Occurrence and flow systems of the anticline-controlled thermal groundwater near Chongqing in eastern Sichuan Basin of China

Mingming Ta, Xun Zhou, Yanqiu Xu, Yuan Wang, Juan Guo and Xinyun Wang

ABSTRACT

A review and assessment of earlier studies shows that the thermal groundwater near Chongqing in the eastern Sichuan Basin of China has a unique occurrence called the 'basin-anticline outcropping' type. Its occurrence and emergence are strongly controlled by the nearly north–south trending anticlines. The basin-anticline outcropping type groundwater is similar to that of the basin type but also has the characteristics of the outcropping type because of the anticlines. The natural hot springs in the study area exist mainly in the outcropping areas of the carbonates, in the middle and the plunging ends of the anticlines where the topography was cut by rivers. They can also rise through the overlying sandstones and form up-flow springs. Geothermal wells tapping the carbonate reservoirs on the flanks of the anticlines also produce thermal groundwater. The groundwater flow can be divided into three levels: (1) shallow circulation system with groundwater of HCO_3-Ca type and low TDS discharging through normal temperature springs, (2) middle circulation system with groundwater of SO_4-Ca type and TDS of 2–3 g/L discharging through hot springs and (3) deep circulation system with groundwater of Cl-Na type and high TDS discharging through hot springs or wells.

Key words | anticline, groundwater flow system, occurrence, Sichuan Basin, thermal groundwater

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HIGHLIGHTS

- The occurrence and emergence of the thermal groundwater near Chongqing in eastern Sichuan Basin of China are strongly controlled by the nearly north–south-trending anticlines, which are different from those of the common deep-fault circulation type controlled by faults.
- The occurrence type of thermal groundwater is called the 'basin-anticline outcropping' type, which is similar to that of the basin type and also shows the characteristics of the outcrop type effected by the anticlines.
- Hot springs mainly exist in the outcropping areas of the carbonates in the middle and the plunging ends of the anticlines where the topography was cut by rivers, or rise through the overlying sandstones and form the up-flowing springs.

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- Along the anticlinal structures, the groundwater flow systems can be divided into three levels: (A) shallow circulation system, (B) middle circulation system and (C) deep circulation system, respectively.
- The unique occurrence and emerging characteristics of thermal groundwater are a supplement to the characteristics of thermal groundwater worldwide.

INTRODUCTION

The occurrence of thermal groundwater can be divided into the buried type and outcropping type from the point of view of natural outcropping conditions of geothermal water (Zhou *et al.* 2006). The former is also called the sedimentary basin type (abbreviated as basin type), which mainly includes the fault basin type and the depression basin type. It refers to the thermal groundwater in the deep-seated aquifers in sedimentary basins without geothermal manifestations on the land surface (or occasional hot springs of low temperature along the edge of the basins) (Zhou *et al.* 2017a).

Examples of basin type thermal groundwater include the deep thermal groundwater resources in Mesozoic and Cenozoic fault basins in the North China Plain (Chen *et al.* 1994); geothermal resources in the western Sichuan depression basin (Cui 2014); thermal groundwater resources in the western Pannonian sedimentary basin in Central Europe (Rman *et al.* 2015); geothermal resources in the Molasse basin in Southern Germany (Dussel *et al.* 2016) and geothermal systems in the western fault basin and eastern depression basin of the Snake Plain in the United States (Reed 1983). On the other hand, the outcropping type refers to the thermal groundwater that emerges on the land surface in the form of hot springs (also known as the hot spring type), which can further be divided into the deep-fault circulation type, non-fault type and volcano-magma related type. The occurrence of geothermal resources of the deep-fault circulation type is strictly controlled by faults of a certain scale (Wang *et al.* 1993). For example, the Xianyang geothermal field in northwest China is controlled by the Weibei fault (Luo *et al.* 2017); the Brady's geothermal field in the United States by a nearly N-NNE trending fault zone (Jolie *et al.* 2015), the hot spring groups in the western Malaysia by the NW-trending fault (Baioumy *et al.* 2015), and the fault-controlled geothermal systems in the southeastern Alaska and the northern Rocky Mountains in the United States (Reed 1983). This type of thermal groundwater occurs along the fault extension of a certain range, and generally shows a zonal distribution. Correspondingly, the emergence of some hot springs of low–medium temperature is not obviously controlled by faults or is independent of faults (non-fault type). The occurrence of this thermal groundwater is confined to the vicinity of the hot springs and the shape of the geothermal reservoir is irregular. Examples include the Baimiao hot spring near Zhangjiakou of China (Zhou *et al.* 2017a), bedrock thermal groundwater in Idaho in the United States (Mariner *et al.* 2006), and the geothermal resources in Zagros of Iran (Mohammadi *et al.* 2010). Volcano-magma related type geothermal fields are related to concealed high temperature magma or modern volcanoes, often with hot springs or fountains of high temperature. Examples include the Tengchong and Yangbajing geothermal fields of Yunnan and Tibet (Guo *et al.* 2007, 2014; Zhang *et al.* 2008), thermal groundwater along the Pacific coast of Mexico (Taran *et al.* 2013), hot springs near the Azores in Portugal (Freire *et al.* 2014), and the Cascade Range (active volcanic chain along the Pacific Northwest) in the western United States (Reed 1983).

The occurrence of the thermal groundwater near Chongqing in the eastern Sichuan Basin of China cannot be classified as basin or outcropping type but combines both types. Strongly controlled by the anticlines, the thermal groundwater occurs along the anticlinal structure line, and the hot springs (wells) mainly exist in the middle, the two flanks and the plunging ends of the anticlines. The hot springs and the normal temperature springs exist in the study area at the same time, and the Yangtze River flows through the whole area (the lowest discharge base level in the study area), which provides a good hydrogeological basis for the application of regional groundwater flow theory in the 'basin-anticline' area. Previous studies on the hot water near Chongqing mostly focused on the hydrochemical characteristics (Yang *et al.* 2011; Xiao *et al.* 2015), the geothermal resources (Cheng *et al.* 2015), the reservoir temperature (Yang *et al.* 2019), the depth of circulation and the source of recharge (Yang *et al.* 2017; Xiao *et al.* 2018).

However, the groundwater flow system and the occurrence characteristics of the thermal groundwater in Chongqing have been seldom examined. The aim of this paper is to identify the unique groundwater flow system and to study the occurrence characteristics of the thermal groundwater and hot springs in the study area to supplement previous work. The results of this study are obtained from a collation, review and reinterpretation of data from earlier studies.

GEOLOGICAL SETTING

The Sichuan Basin is a cratonic sedimentary basin characterized by Mesozoic inland depression (Zhou *et al.* 2017b). The study area (near Chongqiong, including Yuzhong, Jiangbei, Yubei, Beibei, Jiangjin, and Banan districts) is located in the eastern part of the basin, where a series of NE-NNE-trending high-steep folds were developed as the results of the Sichuan Tectonic Movement (Figure 1). Within this area, the anticlines form mountains and the synclines form the valleys, together constituting parallel ridges and valleys. The hilly terrain in the syncline areas is composed of Jurassic red sandstone and mudstone with a thickness of more than 1,000 m (Figures 2 and 3) (Yang *et al.* 2017). The hydrodynamic conditions are poor, and there are no or very few geothermal resources, and only a small amount of subsurface brine is found in the deep parts (Cheng *et al.* 2015). The ridge-like

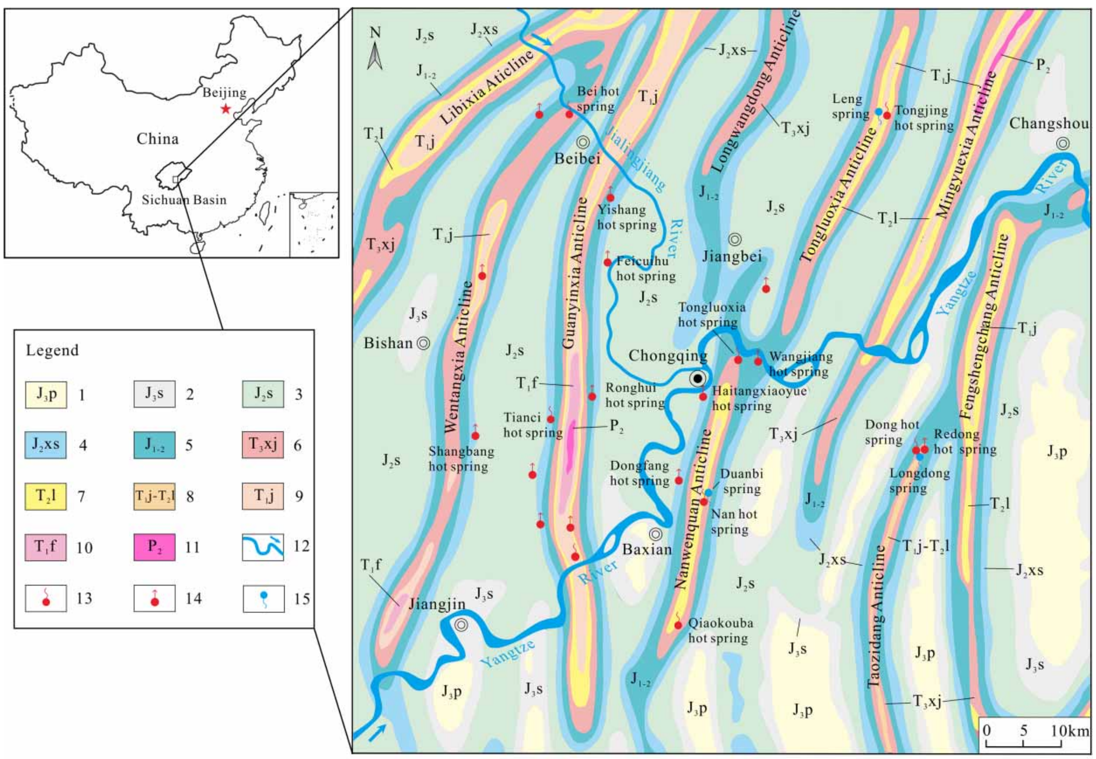

Figure 1 | Map of geothermal geology of the study area. 1 Quartz sandstone of the Upper Jurassic Penglaizhen Group; 2 Sandy mudstone of the Upper Jurassic Suining Group; 3 Sandy mudstone of the Middle Jurassic Shangshaximiao Group; 4 Shale and sandy mudstone of the Middle Jurassic Xiashaximiao Group; 5 Mudstone of the Lower and Middle Jurassic; 6 Feldspathic detritus quartz sandstone of the Upper Triassic Xujiahe Group; 7 Dolomite and Limestone of the Middle Triassic Leikoupo Group; 8 Limestone and Dolomite of the Lower Triassic Jialingjiang and Middle Triassic Leikoupo Groups; 9 Limestone of the Lower Triassic Jialingjiang Group; 10 Marl of the Lower Triassic Feixianguan Group; 11 Chert nodule limestone of the Upper Permian; 12 River; 13 Hot spring; 14 Geothermal well; 15 Normal temperature spring.

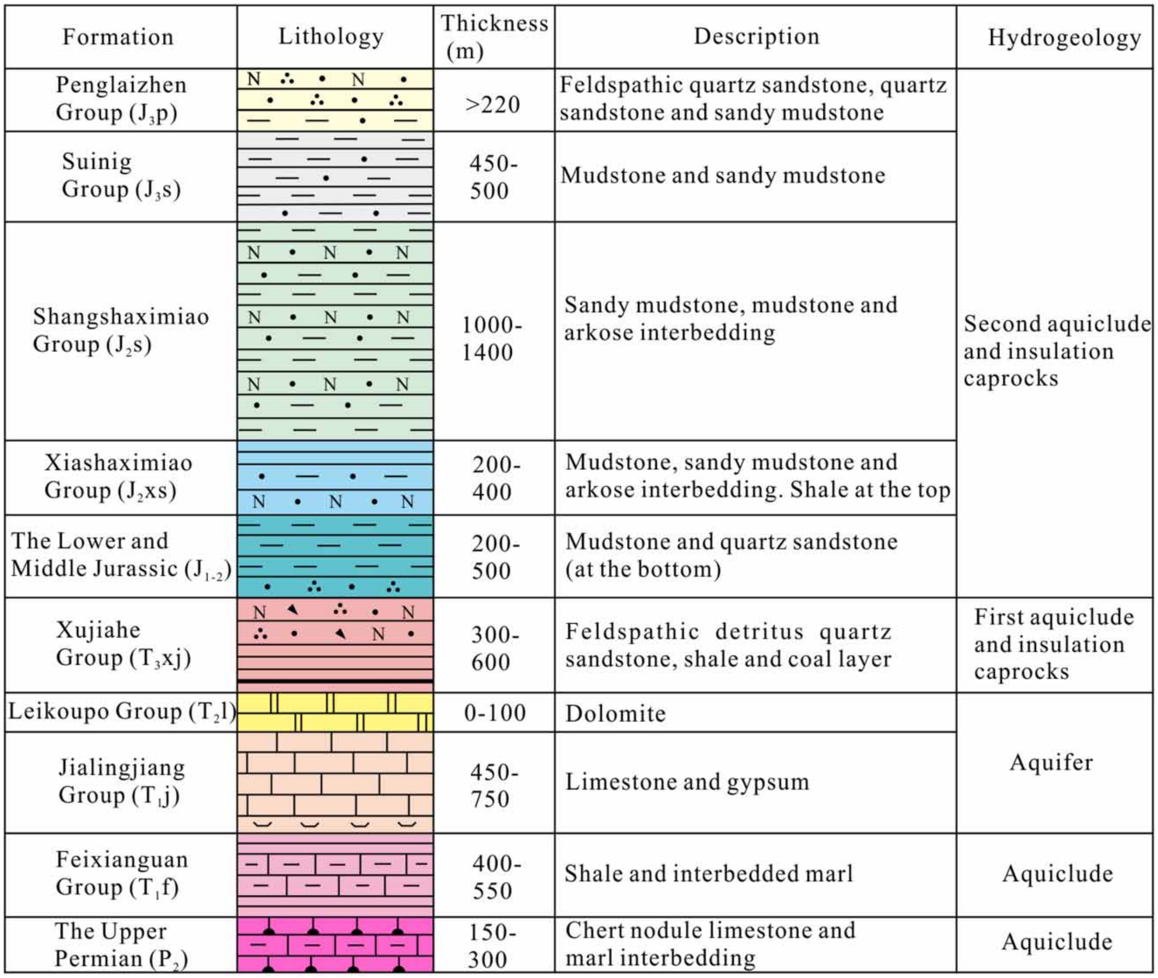

Figure 2 | Stratigraphic column of the outcropping formations in the study area.

landforms consisting of sandstone, shale and thin coal seam of the Upper Triassic Xujiahe Group (T_3xj) occur in the paraxial parts of the two flanks and the plunging ends of the anticlines with a thickness of about 450 m. In the core of some anticlines, such as the Wentangxia anticline, there is the 'one mountain with one ridge' landform (Figure 4(a)). The Upper Triassic Xujiahe Group (T_3xj) together with the overlying Jurassic sandstone and mudstone constitute the insulation caprocks of the geothermal reservoir in the study area (Figure 3) (Li & Liu 2011). At the axis of the anticlines, the carbonate of the Lower Triassic Jialingjiang Group (T_1j) and the Middle Triassic Leikoupo Group (T_2l) are the main geothermal reservoirs in the study area, with a thickness of about 600 m (Xiao *et al.* 2018). Karst valleys were formed in the outcropping areas of the carbonates due to the weathering and river cutting, which constitutes a unique landscape in Chongqing, namely, 'one mountain with one valley and two ridges' (Figure 4(b), such as the middle part of the Tongluoxia anticline, Nanwenquan anticline and Taozidang anticline). The hot water exists in the two flanks of the anticlines and receives the recharge from precipitation in the valley areas. In addition, the landform 'one mountain with two valleys and three ridges' also exists (Figure 4(c)), such as the southern plunging ends of the Wentangxia and Guanyinxia anticlines and the northern plunging end of the Mingyuexia anticline. The thermal groundwater occurring in the two flanks of the anticlines receives recharge from precipitation in the corresponding valley areas. The marl and shale of the Lower Triassic Feixianguan Group (T_1f) constitute the lower confining bed of the thermal groundwater, which sporadically

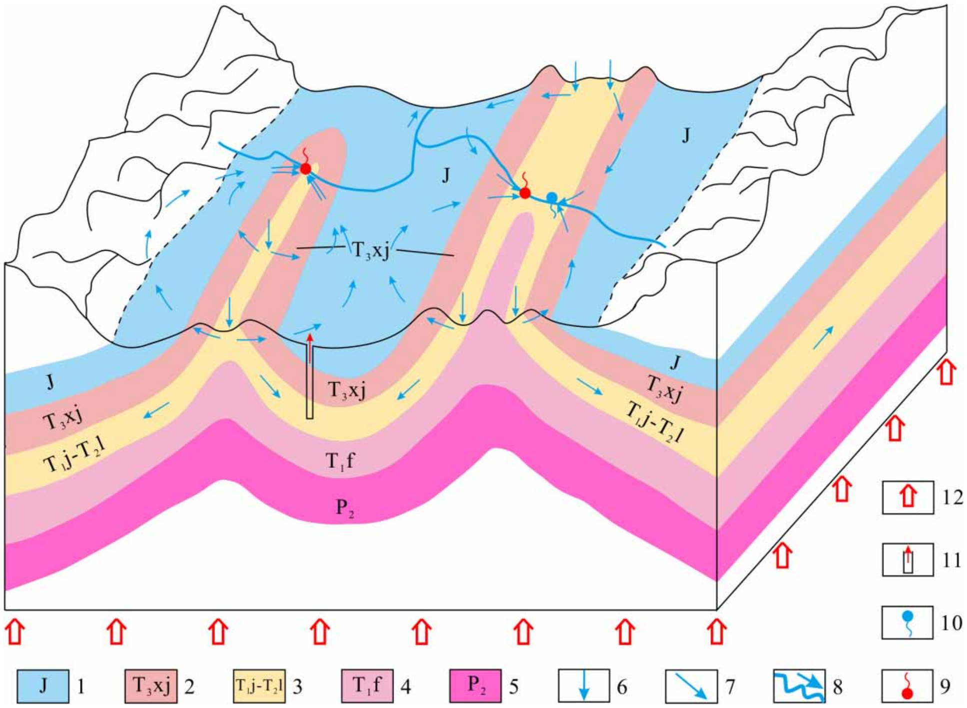

Figure 3 | Conceptual model of the geothermal water occurrence near Chongqing in eastern Sichuan Basin ('basin-anticline outcropping' type). 1 Jurassic sandstone aquiclude; 2 Sandstone aquiclude of the Upper Triassic Xujiahe Group; 3 Carbonate aquifer of the Lower Triassic Jialingjiang and Middle Triassic Leikoupo Groups; 4 Marl aquiclude of the Lower Triassic Feixianguan Group; 5 Chert nodule limestone of the Upper Permian; 6 Infiltration of precipitation; 7 Direction of groundwater flow; 8 River; 9 Hot spring; 10 Normal temperature spring; 11 Geothermal well; 12 Heat flow.

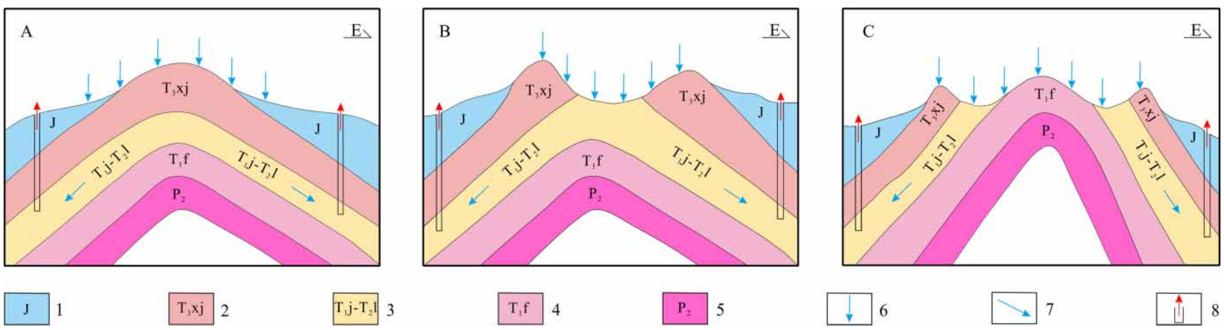

Figure 4 | Schematic cross sections showing the occurrence of geothermal water in the anticlines near Chongqing. Legends are consistent with those in Figure 3 (modified after Ta *et al.* (2018) and Cheng *et al.* (2015)).

outcrop in the axes of some anticlines (e.g. the Wentangxia anticline and Guanyinxia anticline) (Figure 1).

OCCURRENCE CHARACTERISTICS OF THE THERMAL GROUNDWATER

The thermal groundwater in the study area has a unique occurrence called the 'basin-anticline outcropping' type. The occurrence of thermal groundwater is strictly controlled by the anticlines. Horizontally, the hot water distributes in the carbonates in the cores or/and two flanks of the anticlines (Figure 1). Because of the control of the anticlines, the occurrence of the thermal groundwater is consistent with that of the anticlines. In the favorable terrains cut by rivers at the middle and the plunging ends of the anticlines, the thermal groundwater discharges to the surface (mostly in the form of hot springs under natural conditions), which conforms to the characteristics of the outcropping type of geothermal water. Vertically, the thermal groundwater exists in layers coinciding with the formation strike in the two flanks of the anticlines, which is closely characterized by the basin type (Figure 3). The geothermal reservoirs occurring in the paraxial parts of the two flanks of the anticlines present a certain dip angle. The dip angle ranges from 20 to 30° in the relatively gentle flanks, and in the steeper flanks, from 40 to 70° (Zhou et al. 2015). Towards the syncline areas, the geothermal reservoirs become buried and the dipping angle decreases gradually until it approaches zero degree. Under this condition, the discharge of the thermal groundwater occurs mainly through the geothermal wells tapping the geothermal reservoirs.

In summary, the 'basin-anticline outcropping' type thermal groundwater occurs in the deep-seated aquifers in sedimentary basins that rises to the land surface in the form of the hot springs affected by the anticline structures.

EMERGENCE CHARACTERISTICS AND GENESIS OF THE HOT SPRINGS

The hot springs in the study area mainly exist in the outcropping areas of the T_1j–T_2l carbonates in the cores of the anticlines. Wells drilled to the T_1j–T_2l geothermal reservoirs through the overlying Jurassic sandy mudstones and T_3xj sandstones and shales in the flanks of the anticlines also produce thermal water (Figures 1 and 3) (Zeng 2013; Ta et al. 2018, 2019). Examples of hot springs include the Dong hot spring (49.5 °C) in the Taozidang anticline, the Tongjing hot spring (50.3 °C) in the Tongluoxia anticline, the Nan hot spring (39.6 °C) and Dongfang hot spring (well, 49.2 °C) in the Nanwenquan anticline, the Feicuihu hot spring (well, 42.6 °C) and Ronghui hot spring (well, 41.1 °C) in the Guanyinxia anticline, and the Bei hot spring (36.7 °C) and Shangbang hot spring (well, 42.8 °C) in the Wentangxia anticline (Figure 1). The hot springs are all of the SO_4-Ca type with the TDS of 2,038–3,035 mg/L and the temperature of 32.9–52° (Table 1).

The natural hot springs in the study area mainly occur in the low terrain of the valleys cut by rivers in the middle part of the high and steep anticlines (mostly in the riverbed or the foot of the bank slope). The genesis model of these hot springs is as follows: groundwater receives recharge from precipitation in the outcropping areas of the carbonates in the axes of the anticlines, flows along the two flanks of the anticlines to the middle part, and is heated by the heat flow from below, and rises to the surface in the valleys cut

Table 1 | Physical and chemical parameters of the samples

Samples	T	TDS	Hydrochemical type	Samples	T	TDS	Hydrochemical type
Hot spring/well				Dong	49.5	2,722	SO_4-Ca
Bei	36.7	2,330	SO_4-Ca	Tongluoxia	41	3,035	SO_4-Ca
Shangbang	42.8	2,926	SO_4-Ca	Normal temperature spring			
Yishang	32.9	2,923	SO_4-Ca	Longdong	20.7	497	HCO_3-Ca
Feicuihu	42.6	2,684	SO_4-Ca	Duanbi	24	459	HCO_3-Ca
Ronghui	41.1	2,038	SO_4-Ca	Leng[a]	17.4	530	HCO_3-Ca
Tianci	42.6	2,834	SO_4-Ca	Saline spring			
Tongjing	50.3	2,550	SO_4-Ca	Fengjiejiba[b]		25,890	
Wangjiang	40.1	2,860	SO_4-Ca	SC2[c]	37.9	14,095	Cl-Na
Haitangxiaoyue	52	2,929	SO_4-Ca	SC2-2[c]	36.1	14,135	Cl-Na
Dongfang	49.2	2,464	SO_4-Ca	SC3[c]	38	12,408	Cl-Na
Nan	39.6	2,310	SO_4-Ca	Brines			
Qiaokouba	41.3	2,641	SO_4-Ca	Wo 57[d]		105,666	Cl-Na
Redong	43.5	2,720	SO_4-Ca	Chuan 25[d]		352,693	Cl-Na

The water temperature (T) is in °C; the TDS is in mg/L.
Data from [a]Yang et al. (2019); [b]Guo et al. (2019); [c]Guo et al. (2017); [d]Zhou et al. (2015).

by rivers crossing the anticlines (Figure 5(a)). For example, the Nan hot spring exists in the Huaxihe River valley in the middle of the Nanwenquan anticline and the Tongjing hot spring emerges in the Wentanghe River valley in the middle of the Tongluoxia anticline. Some hot springs appear in the plunging ends of the anticline, which can be divided into two types. One is where the groundwater receives recharge from precipitation in the recharge area (the outcropping area of carbonates in the cores of the anticlines) where it is heated by heat from below as it flows to the northern and southern plunging ends of the anticlines. There it rises to the land surface through fractures in the overlying T_3xj sandstone aquicludes and forms hot springs (Zhou *et al.* 2016) (Figure 5(b)). Examples include the Bei hot spring near the Jialingjiang River in the northern plunging end of the Wentangxia anticline and the Tongluoxia hot spring near the Yangtze River in the northern plunging end of the Nanwenquan anticline. Another type is where the groundwater flows along the anticlinal axes towards the southern and northern ends of the anticlines after receiving the recharge from precipitation in the recharge areas and forms the springs in the outcropping areas of the carbonates at the low terrains cut by the rivers (Figure 5(c)). Examples include the Dong hot spring near the Wubuhe River in the northern plunging end of the Taozidang anticline and the Qiaokouba hot spring near the Jiantanhe River in the southern plunging end of the Nanwenquan anticline. Geothermal wells have been constructed mainly in the two flanks of the anticlines with a few in the axes of the anticlines. The wells also reveal the hot water when tapping the carbonate geothermal reservoir (Figure 5(d)). The genesis model of the hot water in these wells is as follows: after

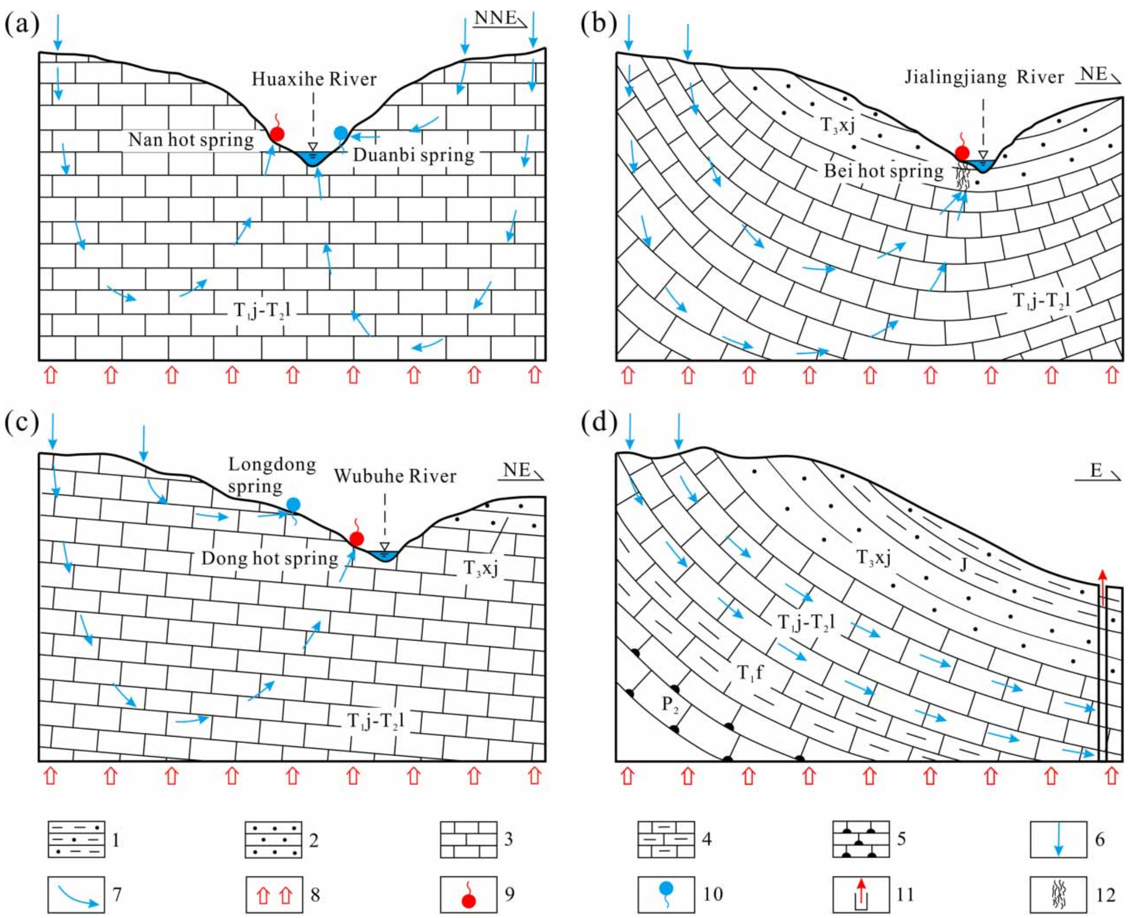

Figure 5 | Schematic profiles showing genesis of the hot springs near Chongqing. 1 Sandy mudstone; 2 Sandstone 3 Carbonate; 4 Marl; 5 Chert nodule limestone; 6 Infiltration of precipitation; 7 Groundwater flow direction; 8 Heat flow; 9 Natural hot spring; 10 Normal temperature spring; 11 Geothermal well; 12 Fracture zone.

receiving recharge from precipitation, part of the groundwater flows to the syncline areas (transverse flow) and is heated by the heat flow. Examples include the Yishang geothermal well in the eastern flank of the Guanyinxia anticline and the Haitangxiaoyue geothermal well in the western flank of the Nanwenquan anticline.

In summary the emerging characteristics of the hot springs in the study area are as follows: Most of the natural hot springs of low-middle temperature exist in the outcropping areas of carbonates in the middle and the plunging ends of the high and steep anticlines, while several appear in the low terrain of sandstones in the plunging ends of the anticlines. Drilled geothermal wells are the main discharge points of thermal groundwater in the two flanks of the anticlines.

GROUNDWATER FLOW SYSTEMS

The genesis model of the thermal groundwater in the study area has been summarized as follows (Cheng *et al.* 2015; Yang *et al.* 2017; Ta *et al.* 2018): The thermal groundwater receives recharge from precipitation in the outcropping areas of the T_1j–T_2l carbonates in the cores of the nearly north–south-trending anticlines, and undergoes subsurface circulation along the eastern and western flanks of the anticlines to varying degrees. After obtaining heat from the heat flow from the depths, the thermal groundwater rises and converges to the low terrain of the outcropping areas of carbonates in the middle or the plunging ends of the anticlines, or in the valleys of sandstone areas cut by rivers and rises to the surface in the form of hot springs as already described. In the two flanks of the anticlines, the deeper the carbonate aquifers are buried, the weaker the groundwater flow is.

Although many researchers support the genesis model of geothermal water as mentioned above, and all of them believe that there is groundwater flow through the bottom of the Yangtze River or Jialingjiang River (the lowest discharge base level in the study area) from north to south along the anticlines (Luo 2000; Luo *et al.* 2006; Cheng *et al.* 2015; Yang *et al.* 2017), we believe that this is not reasonable. On the basis of the occurrence of thermal groundwater, the emergence characteristics of the hot springs and the geological structures, the groundwater flow systems in the study area can be divided into three levels of flow systems along the anticlinal structures (Figure 6).

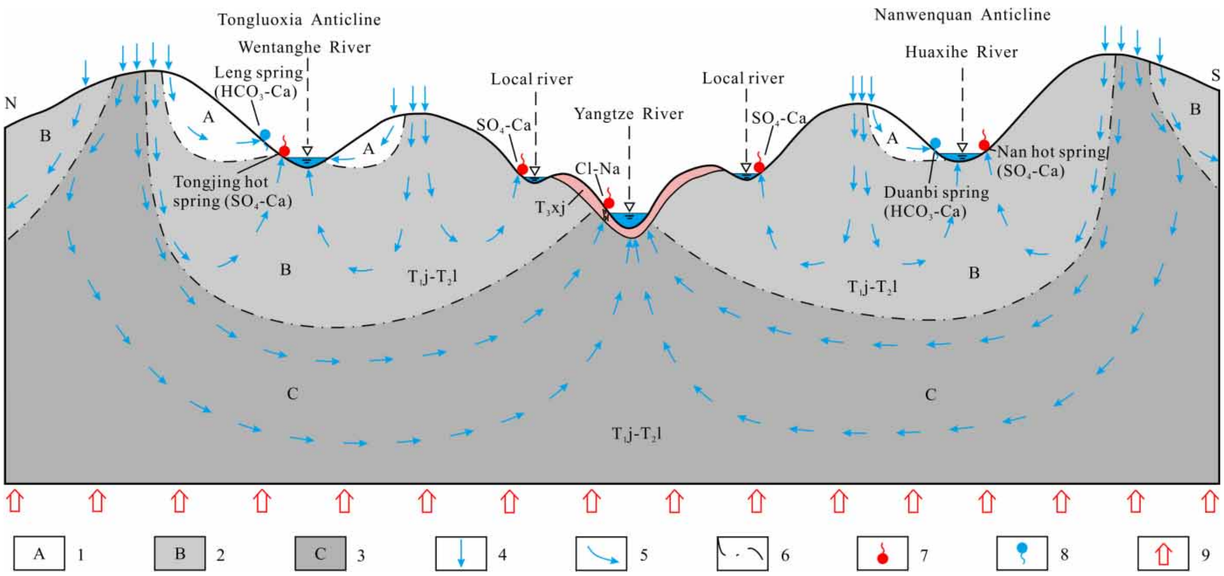

Figure 6 | Conceptual model (profile) of geothermal flow systems of the thermal groundwater along the flanks of the anticlines near Chongqing (take the Tongluoxia anticline – Nanwenquan anticline as an example). 1 Shallow circulation system; 2 Middle circulation system; 3 Deep circulation system; 4 Infiltration of precipitation; 5 Schematic groundwater flow direction; 6 Boundary of systems; 7 Hot spring; 8 Normal temperature spring; 9 Heat flow.

Level A flow system (shallow circulation system)

Precipitation infiltrates and recharges the groundwater in the outcropping areas of the T_1j–T_2l carbonates. After undergoing a shallow circulation, the groundwater rapidly discharges at suitable topographic locations to form the normal temperature springs (Figure 6), for example, the Longdong spring in the northern plunging end of the Taozidang anticline, and the Duanbi and Leng springs in the middle of the Nanwenquan and Tongluoxia anticlines, respectively. The shallow groundwater also discharges to the surface rivers. The groundwater circulation in this flow system is relatively fast. The dissolution of calcite and dolomite in carbonates leads to the HCO_3-Ca type springs and, because of the fast circulation, generally low TDS (<1 g/L) groundwater (Ta *et al.* 2019; Yang *et al.* 2019).

Level B flow system (intermediate circulation system)

The groundwater receives recharge at the outcropping areas of the T_1j–T_2l carbonates in the anticlines (Ta *et al.* 2018, 2019), experiences the intermediate circulation and obtains heat by heat flow from below. Subsequently, part of the groundwater flows to the middle of the anticlines along the anticlinal structure line and rises to the surface in the low terrain of the carbonates cut by rivers, and forms the natural hot springs (such as the Nan hot spring and the Tongjing hot spring in the middle of the Nanwenquan and Tongluoxia anticlines, respectively) (Figure 6). The other part of groundwater flows to the southern or northern plunging ends of the anticlines, respectively, and issues in the form of hot springs in the favorable topographic areas. Examples include the Qiaokouba spring in the southern end of the Nanwenquan anticline, and the Bei and Dong springs in the northern ends of the Wentangxia and Taozidang anticlines, respectively (Figure 6). The groundwater flow path in this system is longer and the subsurface flow becomes weaker, hence the groundwater circulation is slower. Under these conditions, the groundwater mainly reacts with evaporites (gypsum or anhydrite) in the geothermal reservoir, which results in the hydrochemical type of SO_4-Ca and the TDS of 2–3 g/L (Yang *et al.* 2017; Ta *et al.* 2018; Xiao *et al.* 2018).

Level C flow system (deep circulation system)

The Yangtze River and Jialingjiang River, which act as the lowest discharge base level of groundwater in the study area, control the regional groundwater flow system. Groundwater receives precipitation recharge from the karst areas of each anticline. After undergoing the deep circulation along the flanks of the anticlines, it flows to the southern or northern plunging ends of the anticlines (near the Yangtze River or Jialingjiang River), and eventually rises through the sandstones to drain to the Yangtze River or Jialingjiang River (Figure 6), for example, the Fengjiejiba hot spring (TDS of 25.89 g/L) in the northern end of the Yunanchang anticline (eastern Sichuan Basin) (Guo *et al.* 2019). The groundwater in this flow system continues to flow along the anticlinal structural line to the deep flanks, where the geothermal reservoir is relatively closed, and the groundwater circulation becomes very slow. Various dissolved ions originated from the water–rock interactions continuously gather to form the Cl-Na type hot water with relatively high TDS (>10 g/L) (Guo *et al.* 2017, 2019). In addition, the subsurface brines occurring in some deep-buried anticline or syncline areas are in a stagnation state and do not participate in the modern hydrological cycle, for example, the brines at the Wo 57 well in the middle of the Wolonghe anticline (a secondary short-axis low-gentle anticline to the east of the Mingyuexia anticline) and the brines of the Chuan 25 well in the southern end of the Luojiaping anticline (northeastern Sichuan Basin) with TDS of 105.66 and 352.69 g/L, respectively (Zhou *et al.* 2015).

CONCLUSIONS

This paper examines the thermal groundwater, hot springs and groundwater flow systems near Chongqing by the collation, review and reinterpretation of data from earlier studies. The occurrence and emergence of the thermal groundwater here are strongly controlled by the nearly north–south trending anticlines. We have identified the situation as unusual, possibly unique, requiring classification of the type of thermal groundwater by a new name, the 'basin-anticline outcropping' type. While similar to thermal groundwater classed as basin type, it also has the characteristics of that classed as outcropping type because of the anticlines.

The natural hot springs (low–medium temperature) in the study area mainly exist in the outcropping areas of the carbonates, in the middle, and the plunging ends of the anticlines where the topography was cut by rivers. Hot springs also occur where hot water rises through the overlying sandstones. Geothermal wells tapping the carbonate reservoirs on the flanks of the anticlines also produce thermal groundwater.

The groundwater flow in the study area can be divided into three levels: (1) shallow circulation system with groundwater of HCO_3-Ca type and low TDS discharging through normal temperature springs, (2) middle circulation system with groundwater of SO_4-Ca type and TDS of 2–3 g/L discharging through hot springs and (3) deep circulation system with groundwater of Cl-Na type and high TDS discharging through hot springs or wells.

In addition to supplementing earlier studies of the geothermal resources in Chongqing, the results are of important guiding significance for the study or review of geothermal resources in other regions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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