




Thermophysical Dynamics of Ore-forming Fluids in Heat Ore Deposits: Implications for Ore-formation Processes

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ABSTRACT

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In heat ore deposits, the role of ore-forming fluids in geological processes, notably in the genesis and evolution of such deposits, is pivotal. These fluids predominantly encompass aqueous solutions, molten magma, and various gaseous phases, each demonstrating intricate thermophysical attributes and dynamic behaviours within the high-temperature and pressure conditions of the deep crust. Contemporary methodologies and models, constrained by their specificity to certain environments and elements, often fall short in offering a holistic perspective or forecasting capabilities. To bridge this deficiency, a comprehensive set of mathematical models and equations has been constructed in the present study, subsequently facilitating an in-depth examination of the thermophysical properties of ore-forming fluids and the associated ore-formation processes in heat ore deposits. The research is segmented into three primary components: the derivation of thermal and solute diffusion equations; the establishment of mass and energy conservation equations; and the formulation of a solute transfer equation. This integrative approach not merely furnishes a robust theoretical foundation for decoding the intricacies of ore-forming fluids in heat ore deposits but also bears considerable scientific and pragmatic implications.

1. INTRODUCTION

In the geological spectrum, ore-forming activities have consistently been associated with intricate, multi-phase subterranean fluids, notably within high-temperature and high-pressure heat ore deposits. A plethora of such ore-forming fluids, spanning from various aqueous solutions and molten magma to gaseous constituents, have been observed to flow, migrate, and react deep within the crust. These movements and interactions are discerned to directly influence the genesis and spatial distribution of ore deposits [1-4]. Significance has been attributed to these fluids across a broad domain—from metal to non-metal deposits and from rare metals to energy minerals. Despite their undeniable relevance in both historical and contemporary geological timelines, the exploration into their thermophysical properties and dynamic behaviours during the ore-forming process has often been marred by ambiguity and remains a nascent area of research.

Recognising their pivotal role, further investigations into these fluids hold paramount importance for mineral resource exploration and utilisation [5, 6]. Enhanced comprehension not only augments the precision of ore deposit models, facilitating more effective guidance in mineral resource exploration and development, but also extends invaluable theoretical underpinning to diverse disciplines like geological science, geochemistry, material science, and mining engineering [5, 6]. With a global trend indicating a reduction in mineral resources coupled with escalating environmental constraints, insights into the thermophysical properties of ore-forming fluids and their subsequent ore-formation mechanisms stand crucial for championing sustainable and eco-friendly mineral development strategies [7-10].

Historically, the predominant approach to researching ore-forming fluids in heat ore deposits has been anchored in experimentation and observation. Yet, such methodologies are often constrained, yielding only fragmentary insights due to inherent limitations in experimental conditions and observational scopes [11-17]. Current mathematical models and computational techniques, although operational, have been cited to possess inherent challenges. Many such models have been delineated to simulate distinct phenomena under specific settings, thereby failing to capture the holistic dynamism and diversity of ore-forming fluids within multifaceted geological terrains [18]. Critical interactions within multi-component and multi-phase fluid systems, as well as the repercussions of crustal pressure and temperature fluctuations on fluid properties, are frequently eclipsed, undermining their predictive and applicative potential [19, 20].

In light of these observations, the present study embarked on an initiative to circumvent the aforementioned challenges. A comprehensive suite of mathematical models and equations was developed to delve into the thermophysical properties of ore-forming fluids and the associated ore-forming processes within heat ore deposits. This research endeavour has been compartmentalised into three primary segments: initially, the derivation of thermal and solute diffusion equations tailored to capture the physical shifts and diffusion tendencies of these fluids under variable temperatures, pressures, and compositions; following which, the formulation of mass and energy conservation equations provided a dynamic framework to decipher the genesis and metamorphosis of ore deposits; finally, the introduction of a solute transfer equation offered a deeper understanding of their interactions with minerals and rocks across micro and macro realms. Such systematic

investigations not only proffer an enriched theoretical platform for decoding the intricacies of ore-forming fluids within heat ore deposits but also advocate for the refinement of exploration and development stratagems of mineral resources, bearing notable scientific and practical ramifications.

2. THERMAL AND SOLUTE DIFFUSION EQUATIONS: INSIGHTS FROM THE ZHACUN GOLD DEPOSIT

Situated within the confluence of the “Three Rivers” – namely the Jinsha, Lancang, and Nujiang rivers in western Yunnan – the Zhacun Gold Deposit is distinguished by its propitious ore-forming geological conditions. Rich deposits of metals, including but not limited to gold, silver, copper, lead, zinc, and antimony, have been identified. Notably, its diverse ore deposit types and promising exploration prospects have marked it as a pivotal metallogenic belt within Yunnan Province. Extensive explorations, spearheaded by institutions such as the Yunnan Provincial Geological Bureau, Dali Prefecture Geological Bureau, and the Third Geological Brigade, have been conducted since 1960. Between 1960 and 1971, the Shanghuangshan gold-heavy concentrate anomaly area was demarcated, laying the groundwork for gold prospecting in the Yanzijiao-Shanghuangshan vicinity [21]. Subsequent investigations, spanning from 1984 to 1990, illuminated the ore-controlling structure within the Deposit, elucidating aspects such as distribution range, scale, and morphology of the gold-bearing fracture zone. Further examinations between 2005 and 2008 refined the understanding of ore-bearing strata, structures, and mineralised point distributions. The culmination of these endeavours has led to a trove of scientific findings and insights into the geological backdrop, geochemical traits, and ore-forming laws pertinent to the Zhacun Gold Deposit. Such insights have unequivocally influenced subsequent exploration strategies. Nevertheless, a more intricate understanding remains to be pursued, especially concerning the interplay between ore-forming effects and intrusive rocks, potential concealed rock masses in deeper strata, and the ore-forming system at large [21].

Delving deeper, it has been observed that within the confines of the crust, especially in heat ore deposits, ore-forming fluids like hydrothermal solutions, molten magma, and gases navigate their trajectories under heightened temperatures and pressures. The uneven thermal landscape of the deep crust, occasionally accentuated by geothermal activities or alternate heat sources, induces zones of elevated temperatures. Such thermal anomalies are often correlated with a decrement in fluid density. Concurrently, pressure variations across crustal depths impart significant modulations to fluid density. An array of solutes, from metal ions to minerals and gases, found within these subterranean fluids further complicates the density dynamics. Certain conditions have been identified to trigger phase transitions within these fluids, such as transmutations from a liquid to a gaseous or solid state, invariably accompanied by marked density alterations. Low-density fluids typically ascend within the crust, while their high-density counterparts gravitate downwards. This vertical movement instigates free convection, a process further augmented by thermal conduction. During their passage, these fluids are known to engage in chemical reactions with the surrounding mineral matrix, intensifying density gradients and amplifying the vigour of both free

convection and thermal diffusion.

Through the formulation of a thermal diffusion equation, the dynamic evolution of ore-forming fluids in heat ore deposits over time and space is captured. Such an equation delineates solute and temperature distributions under diverse conditions, elucidating the ore-forming mechanism with heightened precision. The implications of this study not only resonate with immediate findings but also extend to broader temporal scales, offering vital insights into the processes that orchestrate deposit formation.

Before constructing the thermal diffusion equation, the physical quantities to be studied (e.g., temperature, density, solute concentration, etc.) should be clarified, and appropriate boundary and initial conditions should be set. Under the assumption that the ore-forming fluid system in heat ore deposits is thermally driven, let Y_e be the temperature, Y_0 be the temperature of the ore-forming fluid system at the outlet, ϑ_0 be the reference density at Y_0 , β be the thermal expansion coefficient, with $\beta=1/\vartheta(\partial\vartheta/\partial Y)$, and ϑ be the density variable, then the fluid state equation was given as follows:

$$\vartheta = \vartheta_0 - \beta\vartheta_0(Y_e - Y_0) \quad (1)$$

Based on the above analysis, it was concluded that changes in temperature also led to changes in the fluid potential of ore-forming fluids in heat ore deposits, thereby driving the movement of those fluids. Let $hx\vartheta_0$ be the initial mass of ore-forming fluids in heat ore deposits, and $\beta hx\vartheta_0(Y_e - Y_0)$ be the volume mass of those ore-forming fluids after thermal expansion, then there was the following fluid potential equation:

$$\Theta = o + hx\vartheta_0 - \beta hx\vartheta_0(Y_e - Y_0) \quad (2)$$

By combining the Boussinesq approximate equation with the above two equations, the thermal diffusion equation for the ore-forming fluids was obtained as follows:

$$i = -\frac{\phi}{\omega}(\nabla o + \vartheta_0 h j - \beta\vartheta_0(Y_e - Y_0) h j) \quad (3)$$

Double diffusion convection is a complex fluid movement phenomenon that often occurs in the hydrothermal ore-forming system in heat ore deposits. In the system, hydrothermal solutions are not only driven by temperature gradients (thermal diffusion), but also influenced by solute concentration gradients (solute diffusion). That is to say, there is a significant temperature difference between the high temperature in the deep crust and the low temperature on or near the surface, and there is a significant spatial distribution difference in the concentration of various solutes (e.g., metal ions, salinity, etc.) in the hydrothermal solutions. At the same time, the porous medium or fracture system in the crust has a certain degree of permeability so that the hydrothermal solutions and solutes can flow freely. When these conditions are met, the double diffusion convection phenomenon is likely to occur in the hydrothermal ore-forming system in heat ore deposits.

Lots of studies have shown that fault structures often serve as ore transport channels and storage sites. The nearly north-south fault (i.e. gold-bearing fracture zone) is closely related to ore forming and controlling in the Deposit, followed by the NEE trending fault and the north-east trending fault. The

above faults may be extensional in the early stage, but later transformed into compresso-shear (or nappe-sliding structures) under the action of Himalayan horizontal compressive stress, which formed a fault breccia belt of tens of kilometers long and was accompanied by the intrusion of intermediate acid to alkaline magma, leading to widespread hydrothermal alteration. Therefore, this group of faults is the main ore guiding and hosting structure in the Deposit, and provides a good channel and storage space for ore-containing hydrothermal solutions in the Deposit. Figure 1 shows the remote sensing mineral geological characteristics and near-ore and prospecting indicators in the Zhacun Gold Deposit [22].

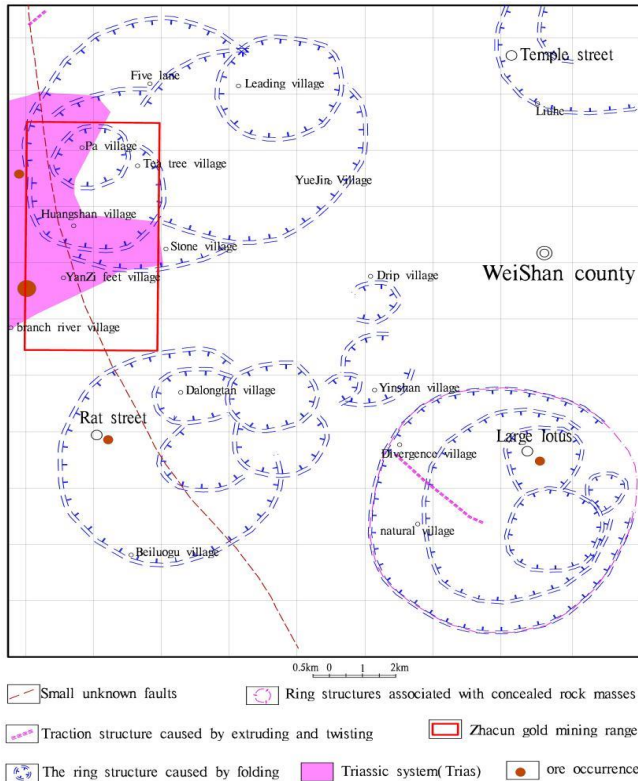


Figure 1. Remote sensing mineral geological characteristics and near-ore and prospecting indicators in the Zhacun Gold Deposit

Construction of a solute diffusion equation aimed to accurately describe how solutes in ore-forming fluids in heat ore deposits were distributed over time and space, which is crucial for better understanding and predicting deposit formation. Meanwhile, solute diffusion in heat ore deposits often has complex interactions with thermal diffusion, fluid flow and other physical processes. Only by establishing an accurate equation model can these interactions be comprehensively analyzed.

Before constructing the solute diffusion equation, the main variables to be studied (e.g., solute concentration, flow rate, etc.) and relevant boundary and initial conditions should be clarified. Let ω , ϑ and ε be the viscosity, density and surface tension of ore-forming fluids in the heat ore deposit, ϑ_0 be the reference density for concentration v_0 , and $\partial\vartheta/\partial v$ be the variation coefficient of density along with concentration, then there was a linear equation of changes between density and concentration as follows:

$$\vartheta = \vartheta_0 + \frac{\partial\vartheta}{\partial c}(v - v_0) \quad (4)$$

i.e.,

$$\vartheta = \vartheta_0 + \frac{\vartheta_a - \vartheta_0}{v_a - v_0}(v - v_0) \quad (5)$$

By combining the Boussinesq approximate equation with the above two equations, the solute diffusion equation of ore-forming fluids in heat ore deposits was obtained as follows:

$$i = -\frac{\phi}{\omega} \left(\nabla \vartheta + \vartheta_0 h j + \frac{\vartheta_a - \vartheta_0}{v_a - v_0} (v - v_0) h j \right) \quad (6)$$

To derive practical and precise thermal and solute diffusion equations, several foundational assumptions are customarily regarded as indispensable. The criteria for the thermal diffusion equation encompass:

(1) The Continuous Medium Hypothesis: This posits that the crust's porous medium or fracture system represents a continuous fluid domain, eschewing microscopic discontinuities.

(2) Constant Thermophysical Properties: This premise holds that within the examined temperature range, thermophysical properties such as thermal conductivity and specific heat capacity remain invariant.

(3) State of Conditions: Depending on the research prerequisites, either steady-state or unsteady-state heat conduction equations are selected.

(4) Negligence of Pressure Effect: Under certain circumstances, the pertinence of pressure on heat conduction is overlooked.

(5) Source Determination: The potential existence of internal heat sources, for instance, heat resulting from radioactive decay, is acknowledged or discounted based on empirical evidence.

On the other hand, the solute diffusion equation mandates:

(1) Fickian Diffusion: This supposition entails that solutes abide by either Fick's first or second law, signifying that solute diffusion is impelled by concentration gradients.

(2) Isothermal Conditions: Certain rudimentary models might predicate that diffusion processes transpire under isothermal conditions.

(3) Invariable Solute Diffusion Coefficient: Given specific temperature and pressure conditions, the solute diffusion coefficient is presumed constant.

(4) Reactivity Assessment: The possible occurrences of chemical reactions, phase shifts, or other processes influencing solute concentration are acknowledged as relevant.

(5) Component Specification: Contingent on the research's aim, equations might pertain solely to a singular solute component, or the interactions between multiple solute components may necessitate contemplation.

(6) Dimensionality Determination: Contingent upon the problem's intricacy and data accessibility, spatial dimensions are postulated as one-dimensional, two-dimensional, or three-dimensional.

While these assumptions underpin the theoretical foundation for articulating thermal and solute diffusion equations, they inherently circumscribe the model's accuracy and applicability breadth. Consequently, in leveraging the devised equations for scholarly or practical undertakings, it is imperative to elucidate the inherent limitations of these assumptions. Additionally, situational modifications or

corrections may be requisite to mirror the extant conditions accurately.

3. CONSTRUCTION OF MASS AND ENERGY CONSERVATION EQUATIONS FOR ORE-FORMING FLUIDS IN THE HEAT ORE DEPOSIT

Fluid flow in heat ore deposits is a key factor, which affects the deposition and enrichment of minerals. The mass conservation equation helps accurately describe this process. Moreover, in addition to the propagation of heat and solutes, the ore-forming fluids in heat ore deposits also involve the transport of various substances, which requires the mass conservation equation for a comprehensive consideration.

Before constructing the mass conservation equation, the physical system and control volume to be studied should be determined, and the boundary conditions of the system should be clarified. Starting further from the basic principle of mass conservation, under the assumption that the mass of fluids flowing in and out is equal to the increase or decrease in fluid mass per unit volume, the mass conservation equation applicable to ore-forming fluids in heat ore deposits was listed. Based on the Euler's method, the mass conservation continuous equation in the differential form was given as follows:

$$\frac{\beta(\partial \kappa)}{\beta y} = \frac{\beta(\partial i)}{\beta z} + \frac{\beta(\partial c)}{\beta t} + \beta \frac{\beta(\partial \mu)}{\beta x}$$

or

$$\frac{\beta(\partial \kappa)}{\beta y} = \nabla \bullet (\partial i) \quad (7)$$

Let ∂ be the fluid density; i , c and μ be the velocity components of ore-forming fluid particles in the heat ore deposit at the spatial point (x, y, z) , then there was the following equation for incompressible fluids:

$$\nabla \bullet i = 0 \quad (8)$$

Energy transfer is a complex but crucial factor in the ore-forming process of heat ore deposits. The energy conservation equation describes this process comprehensively and accurately. The energy conservation equation is closely related to the mass conservation equation as well as thermal and solute diffusion equations. It is an indispensable part of the entire model system to construct a complete energy conservation equation.

Before constructing the energy conservation equation, the energy transfer types to be studied (e.g., conduction, convection, radiation, etc.) and the physical boundaries of the research area and system should be determined based on research needs and objectives, thereby facilitating to establish corresponding energy conservation equation. Let W be the heat per unit area per unit time, y be the temperature, z be the coordinate axis in the normal direction of the cross-section, and η be the thermal conductivity coefficient. The equation for the thermal conduction energy of the ore-forming fluid system in heat ore deposits was given as follows:

$$W = -\eta S \frac{\beta y}{\beta z} \quad (9)$$

For the thermal conduction between fluids in the ore-forming fluid system and solids in heat ore deposits, let η_a and η_d be the thermal conductivity coefficients of rock porous media and ore-forming fluids. The definition formula of the thermal conductivity coefficient was given as follows:

$$\eta = (1 - \kappa)\eta_a + \kappa\eta_d \quad (10)$$

Let W be the heat passing through a given area per unit time, and β be the heat transfer coefficient. The calculation formula for the thermal convection energy of the ore-forming fluid system was given as follows:

$$W = \beta(y_d - y_q), \beta = \frac{w}{\Delta y} \quad (11)$$

Let V_d be the constant-pressure heat capacity of fluids, then the corresponding heat flux equation for thermal convection was given as follows:

$$W_c = \partial V_d Y \quad (12)$$

Let F_a and F_d be thermal conductivity coefficient of solid matrices and ore-forming fluids in heat ore deposits, respectively; W be the heat source or reaction heat; $(\partial v)_l$ be the effective volumetric heat capacity of porous media. The heat conduction energy equation of the ore-forming fluid system was given as follows:

$$(\partial v)_l \frac{\beta Y}{\beta y} + \partial_d v_{od} i \cdot \nabla Y - (\theta F_d + (1 - \theta) F_a) \nabla^2 Y = W \quad (13)$$

4. CONSTRUCTION OF A SOLUTE TRANSFER EQUATION FOR ORE-FORMING FLUIDS IN THE HEAT ORE DEPOSIT

Figure 2 presents a schematic representation delineating the multi-field coupling of ore-forming fluid flow, heat transfer, solute transport, and chemical interactions within heat ore deposits. The dispersion and mobility of solutes, typically metal ions or other valuable entities, within the ore-forming fluids of heat ore deposits are fundamental to the ore-formation mechanism. The solute transfer equation serves to depict this dynamic phenomenon accurately and stands as a crucial element within the system of mass and energy conservation equations. This is paramount for constructing an all-encompassing ore-forming model for heat ore deposits. Insight into the solute transfer mechanism not only facilitates predictions concerning the distribution and quality of ore deposits but also appraises the repercussions of mining activities on the adjacent environment, including soil and water, thus bearing substantial economic implications.

When considering the ore-forming fluids of heat ore deposits as a solution system with a certain concentration, a basic equation describing solute transfer (i.e. the solution transport reaction equation in porous media) was established based on the mass and energy conservation principle. Let θ be the porosity, E_u be the reaction term, v_u be the molar concentration of substance u , B be the total number of species contained in the solution, and F_u be the diffusion coefficient of substance u , then there were:

$$\frac{\beta(\theta v_u)}{\beta y} + i \cdot \nabla v_u - F_u \nabla^2 v_u = \theta E_u \quad (u = 1, 2, \dots, B) \quad (14)$$

The ore-forming process usually involves multiple sets of chemical reaction processes participated by multiple reactive substances. Let $u(k=1,2,3\dots b_1)$ be multiple reactive substances, $k(k=1,2,3\dots b_2)$ be multiple sets of chemical reaction processes, c_u be the stoichiometric coefficient of substance u , and e be the reaction rate, then the reaction term scale expression was given as follows:

$$E_u = c_u e \quad (15)$$

The reaction rate was calculated using the following equation:

$$e_u = \prod_{u \in REI} v_u^{-cuk} \quad (16)$$

Let S be the frequency factor of positive reaction, E be the general gas constant, and R_s be the positive reaction activity energy. The relationship between temperature and the reaction rate constant was characterized by the following equation:

$$j = S \exp\left(\frac{-R_s}{EY}\right) \quad (17)$$

If the reaction rate constant was known at 25°C, then the j - Y relational expression was given as follows:

$$j = j_{25} \cdot \exp\left(\frac{-R_s}{Y} \left(\frac{1}{Y} - \frac{1}{298.15}\right)\right) \quad (18)$$

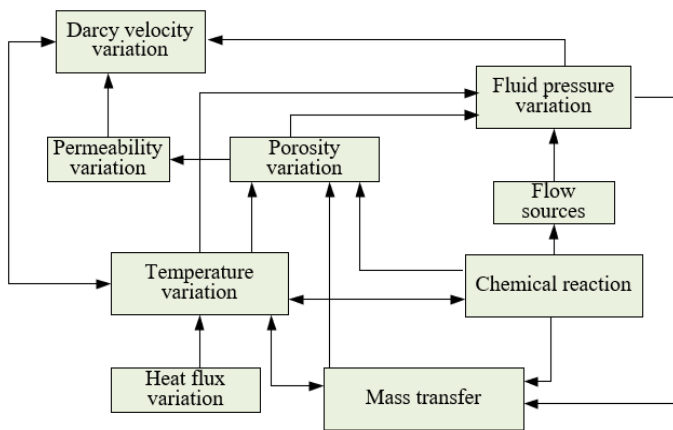


Figure 2. Schematic diagram of ore-forming fluid flow-heat transfer-solute transport-chemical multi-field coupling in heat ore deposits

5. EXPERIMENTAL RESULTS AND ANALYSIS

Table 1 provides the microscopic temperature measurement results and physical parameters of ore-forming fluid inclusions in the Zhacun Gold Deposit. It can be seen from the table that the gas phase ratio of gas-rich phase inclusions is generally higher than that of liquid-rich phase inclusions, which is consistent in all mineralization stages (II, III, and IV), meaning that ore-forming fluids have undergone similar separation and

enrichment processes at different mineralization stages. In mineralization stages II and III, the homogenization temperatures of liquid-rich and gas-rich phase inclusions are similar, but they significantly decrease in mineralization stage IV, which implies that the ore-forming fluids are hotter in the early stage and their temperatures decrease in the later stage. Salinity fluctuates in different mineralization stages, but significantly decreases during mineralization stage IV, which is related to the sources of mineralized fluids and/or fluid-mineral interactions. Density and pressure also show certain differences in different mineralization stages, with stage IV having relatively low density and pressure, which implies that the ore-forming fluids in different mineralization stages are influenced by varying degrees of crustal stress. Kelvin temperature is an indicator of fluid stability, and it has relatively small fluctuations, indicating that the stability of ore-forming fluids is relatively consistent in each stage.

It can be concluded from the above analysis that ore-forming fluids in the Zhacun Gold Deposit exhibit different physical and thermodynamic characteristics in different mineralization stages, which is related to different geological events and environmental conditions involved in the ore-forming process. The ore-forming fluids are hotter in the early mineralization stage (stages II and III), which is related to deeper or different fluid sources. In the later stage (stage IV), the temperature, salinity, density, and pressure of the ore-forming fluids are relatively low, due to changes in crustal stress or in fluid sources. The changes in salinity and gas phase ratio reflect fluid-mineral interactions and the enrichment and separation mechanisms of fluids in different stages.

Figure 3 shows the homogenization temperature histograms of ore-forming fluid inclusions in the Zhacun Gold Deposit in different stages. In stage II, gas-rich and liquid-rich phase inclusions are mainly concentrated in the range of 260-310°C. In stage III, the homogenization temperature of gas-rich phase inclusions is mainly distributed between 240-270°C, while that of liquid-rich phase inclusions is mainly distributed between 250-260°. In stage IV, the homogenization temperature of gas-rich phase inclusions is mainly distributed between 190-250°C. The homogenization temperature range gradually decreases from Stage II to Stage IV, which is consistent with the previous temperature analysis of ore-forming fluids, reflecting different sources or mineralization stages of those fluids. In all stages, the homogenization temperature data points of gas-rich phase inclusions are always more than those of liquid-rich phase inclusions, indicating that gas-rich phase fluids play a more important role in the ore-forming process during these mineralization stages. The temperature concentration areas of gas-rich and liquid-rich are different in different stages, which is related to the sources and composition of ore-forming fluids in different mineralization stages.

It can be seen from the above analysis that different mineralization stages in the Zhacun Gold Deposit exhibit different homogenization temperature distribution characteristics, which further confirms that ore-forming fluids have different physical and thermodynamic characteristics in different stages. The homogenization temperature gradually decreases from stage II to stage IV, which is related to changes in the sources of ore-forming fluids or crustal stress in different mineralization stages. The homogenization temperature distribution of gas-rich phase inclusions in all stages is more concentrated than that of liquid-rich phase inclusions, which means that gas-rich phase fluids play a more important role in the ore-forming process.

Figure 4 shows the salinity histograms of ore-forming fluid inclusions in the Zhacun Gold Deposit in different stages. In stage II, the salinity distribution of gas-rich phase inclusions is mainly concentrated in the range of 3-6%, while that of liquid-rich phase inclusions is mainly concentrated in the range of 3-5%. In stage III, the salinity of gas-rich phase inclusions is mainly distributed in the range of 2-7%, while that of liquid-rich phase inclusions is mainly concentrated in the range of 3-4%. In stage IV, the salinity of gas-rich phase inclusions is mainly concentrated in the range of 0-3%. The salinity gradually decreases from stage II to stage IV, which is related to changes in the sources of ore-forming fluids or in the ore-forming process. The salinity distribution data points of gas-rich phase inclusions are always more than those of liquid-rich phase inclusions in all stages, which means that gas-rich phase inclusions play a more important role in the ore-forming process.

It can be seen from the above analysis that salinity shows a clear variation trend in different mineralization stages in the Zhacun Gold Deposit, which is related to the properties of ore-forming fluids and different stages of the ore-forming process. Due to more interactions between ore-forming fluids and surrounding rocks, or different fluid sources in different mineralization stages, salinity gradually decreases as the mineralization stage progresses. Gas-rich phase inclusions exhibit higher salinity distribution density in various stages, indicating that they play a more important role in the ore-forming process.

The analysis of Table 2 shows that the cations are mainly Na^+ and Ca^{2+} , followed by K^+ and Mg^{2+} , and their content is $7.0\sim 8.4 (\times 10^{-9})$, $5.7\sim 8.9 (\times 10^{-9})$, $0.31\sim 2.40 (\times 10^{-9})$, and $0.99\sim 2.40 (\times 10^{-9})$, respectively. The anions are mainly SO_4^{2-} and Cl^- , and their content is $20.9\sim 30.2 (\times 10^{-9})$ and $10.1\sim 13.9 (\times 10^{-9})$, respectively. The F^- content is relatively low in quartz inclusions, which is $0.34\sim 0.55 (\times 10^{-9})$. However, the F^- content in pyrite inclusions reaches 14.0×10^{-9} . The main components of inclusions are H_2O and CO_2 .

Figure 5 shows the radial distribution function (RDF) values of liquid phase composition Na^+ cations at different temperatures. Gas-rich and liquid-rich phase inclusions usually provide information on the physical and chemical conditions of ore-forming fluids, such as temperature, pressure,

and salinity. In stage II, the frequency distribution of gas-rich phase inclusions shows a wider range than that of liquid-rich phase inclusions, which indicates that the gas-rich phase environment is more complex or variable than the liquid-rich phase environment in this stage. Compared with stage II, the frequency of gas-rich phase inclusions is more concentrated in the intermediate value in stage III, indicating that the ore-forming fluid environment in this stage is relatively stable. The RDF value varies as the temperature decreases, which means that the distribution and interaction of Na^+ ions also vary at different temperatures. At higher temperatures (e.g., 5000K, 4500K, etc.), the distribution of Na^+ is relatively stable. At low temperatures (e.g., 300K), there is a significant fluctuation in the RDF value, which is related to the change in liquid phase structure caused by temperature decrease.

Figure 6 shows the RDF value of ions (Na^+ , Ca^{2+} , and SO_4^{2-}) at different distances (radial distances) at different temperatures (300K, 2000K, 4200K, and 5000K). RDF is used to describe the average density of particles (ions in this case) within a given distance range. A high RDF value indicates high density or clustering, while a low RDF value indicates low density or less clustering.

All ions (Na^+ , Ca^{2+} , and SO_4^{2-}) exhibit significant clustering (a high RDF value) at distances of 10 and 12 at 300K. The overall RDF value decreases at 2000K, indicating a more uniform distribution of ions in space. The distribution of all three ions at each distance point is relatively uniform, but some small peaks can still be observed. Due to the greater kinetic activity caused by high temperature, the RDF values are further averaged at 4200K and 5000K. The RDF values of Na^+ , Ca^{2+} , and SO_4^{2-} are almost the same at these two temperatures, indicating that the increase of temperature makes the spatial distribution of ions more uniform.

It can be seen from the above analysis that the kinetic activity of ions increases as the temperature increases, leading to their more uniform distribution in space. The clustering or preference between specific ions decreases at high temperatures. The RDF distribution of the three ions is very similar at 4200K and 5000K, which means that chemical properties of the ions have a reduced impact on their distribution in liquids at these temperatures.

Table 1. Microscopic temperature measurement results and physical parameters of ore-forming fluid inclusions in the Zhacun Gold Deposit

Stages	Minerals	Types	Gas Phase Ratio (%)	Homogenization Temperature (°C)	Freezing Temperature (°C)	Salinity (%NaCl)	Density (g/cm ³)	Kelvin Temperature	Pressure/bar
II	Quartz	Liquid-rich phase inclusions	5~20	256~328	-13.5~2.5	4.1~19.1	0.61~0.76	528~628	51~148
		Gas-rich phase inclusions	55~90	258~329	-8.7~2.5	5.2~12.6	0.62~0.78	529~614	47~135
III	Quartz	Liquid-rich phase inclusions	5~25	225~315	-7.5~1.8	3.1~12.1	0.63~0.82	478~625	22~124
		Gas-rich phase inclusions	55~80	255~287	-5.6~2.6	4.6~8.7	0.72~0.76	487~558	23~81
IV	Quartz	Liquid-rich phase inclusions	5~35	175~245	-3.1~0.5	0.9~4.8	0.77~0.88	467~552	12~54

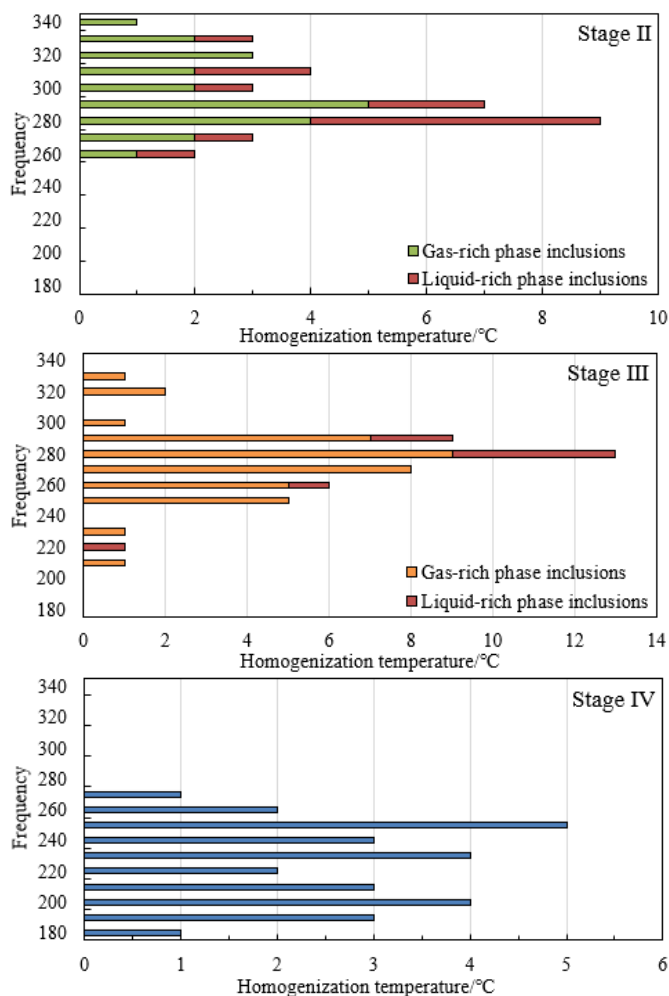


Figure 3. Homogenization temperature histograms of ore-forming fluid inclusions in the Zhacun Gold Deposit in different stages

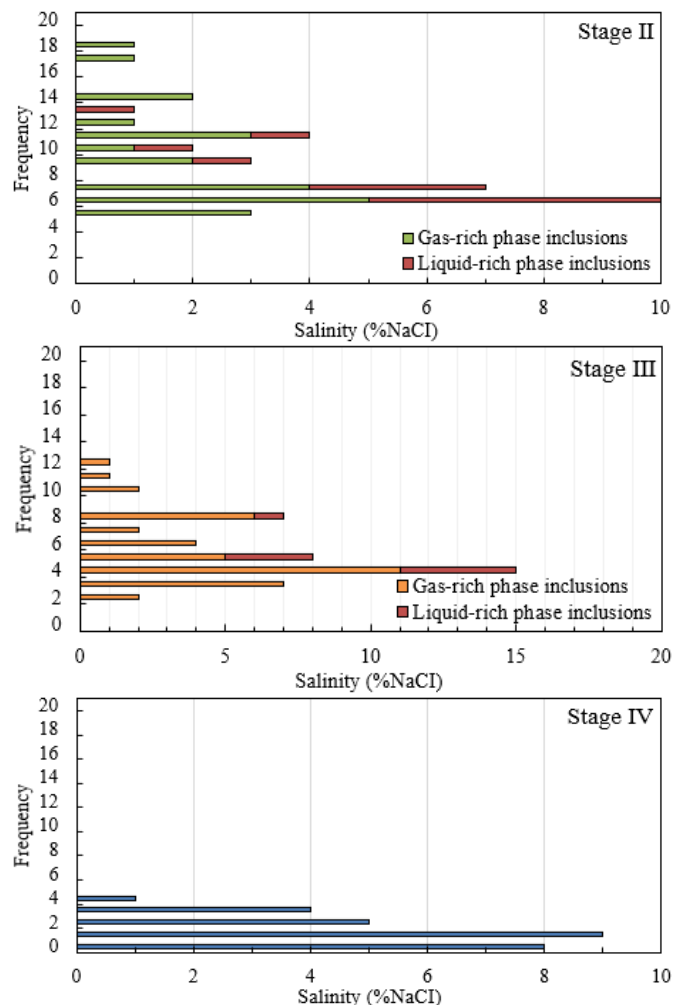


Figure 4. Salinity histograms of ore-forming fluid inclusions in the Zhacun Gold Deposit in different stages

Table 2. Content of inclusion composition in the Zhacun Gold Deposit

Sample No.	Tested Minerals	Water Volume (mg)	Cations ($\times 10^{-9}$)				Anions ($\times 10^{-9}$)			CO_2
			Na^+	K^+	Ca^{2+}	Mg^{2+}	F^-	Cl^-	SO_4^{2-}	
Z-2	Quartz	24.9	7.0	0.65	8.9	2.2	0.44	10.1	24.4	
Z-3	Quartz	18.1	8.7	0.61	8.8	2.4	0.55	13.9	30.2	
Z-5	Quartz	29.2	8.4	0.31	5.7	0.99	0.34	12.4	20.9	
In the ore zone	Pyrite	444	0.59	4.39	12.9	1.507	14.0	3.8		29.0
In the ore zone	Pyrite	1778	3.57	0.83	0.50	0.05	0.10	7.4		3.1

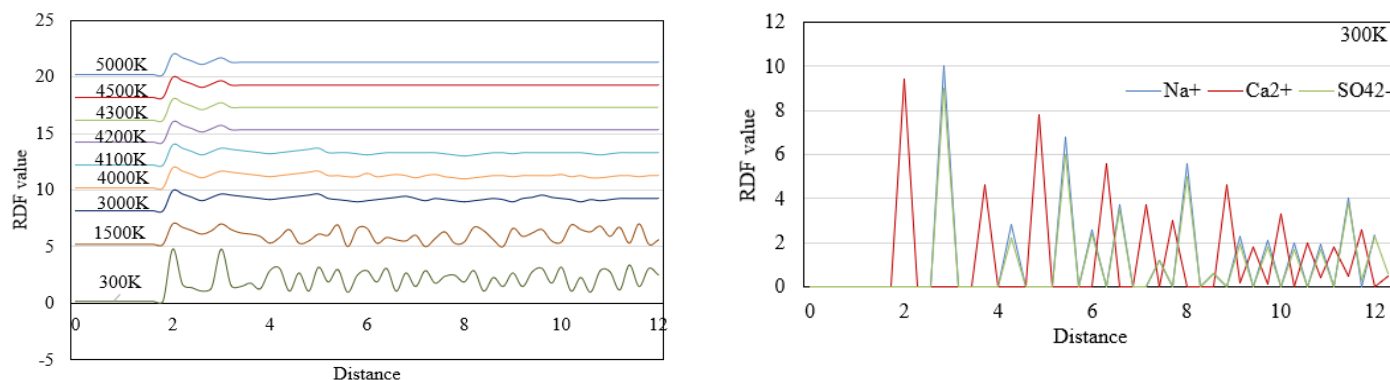


Figure 5. Total RDF of liquid phase composition Na^+ cations at different temperatures

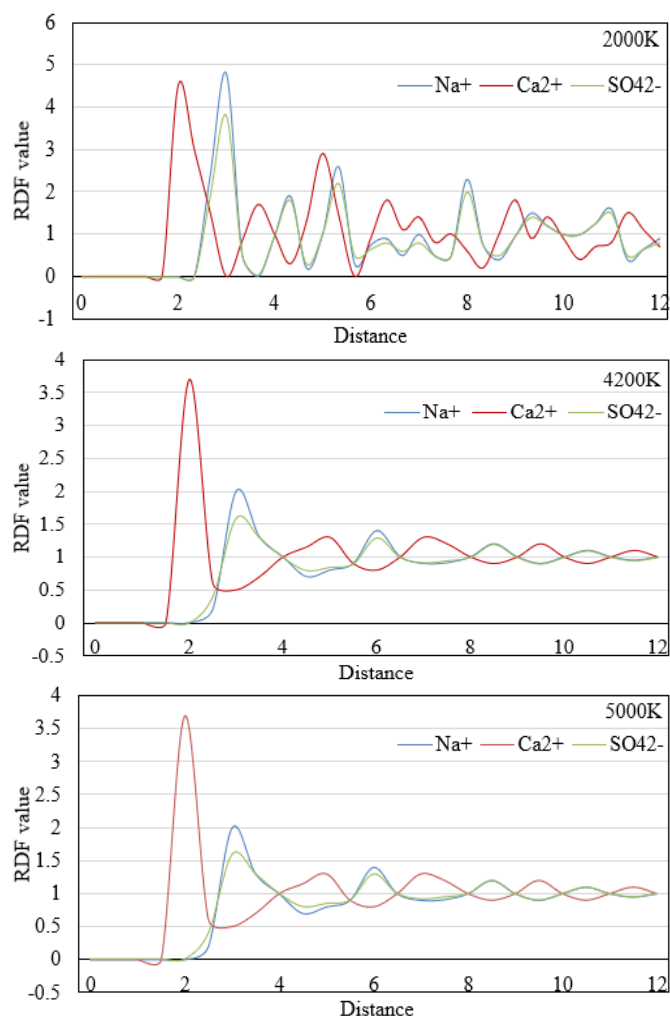


Figure 6. RDF of different ions at different temperatures

6. CONCLUSION

This article deeply analyzed the thermophysical properties of ore-forming fluids and the ore-forming process in the heat ore deposit by constructing a set of comprehensive and accurate mathematical models and equations. The research content is divided into three parts, namely, construction of thermal and solute diffusion equations, construction of mass and energy conservation equations, and construction of the solute transfer equation. The experimental results focused on the behaviors of different types of ions in liquids, especially the RDF at different temperatures. The composition and temperature of liquids significantly affected the distribution and interaction of ions. This study also discussed how to affect the properties of liquids by changing their composition or adding other substances (e.g., sugar, salt, etc.). The experimental results showed that different liquid components affected liquid properties and ionic behaviors differently. For example, addition of sugar and salt changed the physical properties of liquids, such as viscosity and density. As the temperature increased, the RDF value of ions tended to become uniform, indicating that the distribution of ions in liquids became more uniform. Due to electric charges, sizes, and interactions, different types of ions exhibited different RDF characteristics under the same environmental condition. The RDF of various types of ions tended to be consistent at extremely high temperatures, maybe because the kinetic

activity of ions increased and the influence of chemical properties decreased at high temperatures. The above conclusions enhanced the understanding of liquids and ion dynamics, and provided useful information for industrial applications, such as electrolyte design, water treatment, and energy storage. However, more experimental data and theoretical models are needed to further refine these observations and conclusions.

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