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Geochemistry and Scaling Potential for High Temperature Geothermal Systems Along the Himalayan Belt in China

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ABSTRACT

High temperature geothermal resources in China are mainly existed along the Himalayan belt which belongs to one of the global geothermal belts, but itis not well exploited yet. This paper tries to summarize the geochemical characteristics and possible scaling potential of geothermal fluids in typical high temperature geothermal systems along this belt and provide evidences for further development. Geochemical data of 79 samples from springs and boreholes were collected and analyzed. Results show that strong surface manifestations were observed in Tibet, Western Sichuan and Yunnan area but not in Xinjiang area; reservoir temperature is assessed to be 170-275 ^{o}C for most of the geothermal systems along the belt though the measured surface temperature is much lower. Geothermal fluids are Cl-Na, HCO_3-Na or Cl·HCO_3-Na type dominated and pH ranges from 6.4 to 9.5. Total dissolved solids vary from 170 mg/L to about 4400 mg/L and minor elements like Li, Rb and Cs are in high concentrations. Calculations show that calcite, quartz, chalcedony and amorphous silica are over saturated at wellhead conditions for fluid from these four areas. However, fluid composition reconstruction using WATCH program indicates that at reservoir conditions, calcite from geothermal fluid of Tibet and Taxian of Xinjiang is mainly under saturated while that in Western Sichuan and Yunnan area is over-saturated; quartz, chalcedony and amorphous silica are all under saturated. The oversaturation of calcite is caused by CO_2 degassing and pressure decrease during upwelling process. Combined with results from adiabatic boiling simulation from reservoir to surface conditions, it's indicated that calcite scaling will happen in Taxian of Xinjiang, Western Sichuan and Yangbajing, Yangyi and Gulu geothermal system in Tibet area while quartz scaling are likely to occur in Yunnan and Dagejia & Langjiu geothermal system in Tibet area.

1. INTRODUCTION

High temperature geothermal resources in China are mainly existed along the Himalayan belt in the northwest which belongs to the global geothermal belts. Strong tectonic collision between the Indian Plate and Euro-Asian Plate provide possibilities of its existence (Hoke et al., 2000; Zhang et al., 2017). It starts from the Taxian area in Xinjiang Autonomous Region, eastwards to Ali area in Tibet and existed following the Yarlu Zangbo River, turns southeast to Western Sichuan basin and finally goes to the Tenchong area in the Yunnan province through Gaoligong Mountain (Figure 1).

Strong surface manifestations are observed along the geothermal belt, in forms of boiling springs, hot springs, geyser, fumaroles and hydrothermal explosion, etc, most of which occur at an altitude higher than 4000 m (Tong et al, 1978;Liao, 2018).. Famous geothermal sites in this belt include Xinjiang(Taxian), Tibet (including Dagejia, Langjiu, Yangbajing, Yangyi and Gulu geothermal systems), Western Sichuan (including Kangding, Batang, Daocheng and Hailuogou geothermal systems) and Tenchong, among which, power plant had been built in Yangbajing and Yangyi geothermal field and the total capacity amounts to about 44 MWs. However, due to the special geographic location, natural environment conditions and also the demand of energy for economy development, exploration and exploitation of geothermal resources along this belt are limited. In addition, chemical properties of geothermal fluids are also a key factor of sustainable development for both power generation and direct utilization. Scaling and corrosion had caused the close of Langjiu power plant and it's still an important problem in the Yangbajing plant (Dor and Zheng, 2009). Therefore, it's important to figure out the geochemical characteristics and scaling potential of geothermal fluids along this belt for further exploitation. This paper tries to present the basic geochemistry and possible scaling problems of geothermal fluids along this belt based on deep fluid compositions reconstruction and evaluation.

2. GEOLOGICAL SETTINGS

The Himalayan geothermal belt is formed by tectonic movement of the upper mantle and crust during the Himalayan period and has been lasted for millions of years (Tong et al, 1978). The Taxian site is located in the Western Pamir syntax (Figure 1, site A) and the main reservoirs are probably syenite of Himalayan period and gneiss of Proterozoic period. Right-slip faults in the eastern side and left-slip faults along the western side are widely developed and they are extensional stress dominated, indicating possible channels for deep circulation (Li et al., 2018). Comparatively, the Western Sichuan site locates in the Eastern syntax (Figure 1, site C) and dominant reservoirs are biotite granite and sandy slate of Triassic period. All the geothermal systems show a zonal distribution along the interaction area between three main large-scale strike-slip fault zones with orientation of NW-SE and faults system of NE-SW. These two syntaxes are two singular points of continental collision between Indian and Eurasian Plates and surface manifestations are only observed in the Eastern syntax (Figure 1, sites A and C). The Tibet geothermal sites are widely existed in those areas between these two syntaxes where large scale suture belts are E--W oriented while geothermal systems are occurred along the faults system that are perpendicular to the suture belts (Figure 1, site B). Tenchong geothermal site is located in the south of the Himalayan belt and the dominant reservoir is granite of late Cretaceous period (Figure 1, site D). Faults systems of S-N, NW and NE orientation control the distribution of water and heat. .

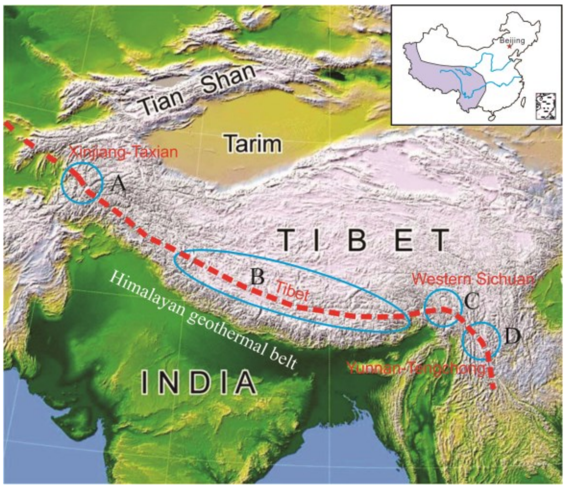

Figure 1: The location of Himalayan geothermal belt in China

It is observed that surface manifestations including boiling springs, geysers and even fumaroles are strong in Tibet, Tenchong and Western Sichuan area but it's totally different in Taxian area of Xinjiang where no surface manifestations is observed. This may be controlled by the tectonic background. It is already verified that there are magma sources in the Tenchong area and melting bodies with high temperature in Tibet area, which could provide sufficient heat for geothermal systems. In Western Sichuan, though there's no evidences showing existence of magma in subsurface, results from geophysical detection and gas geothermometer show that there may be melting bodies with temperature up to 500℃.

3. DATA COLLECTION AND DESCRIPTIONS

All the geochemical data are cited from the published references (Zhao et al., 1998; Shen et al., 2011; Guo and Wang 2012; Duan, 2014; Liu, 2014; Guo et al., 2017; Tian et al., 2018; Li et al., 2018) and only springs and boreholes with temperature higher than 50℃ are collected. Typical geothermal systems analyzed are Taxian in the Taskorgan basin of Xinjiang; Dagejia, Langjiu, Yangbajing, Yangyi and Gulu in the Tibet area; Kangding, Batang, Daocheng and Hailuogou in the Western Sichuan area; and Tenchong in the Yunnan area (Table 1). 79 data in total were collected and analyzed.

Table 1: Statistical information of geochemical fluids from typical geothermal systems of the Himalayan belt

Locations	Name of geothermal systems	Sample numbers	pH	Temperature (℃)	SiO_2(ppm)
Xinjiang	Taxian(TX)	4	6.40～8.60	61～155	69.3～273
Tibet	Dagejia(DGJ) Langjiu(LJ) Yangyi(YY) Yangbajing(YBJ)	48	6.84～9.14	54～198	22.7～684
Western Sichuan	Kangding(KD) Batang(BT) Daocheng (DC) Hailuogou(HLG)	14	6.65～9.50	62～178	45.8～367
Yunnan	Tengchong(TC)	13	6.42～8.93	82～97	184～890

4. RESULTS AND DISCUSSIONS

4.1 Hydrogeochemistry of Geothermal Fluids

pH of geothermal fluids varies from 6.4 to about 9.5 and pH higher than 8.5 are often related to boiling springs or water from boreholes with temperature higher than the local boiling point where CO_2 degassing occurred (Table 1). Most of the geothermal fluids (Tenchong, part of Western Sichuan and Tibet) are Na-dominated as showed in Figure 2, where concentration of Na^+ varies from 143 mg/L to more than 1200 mg/L and it takes more than 75% of the total cations. And Ca^{2+} in geothermal fluid of part of Tibet and Western Sichuan was the second dominant cation and it's about 25-37%. Concentrations of K^+ varies from less than 1 mg/L to more than 142 mg/L and average value is about 60 mg/L. K^+ in geothermal fluid of Taxian area is as high as more than 110 mg/L but it varies a lot in geothermal fluid of Tibet. It should be mentioned that Mg^{2+} content is very low in geothermal fluid in Tenchong, Tibet and Western Sichuan area most of which are less than 1 mg/L. However, it's around 10.3-15.4 mg/L in geothermal fluid of Taxian area, indicating that more minerals containing Mg from reservoir are dissolved. Rock properties indicate that the reservoir mineral compositions along this geothermal belt are mainly K-feldspar, quartz, albite, plagioclase, biotite, magnetite and amphibole. Therefore, it's assumed that all these cations are sourced from the following processes:

(1) thermo-metamorphism of limestone (Eq.1); (2) dissolution of carbonates ($CaCO_3$, $MgCa(CO_3)_2$, e.g. Eq.2) and alumino-silicate minerals ($KAlSi_3O_8$, $CaAl_2SiO_8$-$NaAl\ Si_3O_8$, $K\ (Mg,Fe)_3(AlSi_3O_{10})\ (OH,F)_2$, e.g. Eq.3);

$$CaCO_3 \xrightarrow{400^\circ} CaO + CO_2 \uparrow \tag{1}$$

$$CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^- \tag{2}$$

$$5KAlSi_3O_8 + 4H^+ + 16H_2O \rightarrow KAl_5Si_7O_{20}(OH)_4 + 8H_4SiO_4 + 4K^+ \tag{3}$$

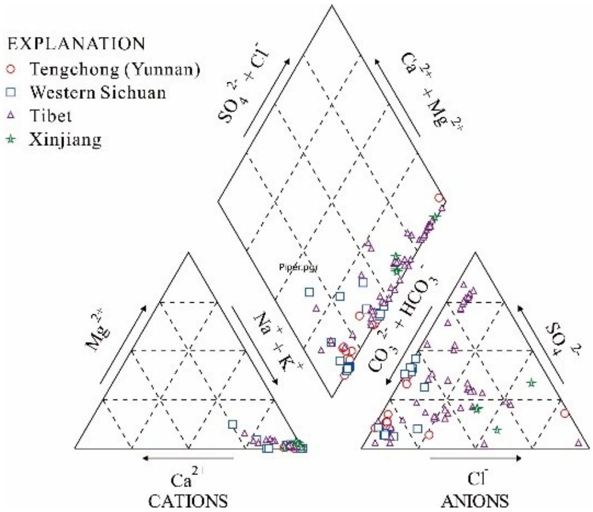

Figure 2: Piper diagram of geothermal fluids in the Himalayan belt

For anions, it is much more complicated. In Taxian area of Xinjiang, it's SO_4^{2-} dominated while in Tenchong of Yunnan and Western Sichuan, it is HCO_3^- dominated, which takes more than 50% of the total anions (Figure 2). In Tibet, for geothermal fluid from different areas, dominant anions are different. For example, it's HCO_3^- dominated in Yangyi area but Cl^- dominated in Yangbajing area. This is probably controlled by the reservoir rock compositions, water-rock interactions under different reservoir temperature conditions and whether there is a magma source.

Concentrations of B in geothermal fluid of Tibet and Tenchong area are as high as 110 mg/L where that in Western Sichuan area is as low as less than 2.20 mg/L. Content of Li show the same feature that it's up to more than 61.0 mg/L and 25.0 mg/L respectively in geothermal fluid of Tenchong and Tibet area. In addition, Rb and Cs element are also showed high content in Tibet and Tenchong areas. This enrichment indicating that there may be magma or melting body sources at deep crust and this is also evidenced by geophysical surveys. In Tenchong area, magma sources existed at a depth of 3-9 km and 16-24 km while in Yangbajing geothermal field of Tibet, it's assumed to be at 9.5-10.7 km with thickness of 5 km (Zhang et al., 2013). This may be the reason that surface manifestations are strong in Tibet and Tenchong area but quite in Taxian area.

4.2 Reservoir Temperature Prediction

There are lots of geothermometers to calculate reservoir temperature based on thermodynamic equilibrium. However, because most of the data were collected from references, data quality and geochemical processes samples going through were not clear and this will greatly affect the result. In addition, because samples with boiling process are widely existed along the belt, for typical geothermal field, only one group of data were chosen to assess the reservoir temperature using Quartz geothermometer with and without boiling to 100℃ (Anòrsson et al., 1998).

It should be mentioned that calibration needs be done since all the selected samples were not boiling to 100 ^oC as altitude of the studied areas varied from less than 1500 m to about 5000 m, causing local boiling point varied from 84 to 95 ^oC. Calibration method of using silica content at reservoir conditions is proposed. Results show that at reservoir conditions, silica content is much lower than that analyzed from water samples collected at surface conditions due to various extent of steam loss from boiling. And calibrated temperature was several degrees higher than that calculated from Quartz geothermometer with adiabatic boiling to 100 ^oC. This is because at field sampling conditions, boiling temperature was lower and more steam would lost from the reservoir fluid and lead to under-estimation of reservoir temperature. In all, reservoir temperature for geothermal fields along the Himalayan belt can be as high as 275 ^oC and for most of them, it's about 200 ^oC which can be good resources for power generation and direct utilizations.

Table 2: Reservoir temperature prediction based on calibrated quartz geothermometer (℃)

Name of geothermal field		Measured SiO_2 (mg/L)	Reconstructed SiO_2 (mg/L)	Quartz after boiling to 100℃	Calibration using reconstructed SiO_2 (℃)
Yunnan	RH	890	572	283	275
	PZH	244	204	174	183
Western Sichuan	KD	355	279	200	205
	BT	254	191	176	219
Tibet	YBJ	684	464	256	253
	YY	373	286	204	209
	DGJ	350	270	199	205
	LJ	185	157	156	166
	GL	132	116	137	148
Xinjiang	TX	273	203	181	222

4.3 Scaling Potential Assessment

Both saturation indices (SI) of geothermal fluid collected at surface and reconstructed using wellhead data are calculated. Reconstruction is done by the spring boiling model in WATCH program. Minerals including calcite, quartz, chalcedony and amorphous silica (Sil.amorph) are assessed.

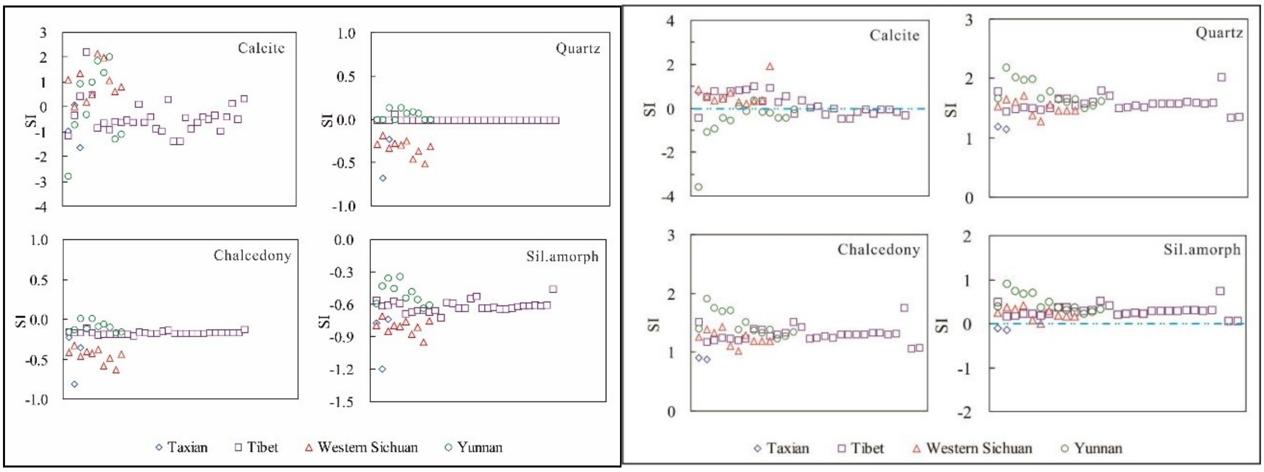

Figure 3: Saturation indices of geothermal fluids at reconstructed (left) and wellhead (right)

Results show that under reservoir conditions, geothermal fluids from the four studied areas are all under-saturated with respect to quartz, chalcedony and Sil.amorph; but at surface conditions, all these silica minerals become over-saturated especially for quartz and chalcedony except geothermal fluid from Taxian area of Xinjiang area (Figure 3). Therefore, silica scaling may be a problem in Tibet, Western Sichuan and Yunnan area. However, precipitation of quartz is very slow due to the kinetics and indicates that quartz scaling won't happen in these areas. SI of Sil. Amorph are higher than 0 indicating that this may become scaling problem. Though SI of chalcedony is around 1-2, it will not probably precipitate because it's always formed under low temperature and pressure conditions. This is consistent with the field observation that Sil. Amorph scaling occurred in Tenchong area of Yunnan and part of Tibet area but did't show up in Western Sichuan and Taxian area.

For calcite under reservoir conditions, most of the geothermal fluids in Tibet and Taxian are under-saturated while that in Western Sichuan and Yunnan area is over-saturated (Figure 3). When the geothermal fluid comes to the surface, most of them become calcite over-saturated especially that of Western Sichuan and Tibet. Therefore, calcite scaling is probably occurring in Tibet and Western Sichuan. This is almost consistent with that observed in the field. Sinter and carbonate scales are widely existed in Tibet and Western Sichuan area. The geothermal power plant in Yangbajing (YBJ) and Langjiu (LJ) area are seriously affected by the calcite scaling problem. In the YBJ area, it needs to be periodically removed at about several days a time while at LJ area, the power plant was already closed after it had run for two or three years. In addition, serious calcite scaling problem was detected at one geothermal exploration well in Western Sichuan area that was planned to generate power. During 48 hours of pumping test, thickness of calcite precipitated in the pipeline is amounted to 3 cm and the pipe was almost plugged. Therefore, calcite scaling will be the main problem for geothermal fluid exploitation along the Himalayan belt.

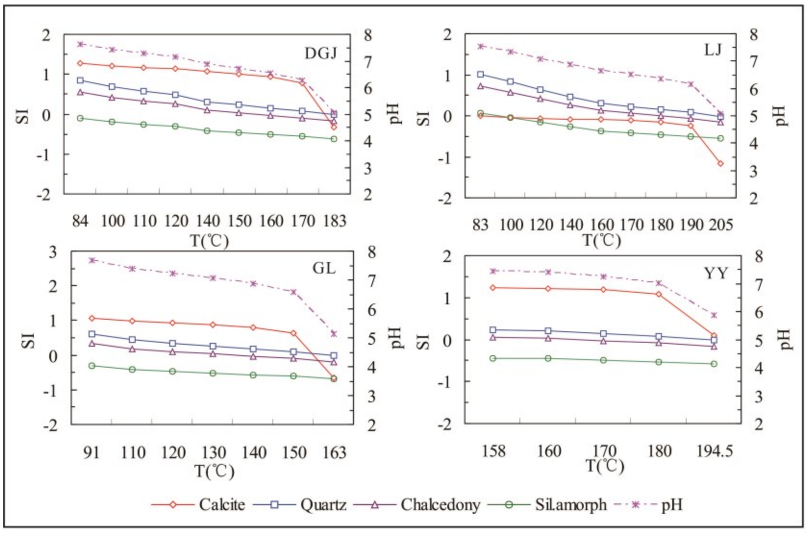

Figure 4: SI and pH changes when geothermal fluid upwelling to the surface

In order to understand the SI and pH changes during upwelling process and its impact on scaling, boiling calculations are carried out for typical samples from these four areas. In Tibet area, data for DGJ, LJ, GL and YY are chosen. Results show that the deep reservoir temperature is from about 160 ºC to more than 200 ºC and the pH is around 5.0 – 6.0. When boiling happened, the pH and SI of minerals including calcite, quartz, chalcedony and Sil.amorph keep increasing. In DGJ and LJ area, quartz and chalcedony become over-saturated after boiling while in DGJ, GL and YY area, calcite turns to be over-saturated, indicating that calcite scaling may happen.

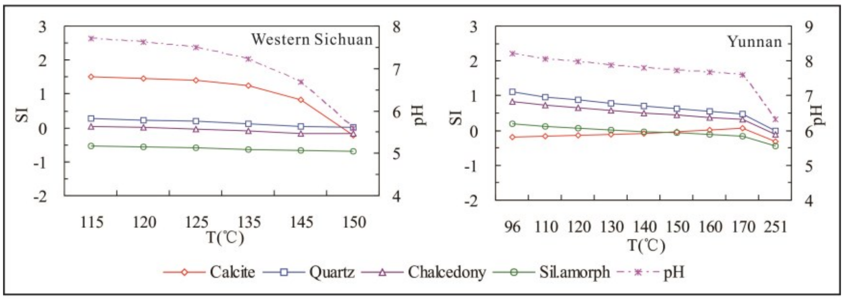

Figure 5: SI and pH changes during boiling for geothermal fluid from Western a Sichuan and Yunnan area

For geothermal fluid from Western Sichuan area (Figure 5), during boiling process, calcite became more and more over-saturated and then scale formed. However, it's different in Yunnan area: calcite became a bit over-saturated after boiling and then turned to be under-saturated due to solubility increase with temperature decrease.

5. CONCLUSIONS

Geochemical characteristics of thermal fluid and its scaling potential of possible minerals along the Himalayan belt in China were analyzed and studied based on the data of 79 samples. Results show that geothermal fluids are mainly Cl-Na, HCO_3-Na or Cl·HCO_3-Na type with total dissolved solids varying from 170 to about 4400 mg/L and pH ranges from 6.4 to 9.5 at surface conditions. Minor elements like B, Li, Rb and Cs are abundant in geothermal fluid from Tibet and Yunnan area while those in Western Sichuan and Taxian of Xinjiang area are much lower, providing evidences for the determination of deep sources from magma or melting body in the crust. Reservoir temperatures were predicted based on reconstructed silica concentrations and it is about 170-275 ºC for most of the geothermal systems though measured temperature at surface is much lower. SI calculations for minerals of calcite, quartz, chalcedony and Sil. Amorph at wellhead and reservoir conditions respectively indicate that calcite scaling is mainly occurring in Western Sichuan and part of Tibet areas while silica scaling of Sil. Amorph is dominantly happening in Tenchong geothermal field of Yunnan area. Therefore, different scale prevention and removal methods should be considered when high-temperature geothermal resources are exploited along the belt.

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