast values of the surface water temperatures in the neighboring area, Port West, which is next to a farming area (Figure 2); the temperature comparison chart is shown in Figure 6.

There is a clear seasonal variation in the seawater temperature in the western Yellow Sea region (Hou et al., 2010), with an increasing trend in April and the highest annual surface water temperature from June to August; the highest values in 20 m and 30 m of seawater start in August–October (Quan et al., 2013), which is also similar to the time when the water temperature in the No. Lu 32 well exhibits an increasing trend (Figure 6). As the coastal area of the Jiaodong Peninsula has experienced severe seawater backflow in recent years, we cannot eliminate the possibility that seawater backflow and other factors influence the water temperature in the observation well.

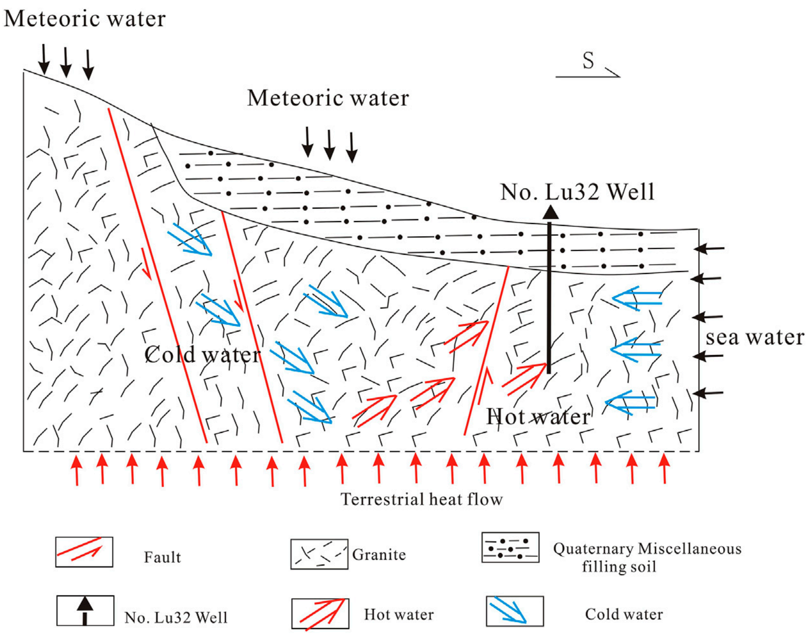

FIGURE 7
Genetic model of the No. Lu 32 well.

5.4 Genetic model

Through analyzing hydrochemical characteristics and hydrogen and oxygen isotope characteristics, combined with geochemical and geological survey results, the genesis of groundwater can be comprehensively inferred, providing a scientific basis for the analysis of water temperature change characteristics (Sui et al., 2020; Du et al., 2023). The Na^+, K^+, and Cl^- concentrations were relatively high, which may be related to the influence of seawater, while the hydrogen and oxygen isotopes showed that meteoric water may be the source of the No. Lu 32 well. Based on the surrounding geological features, as well as the groundwater and seawater, the groundwater genetic model of the No. Lu 32 well was established (Figure 7). Figure 7 shows that the water level is influenced by meteoric water, while the water temperature changes produce a certain annual pattern of variation due to the influence of seawater. Our research conclusion is similar to the groundwater study in the adjacent area of the Huanghai Sea (Gao et al., 2016; Sun et al., 2023).

6 Conclusion

The water chemistry type of the No. Lu 32 well is Cl–Na, which indicates intermediate mineralization water with a mixed origin. The Na–K–Mg ternary diagram analysis reveals that the water is unsaturated, the water–rock interaction state has not yet reached ionic equilibrium, and the water–rock interaction is still ongoing, indicating that the No. Lu 32 well exhibits the characteristics of shallow water. The hydrogen and oxygen isotope distributions are near the meteoric water line, and it is presumed that the No. Lu 32 well and the neighboring wells are influenced by meteoric water. Since the water temperature of the No. Lu 32 well has some quasi-synchronous and morphological similarity with seawater temperature, the results of the water chemistry and isotope analysis of this well also indicate that the groundwater is influenced by seawater. A comprehensive analysis suggests that the No. Lu 32 well is affected by various factors, including seawater backflow infiltration and shallow water.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

GD: methodology, data curation, and writing—original draft preparation. SS: writing—review and editing. BZ: methodology, conceptualization, and writing—review and editing. LS: writing—review and editing. XC: writing—review. HR: methodology, data curation, and validation. MS: editing. LW: editing.

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Conflict of interest

Author LW was employed by CNPC East China Design Institute Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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