

Article

Determining the Paleostress Regime during the Mineralization Period in the Dayingezhuang Orogenic Gold Deposit, Jiaodong Peninsula, Eastern China: Insights from 3D Numerical Modeling

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Abstract: The Dayingezhuang orogenic gold deposit, located in the northwestern Jiaodong Peninsula, is hosted by the Zhaoping detachment fault, but the paleostress regime during the mineralization period remains poorly understood. In this study, a series of numerical modeling experiments with variable stress conditions were carried out using FLAC3D software to determine the orientation of paleostress and the fluid migration processes during the ore-forming period. The results show that the simple compression or tension stress model led to fluid downward or upward flow along the fault, respectively, accompanying the expansion deformation near the hanging wall or footwall of the Zhaoping fault, which is inconsistent with the known NE oblique mineralization distribution at Dayingezhuang. The reverse and strike-slip model shows that the shear stress was distributed in the gentle dip sites of the fault, and the expansion space occurred in the geometric depression sites of the fault, which is also inconsistent with the known mineralization distribution. The normal and strike-slip model shows that shear stress was distributed in the sites where the fault geometry transforms from steep to gentle. In addition, the expansion deformation zones appeared at sites with dip angles of 35~60° in the footwall and extended along with the NE-trending distribution from shallow to deep levels. The numerical results are quite consistent with the known mineralization, suggesting that the fault movement during the mineralization stage is a combination of the local strike-slip and the NW–SE extension in the Dayingezhuang deposit. Under this stress regime (σ_1 NE–SW, σ_2 vertical, σ_3 NW–SE), the NE dilation zones associated with fault deformation served as channels for the ore-forming fluid migration. Based on the numerical modeling results, the deeper NE levels of the No. 2 orebody in the Dayingezhuang deposit have good prospecting potential. Thus, our study not only highlights that gold mineralization at Dayingezhuang is essentially controlled by the detachment fault geometry associated with certain stress directions but also demonstrates that numerical modeling is a robust tool for identifying potential mineralization.

Keywords: numerical modeling; paleostress regime; rock deformation; fluid migration; Dayingezhuang orogenic deposit



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1. Introduction

The Jiaodong Peninsula is the largest gold production area in China, with >4500 t of known gold resources [1]. Most of the gold deposits in the Jiaodong Peninsula are characterized by similar mineralization occurrences. For example, orebodies are usually situated

in the footwall of regional fault zones [1–3]; the fertile ore zone displays stepped vertical geometry and is associated with fault dip changes [4,5]; orebodies and their controlling faults have specific dip angles [3,6]; and they have the identical phyllic–silicification–potassic alteration halos around the ore-controlling fault [3,5,7]. Therefore, the gold deposits in the Jiaodong region were formed by the coupling of structure deformation and fluid flow.

The Dayingezhuang gold deposit is located in the middle section of the Zhaoping fault, northwestern Jiaodong Peninsula, and shares similar geological characteristics with other Jiaodong gold deposits. Previous studies have always debated the activity of regional detachment faults and paleostress regimes and have proposed NW–SE compression [8] and NW–SE extension [9–11], the coupling of normal slip and strike-slip tectonic activities [12], the transformation from a NW–SE extensional to a NW–SE compressional tectonic system [13], NNW compression → NE–SW extension → E–W compression → NE–SW extension [14,15], and multi-transformation from NW–SE compression to shear compression, shear tension, and extension [16,17]. While it has been well documented that the orebodies are tectonically controlled, which stress background has influenced the mineralization and how fluids migrated from the source to trap are still poorly understood.

Structural controls on hydrothermal mineralization are attributed to the structure's influence on the fluid flow [18–20]. Coupled deformation and fluid flow numerical models have been widely used to find favorable locations of ore-forming pooling zones in many hydrothermal deposits [21–28]. Numerical simulation can simulate the interaction of structure, rock deformation, and fluid flow and reproduce a large number of tectonic evolution scenarios in a short time [24,28,29]. For example, Zhang et al. [30] presented the results of 3D case-study models (with deformation and fluid flow coupling) on the Hodgkinson Province and were able to generate some potential gold mineralization targets. Cui et al. [24] investigated the fluid flow in Proterozoic basins that host unconformity-related uranium deposits and focused on the development of specific fluid flow patterns, which are determined by the relative roles of strain rates and a variety of hydraulic properties. Li et al. [28] presented a 2D dynamic modeling of fluid flow coupled with mechanical compression and heat transport in the hydrothermal uranium-bearing Athabasca basin. Liu et al. [31] used numerical modeling to reproduce the deformation process of the Baiyun gold deposit during the mineralization period, suggesting gold mineralization is influenced by the dip angle and dip direction of the lithological interface. Hu et al. [32] used a coupled numerical model for discussing the genesis of the Chating porphyry copper-gold deposit and calculating the time duration of the mineralizing hydrothermal system. Liu et al. [33] simulated the intrusions' cooling and related fluid flow processes in the Dawangding deposit and demonstrated that the high dilational zones were produced by coupled mechano-thermo-hydrological processes and that these controlled the gold orebodies. These studies indicate both the feasibility and usability of numerical simulation modeling for understanding the influence of tectonic fluid coupling on mineralization. Hence, if given the physical parameters of the rocks and assuming a variety of paleostress conditions, we can determine the paleostress backgrounds and fluid migration patterns of the metallogenic period based on the comparison of the simulation results and known mineralization distributions.

In this study, we selected the large-scale (Au > 150 t) Dayingezhuang gold deposit as a case study of the gold deposits in the Jiaodong Peninsula to discuss the various possible paleostress states, the related deformation processes, and the structurally influenced fluid flow. Various stress orientation models were tested to explore the hydrodynamic relationships more fully and to systematically investigate the effects of deformation on fluid flow patterns. The effect of tectonic stress on ore-forming fluid flow is discussed in light of the numerical modeling results and was further used to identify prospective areas at greater depth in the Dayingezhuang system. The results of the present study may have important implications for the origin and exploration of gold deposits in the Jiaodong Peninsula.

2. Geological Background

The Jiaodong Peninsula is situated in the southeastern margin of the North China Craton and is bounded by the Wulian–Rongcheng fault to the east and the NNE-trending Tan–Lu Fault Zone to the west [2]. Supracrustal rocks in the northwestern Jiaodong Peninsula are metamorphosed Precambrian sequences and Mesozoic intrusions [34]. The main structures are three regional detachment faults trending NNE and NE [35] from west to east: Sanshandao, Jiaojia, and Zhaoping (Figure 1).

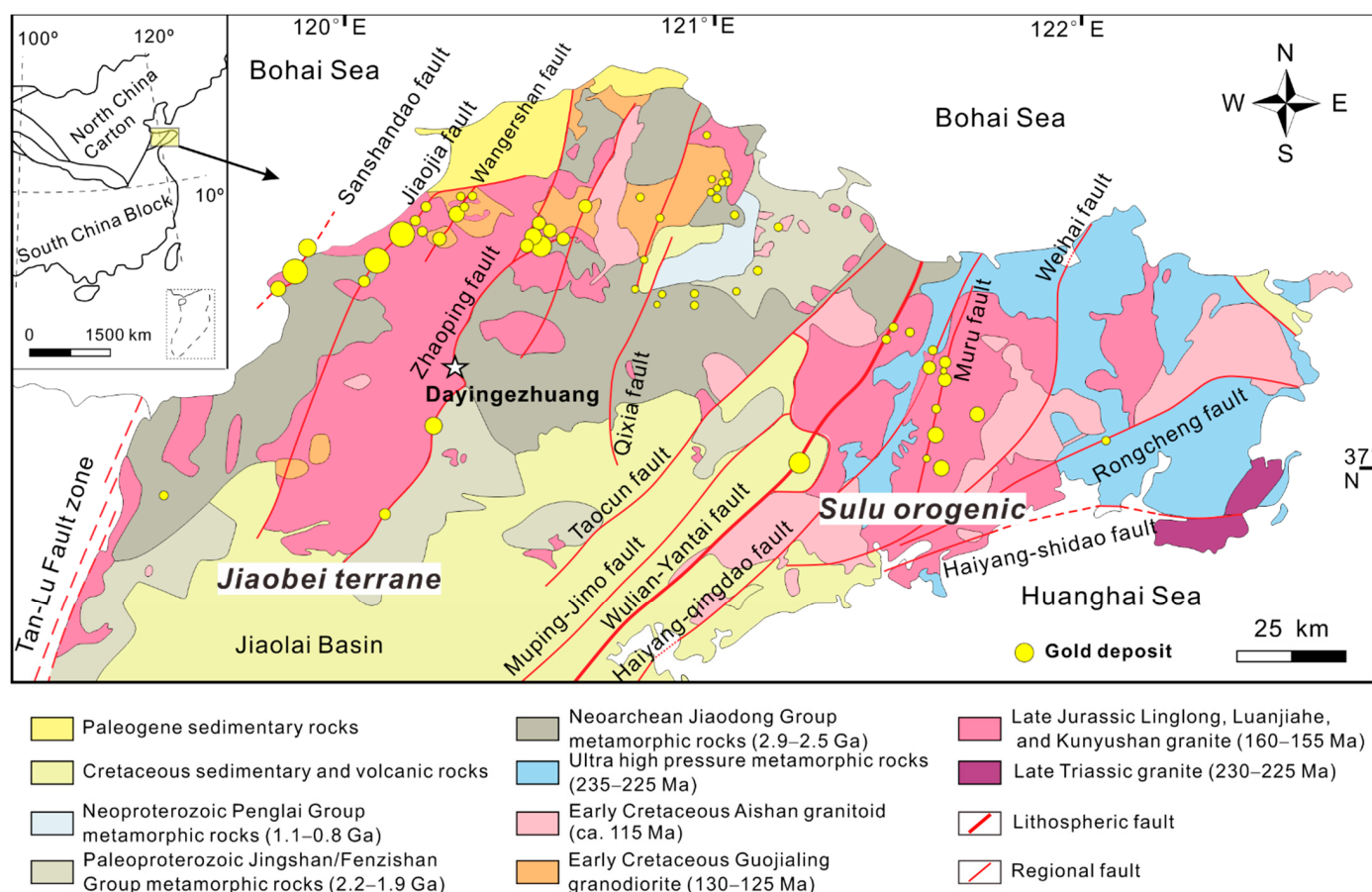


Figure 1. Geological map of the Jiaodong gold province showing the distribution of major fault zones, formations, intrusions, and gold deposits (modified from [36]).

The Dayingezhuang gold deposit is located in the northwest Jiaodong Peninsula [13,35]. The ore-controlling Zhaoping fault zone in Dayingezhuang strikes SW–NE with a dip ranging from 30° to 60° (Figure 2). The Zhaoping fault is offset by about 260–300 m at the surface by the E–W trending Dayingezhuang sinistral-slip fault. The formations at Dayingezhuang are dominated by Archean Jiaodong group metamorphic rocks and Quaternary rocks distributed in the east. The Jurassic Linglong granite and minor NE–NNE-striking dikes occur in the west of the Zhaoping fault. The Dayingezhuang gold deposit displays successive alteration zonation patterns from the center (orebody) outward (Figure 3) [11]. Gold mineralization mainly occurs in the cataclastic rocks with intense microfractures in the footwall of the Zhaoping fault [35]. The gold mineralization zone extends 700–900 m along the dip direction, with varying thicknesses ranging from 2 to 30 m. Two major orebodies (No. 1 and No. 2) are located in the south and north of the Dayingezhuang fault, respectively (Figure 2).

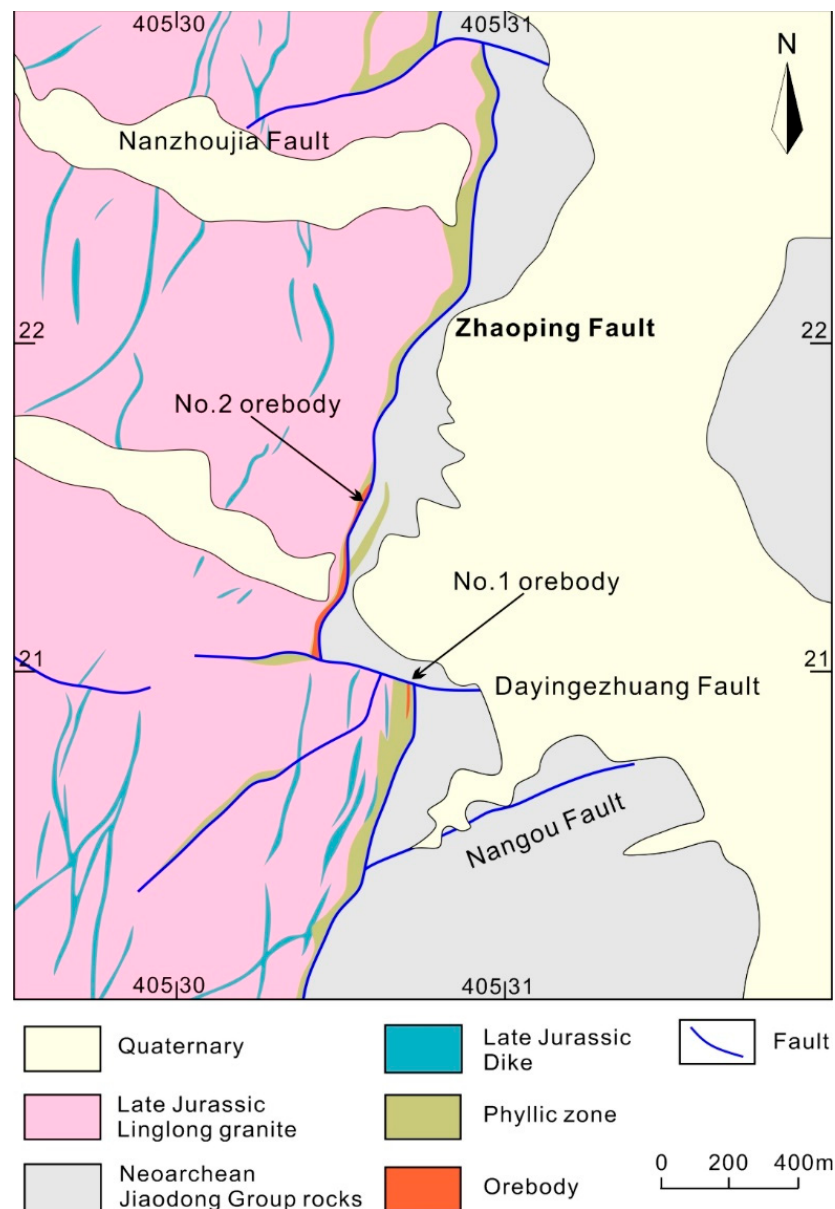


Figure 2. A simplified geological map of the Dayingezhuang gold deposit [37].

Two types of ore (disseminated and quartz vein) have been distinguished in the Dayingezhuang gold deposit [11]. Disseminated ore occurs in the footwall of the Zhaoping fault with relatively large reserves (90%) and low grades (<5 g/t), and it is linked to brecciation and intense quartz–pyrite–sericite alteration. Vein-type ores have smaller reserves but higher grades (typically >8 g/t), and mainly occur in secondary faults and fractures in the phyllic alteration footwall zone or with weak quartz–pyrite–sericite alteration, which occurs at varying distances from the Zhaoping fault [37–41]. The timing of the Dayingezhuang gold mineralization was reported to be ca. 133 to 127 Ma, which is slightly earlier than other gold deposits in the Jiaodong Peninsula [13]. The trapping temperatures of the fluid inclusions ($\text{CO}_2\text{--H}_2\text{O}$, aqueous fluid, and $\text{CO}_2\text{--H}_2\text{O}\pm\text{CH}_4$) in Au-bearing quartz veins at Dayingezhuang are between 360 and 280 °C [42,43].

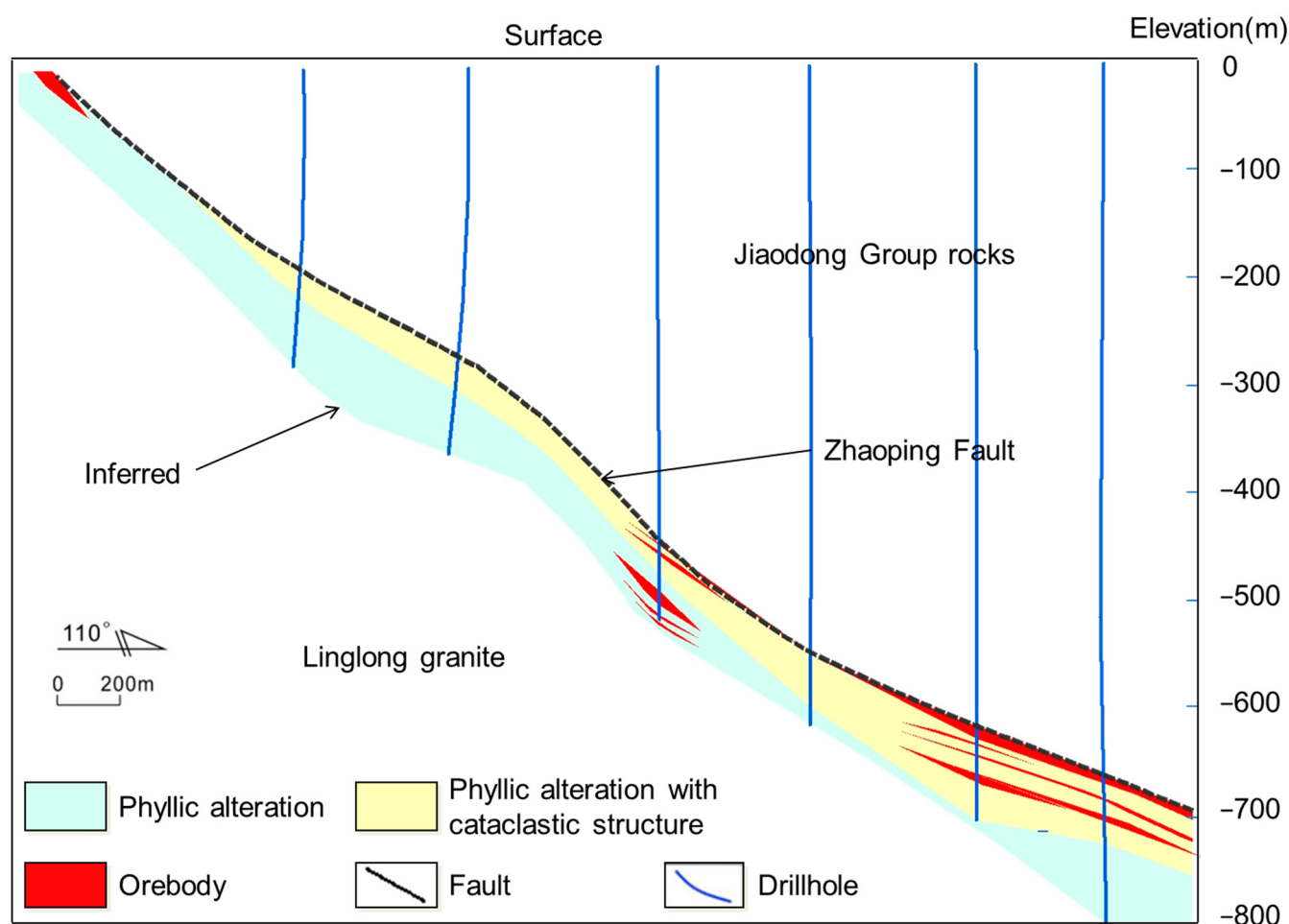


Figure 3. Geological section of the Dayingezhuang gold deposit. The cross-sections illustrate that orebodies mainly occur near the fault interface in the footwall.

3. Method

3.1. Numerical Simulation Methods

Typically, in structural geology, stress inversion is mostly based on the Wallace–Bott hypothesis [44,45], which stipulates that the shear stress resolved onto the fault plane is parallel to the slip vector when the fault occurred and can be used to determine the stress tensor. Dupin et al. [46] and Pollard et al. [47] pioneered the numerical method (3D distinct element method) to check the validity of the Wallace–Bott hypothesis. Pascal applied the Sortan analytical method [48] and 3D distinct element method [49] to investigate fault slip movement to validate the Wallace–Bott hypothesis for tested geometries and boundary conditions. Since the geometric complexity of fault surfaces and fault networks may induce heterogeneity in fault slip directions, Maerten et al. [50,51] have explored the consequences of the varying geometry of intersecting faults in slip directions and used elastic modeling to invert fracture data. Lejri et al. [52] used the 3D boundary element method to conduct research on geomechanical multi-parameters and to understand the effect of each parameter on the misfit angle between geomechanical slip vectors and the resolved shear stresses. The paleostress analysis method based on the superposition principle can recover the distal stress state of multiple tectonic events effectively [53]. The iteratively coupled double system can estimate the paleostress by measuring displacement discontinuity on some parts of the faults. Many algorithms have been developed for stress inversion and have been successfully applied in many studies [53–57].

For the coupled interaction between fluid flow and tectonic deformation in most hydrothermal mineral systems, the numerical model should include a dynamic evolution

process. Fast Lagrangian analysis of continua three-dimensional (FLAC3D), which uses an iterative process and defines models as isotropic elastic–plastic Mohr–Coulomb material, is suitable for simulating fluid flow and heat transport in porous media caused by rock deformation [18,58]. It has been successfully applied to various hydrothermal ore-forming systems [18–20,22]. Concerning the hydrothermal–structural coupling ore-forming system, we used FLAC3D to conduct the paleostress inversion and investigate the favorable position of mineralization in the Dayingezhuang deposit model. The fault and the surrounding wall rocks in the model are treated as continua and divided into blocks. The equation of the coupling process is described as follows [58]:

$$q^W = -k \nabla (P - \rho_w g \cdot x) \quad (1)$$

$$q^T = -k^T \nabla T \quad (2)$$

$$\frac{\partial \zeta}{\partial t} = -q_{i,i} + q_v^W \quad (3)$$

$$C^T \frac{\partial T}{\partial t} + \nabla q^T + \rho_0 c_w q^W \cdot \nabla T - q_v^T = 0 \quad (4)$$

$$\rho \frac{dv_i}{dt} = \sigma_{ij,j} + \rho g_i \quad (5)$$

$$\frac{\partial \varepsilon_{ij}}{\partial t} = \alpha_t \frac{\partial T}{\partial t} \delta_{ij} \quad (6)$$

$$\frac{\partial y}{\partial x} = M \left(\frac{\partial \zeta}{\partial t} - \alpha \frac{\partial \varepsilon}{\partial t} + \beta \frac{\partial T}{\partial t} \right) \quad (7)$$

The model is controlled by a series of partial differential equations, including Darcy's Law (Equation (1)) to describe fluid flow in porous media, Fourier's Law (Equation (2)) to describe heat conduction, the conservation law (Equations (3)–(5)) to describe the conservation of mass, energy, and momentum, and the equation of state (Equations (6) and (7)) to describe the coupled constitutive relations of heat, force, and flow [59]. The mathematical symbols and scientific significance of the formula are described in Table 1.

Table 1. Mathematical symbols and scientific meanings in equations.

Symbol	Meaning
q^W	fluid-specific discharge
k	coefficient of fluid mobility
P	pressure of the pore fluid
ρ_w	fluid density
g	gravitational acceleration
q^T	heat flux
k^T	effective thermal conductivity
T	temperature
ζ	variation of fluid content
q_v^W	volumetric fluid source
$q_{i,i}$	vector of fluid-specific discharge in the x_i direction
C^T	effective specific heat
q^T	heat flux
ρ_0	reference density of the fluid
c_w	specific heat of the fluid
q_v^T	thermal fluid source
ρ	bulk density of the porous medium
σ_{ij}	stress tensor of the solid
v_i	velocity component in the x_i direction
g_i	component of gravitational acceleration in the x_i direction

Table 1. Cont.

Symbol	Meaning
ε_{ij}	thermal strain tensor
α_t	coefficient of linear thermal expansion
δ_{ij}	Kronecker delta
ζ	variation in fluid content
M	Biot modulus
α	Biot coefficient
ε	volumetric strain
β	volumetric thermal expansion of the porous matrix

Three-dimensional geological modeling approaches reported in [37,60] were used in this study for model construction. Most geoscientific numerical simulations include conceptual, mathematical, and simulation modeling [31,33,61–63]. This study improved the workflow, and the detailed workflow of the numerical simulation is shown in Figure 4. Firstly, the data of geological exploration were collected and digitized based on summarizing the existing metallogenic regularities of the study area. Because the Zhaoping main fault zone was offset by the Dayingezhuang fault, the Zhaoping fault zone was reconstructed before numerical modeling. The thickness of the fault zone was 50 m, and the Zhaoping fault interface was joined together by the way of node displacement to restore the geometric structure of the fault in the ore-forming period. The solid model of the geological unit was built up based on the closed surface model. Finally, the solid model data format was converted into a tetrahedral grid model data format and imported into FLAC3D software for numerical simulation. The detailed workflow of numerical simulation is shown in Figure 4.

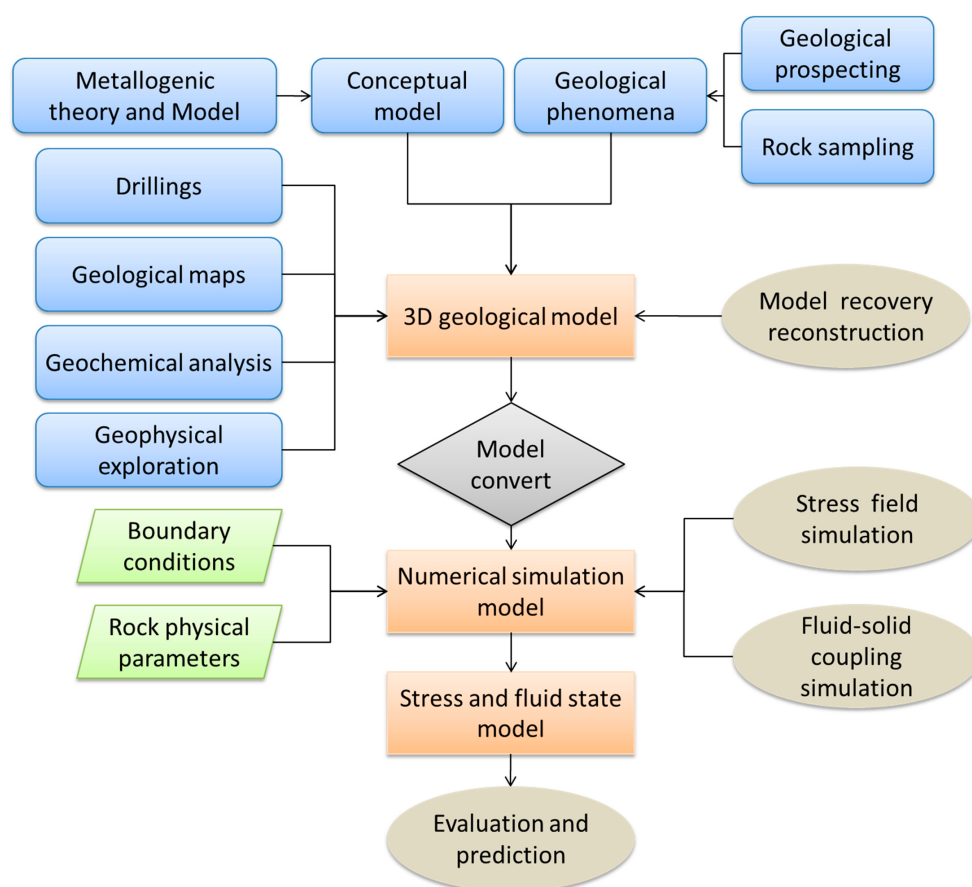


Figure 4. Numerical simulation workflow.

3.2. The Model Setup

It was necessary to create a simplified conceptual model, including the fault zones, Jiaodong group (hanging wall), and Linglong granite (footwall), to build the numerical model of the Dayingezhuang gold deposit. Concerning the post-ore erosion, we added a cover of the Jiaodong Group with a thickness of 7–8 km, which has been suggested by previous studies [40,64,65], and assumed the geothermal gradient was 30 °C/km [66]. The size of the model was 7 km in the north–south and west–east horizontal direction, and 10 km in the vertical. An idealized model was constructed to reflect the geologic features of the Dayingezhuang gold deposit according to the geological cross-section and data (Figure 5a–c). In the model, we combined rocks with similar physical properties or small volumes. The heterogeneity and anisotropy concerning permeability were ignored. The simplified Jiaodong Group, Zhaoping fault, and Linglong granite are the main geologic units at Dayingezhuang (Figure 5d), fundamentally replicating the main geological features of the deposit. Despite the simplified nature of the deposit model, it helps us well understand fluid flow in and around the fault during tectonic deformation and the influence of fault geometry on fluid flow.

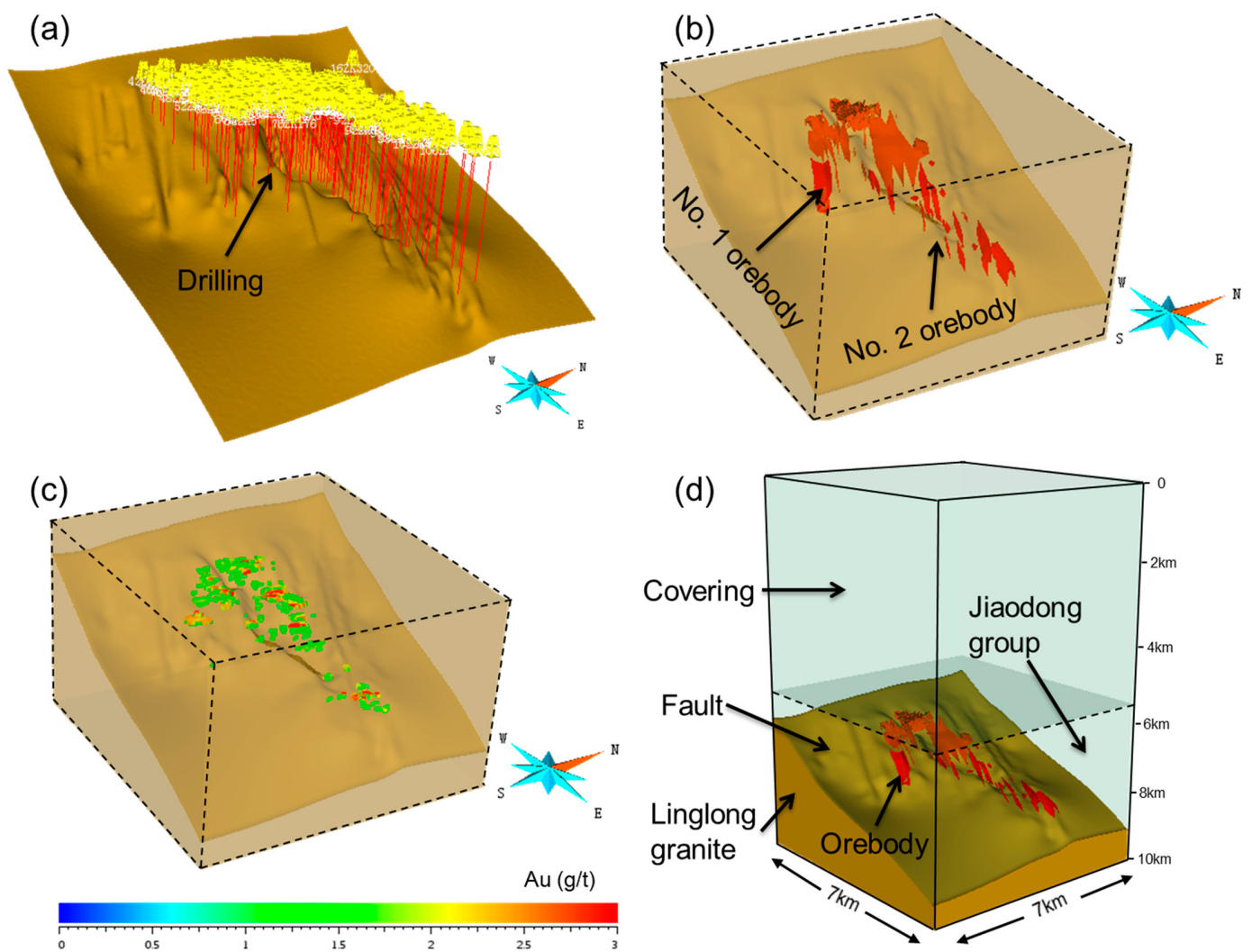


Figure 5. (a) 3D models of the fault and drill holes; (b) 3D models of fault and orebody; (c) gold grade distribution; (d) numerical simulation model.

3.3. Experiment Settings and Modeling Parameters

The physical properties of rocks in the Dayingezhuang deposit were determined (Table 2) based on similar numerical modeling and published compilations [15,18,24,29,67]. During the deformation and fluid flow simulation, the parameters describing the properties were kept constant. Some simplification was performed so that rock units with similar mechanical characteristics were assigned the same properties and all geological units were treated as homogeneous. The fault zone was considered a weak zone with lower mechanical properties and higher permeability relative to the surrounding rock [68].

The boundary conditions of the model were set as follows:

- (1) The base of the model was fixed vertically but moved freely horizontally. The top deformed freely in both the vertical and horizontal directions during the tectonic deformation. Most geological strain rates ranged from 10^{-11} to 10^{-17} s^{-1} [69]; thus, the strain rate range from $1 \times 10^{-13} \text{ s}^{-1}$ to $3 \times 10^{-13} \text{ s}^{-1}$ was assigned at the boundaries in our model [15]. To avoid geometric errors caused by the distortion of the meshes, all models in our study were compressed to a maximum strain of 1%.
- (2) The initial temperature distribution in the model was determined purely by heat conduction, with the temperature at the top parts of the model kept at 20°C , while the temperature at the bottom of the model was assigned and fixed according to the geothermal gradient of $30^\circ\text{C}/\text{km}$ [65,70]. The side boundaries were treated as insulated from heat transport.
- (3) The initial pore pressure gradient was set as hydrostatic. The eroded part of the hanging wall was treated as fixed pore pressure and stress surfaces [24,29]. Fluid flowed out of the model freely at the top boundary, while the bottom and vertical boundaries were assumed to be impermeable.

Table 2. The parameters of the numerical simulation model for the Dayingezhuang gold deposit.

Density of Rock Unit and Lithology	Denudation Layer	Jiaodong Group	Fault	Linglong Granite
Density (kg m^{-3})	2.10	3.80	2.50	2.67
Bulk modulus (10^{10} Pa)	5.70	2.94	8.60	4.16
Shear modulus (10^{10} Pa)	4.10	2.20	7.20	3.38
Cohesive strength (10^6 Pa)	2.6	3.8	4.0	4.2
Tensile strength (10^6 Pa)	1.3	1.8	2.2	2.3
Friction angle	16	30	15	32
Dilatancy angle	4	3	4	3
Permeability (10^{-12} m^2)	1.6	1.6	3.0	1.5
Porosity	0.30	0.30	0.40	0.25
Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	2.3	2.3	4.0	2.4

Simple mechanical compression (Figure 6a) and tension states (Figure 6b) were used to test the relation of compression or tension stress on the flow of the fluid. Model 3 (Figure 6c) and Model 4 (Figure 6d), based on mechanical compression (Model 1) and tensile states (Model 2), respectively, were used to test the favorable sites of expansion deformation and fluid flow patterns of the Dayingezhuang deposit and to determine the orientation of paleostress during the mineralization period [49,50].

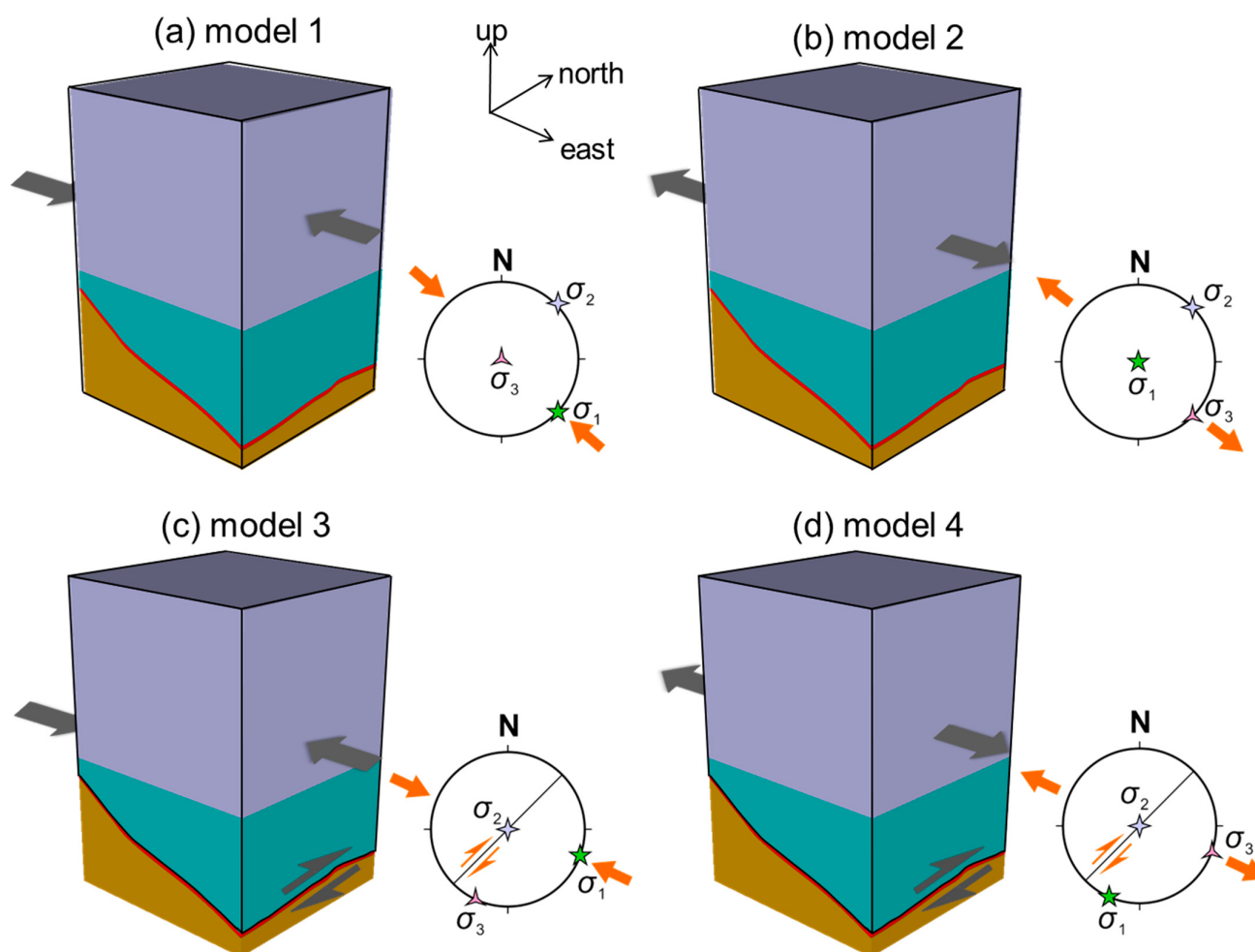


Figure 6. The setting of boundary conditions in the experiment and the kinematic states of models showing (a) compression in the NW–SE direction; (b) extension in the NW–SE direction; (c) extension in the NW–SE direction with dextral strike-slip; (d) extension in the NW–SE direction with dextral strike-slip. The paleostress directions for several models are also shown.

4. Results

The top of the model was interpreted as compressed by 7 km of overlying cover, and the initial mechanical equilibrium was calculated. After equilibrium was reached, a constant convergence velocity was applied to the model boundary to simulate compression, tension, and strike-slip. All models in our study were compressed or stretched to a maximum strain of 1%. Here, a series of experiments in which compressive and tensile stresses were applied was used to evaluate whether the fluid flow patterns and volumetric strain were consistent with the distribution of known orebodies at Dayingezhuang.

4.1. Model 1: Compression in NW–SE Direction

The model was subjected to a constant compression using the parameters in Table 2. A constant compressive velocity of 1.0×10^{-10} m/s was applied to the left and right boundaries of the model to induce a bulk strain rate. The results show the volumetric strain distribution, shear strain distribution, and fluid flow patterns at the 0.5% and 1% bulk shortening stage (Figure 7). The model was in a compression state, and the deformation was distributed on the interface between the hanging wall and the fault, ranging from 1000 to −1000 m. The inhomogeneity of the rock properties resulted in inhomogeneous bulk strain, and the maximum expansion volume strain of the fault zone was 8.0×10^{-3} . The fluids migrated upward to the fault because of the increase in the pore pressure in the

footwall granite during deformation. The fault zone acted as the conduit for fluid migration and transported fluids from depths into the Jiaodong Group units. When the volume strain was 0.5%, the fluid migration was mainly upward, and when the volume strain was 1%, the fluid migrated into the dilated sites. The average fluid velocity of the surrounding rock was about 2.4×10^{-5} m/yr, and the maximum fluid velocity of the fault zone was 6.5×10^{-5} m/yr.

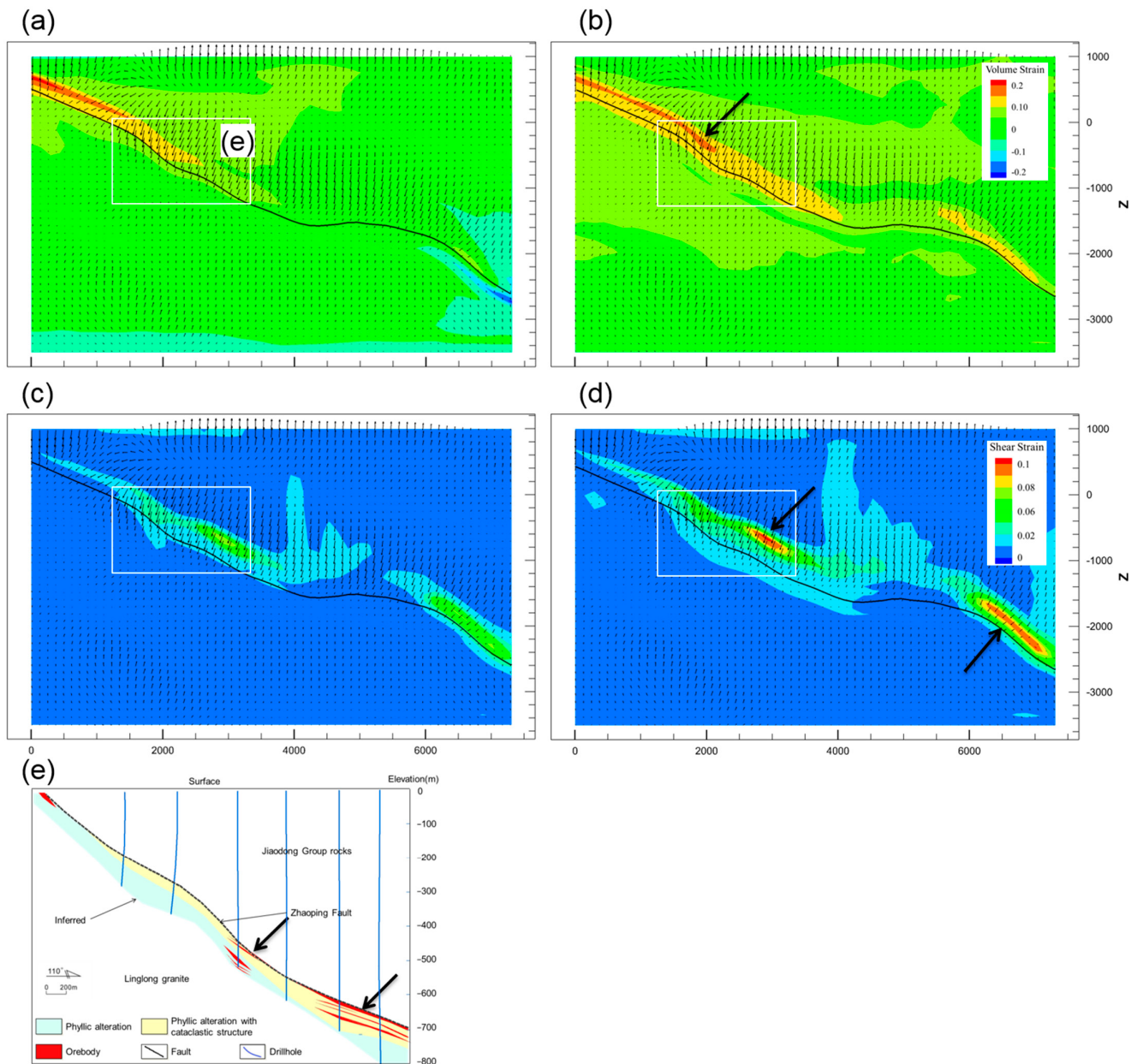


Figure 7. The volumetric strain, shear strain distribution, and detailed fluid flow vectors at a strain rate of 10^{-11} s^{-1} . In the figure, the rectangular box is the scope of the cross-sections; thick arrows indicate areas of intense strain or mineralization; the vector arrows represent the Darcy flux and are used to indicate the direction of flow. (a) 0.5% volumetric strain, (b) 1.0% volumetric strain, (c) 0.5% shear strain, (d) 1.0% shear strain, and (e) corresponding geological section.

4.2. Model 2: Extension in NW–SE Direction

The second model was tested to evaluate whether the volumetric strain and fluid flow patterns were due to the tensile tectonic stress. Tensile stresses were applied in this model and other parameters were the same as in the first model. A constant tensile velocity of

1.0×10^{-10} m/s was applied to the left and right boundaries of the model to induce bulk strain rates.

After 0.5% bulk shortening (Figure 8a,c), intensive dilation occurred in the wedge area of the fault zone under the influence of tension movement. Fluid flowed slowly towards the fault with fluid flow rates of about 2.1×10^{-5} m/yr. After 1.0% tension strain (Figure 8b,d), the fault zone was the site of intensive shear strain accumulation, and the shear strain in the wedge area was further enhanced. The difference in shear stress caused by topography began to affect the hydrothermal system and there was a differential dilation deformation on the fault footwall below -1500 m. The maximum positive volumetric strain inside the fault zone was 2.4×10^{-2} , and the fluid flow rate was about 6.2×10^{-5} . It is interesting to note that tectonic stresses gave rise to local expansive deformation to drive downward flow in the model (Figure 8b).

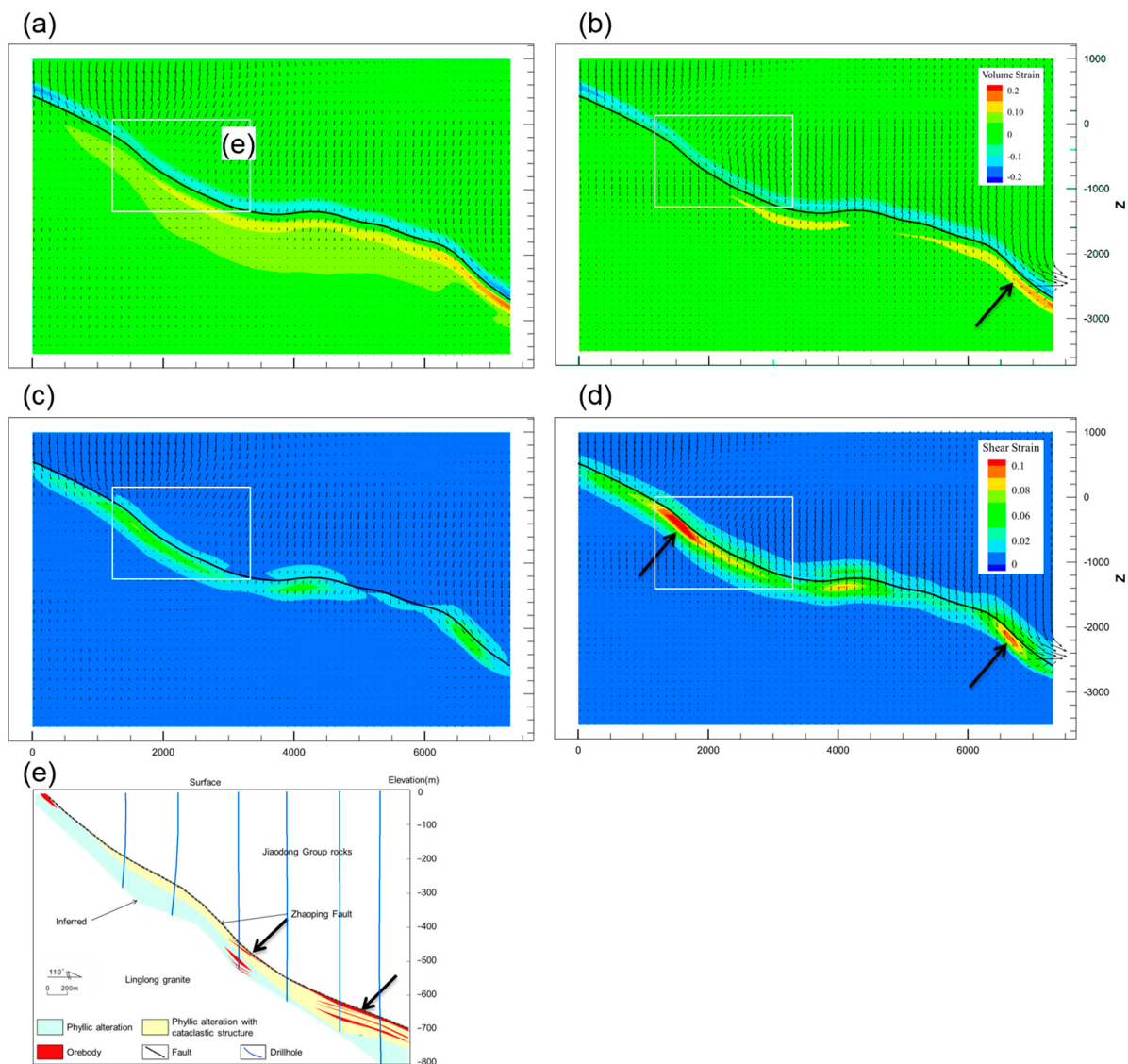


Figure 8. The volumetric strain, shear strain distribution, and detailed fluid flow vectors at a strain rate of 10^{-11} s^{-1} . In the figure, the rectangular box is the scope of the cross-sections; thick arrows indicate areas of intense strain or mineralization; the vector arrows represent the Darcy flux and are used to indicate the direction of flow. (a) 0.5% volumetric strain, (b) 1.0% volumetric strain, (c) 0.5% shear strain, (d) 1.0% shear strain, and (e) corresponding geological section.

4.3. Model 3: Compression in NW–SE Direction with Dextral Strike-Slip

The scenario with compression and strike-slip was tested to evaluate the influence of reverse strike-slip. The velocity applied was the same as in the previous two models (i.e., 10^{-11} s^{-1}), and the strike-slip shear stress was applied to the hanging wall and footwall, respectively. At the initial stage, the fluid flow of the whole model was similar to that of Models 1 and 2 (Figures 7a and 8a), and the maximum fluid velocity of the fault zone was $2.4 \times 10^{-5} \text{ m/yr}$. The fault zone still maintained the most significant volumetric strain localization, with a maximum of 3.6×10^{-2} .

After 1% bulk shortening, the overall distribution patterns of shear and volume strain and related fluids changed (Figure 9b,d) when compared to Models 1 and 2. The volume strain was distributed in the gentle region of the fault and located at depths from -1000 to -1500 m . The fluid tended to flow into the fault zones and migrated upward into the shallow regions along the fault zone; the maximum fluid velocity of the fault zone was $2.7 \times 10^{-5} \text{ m/yr}$.

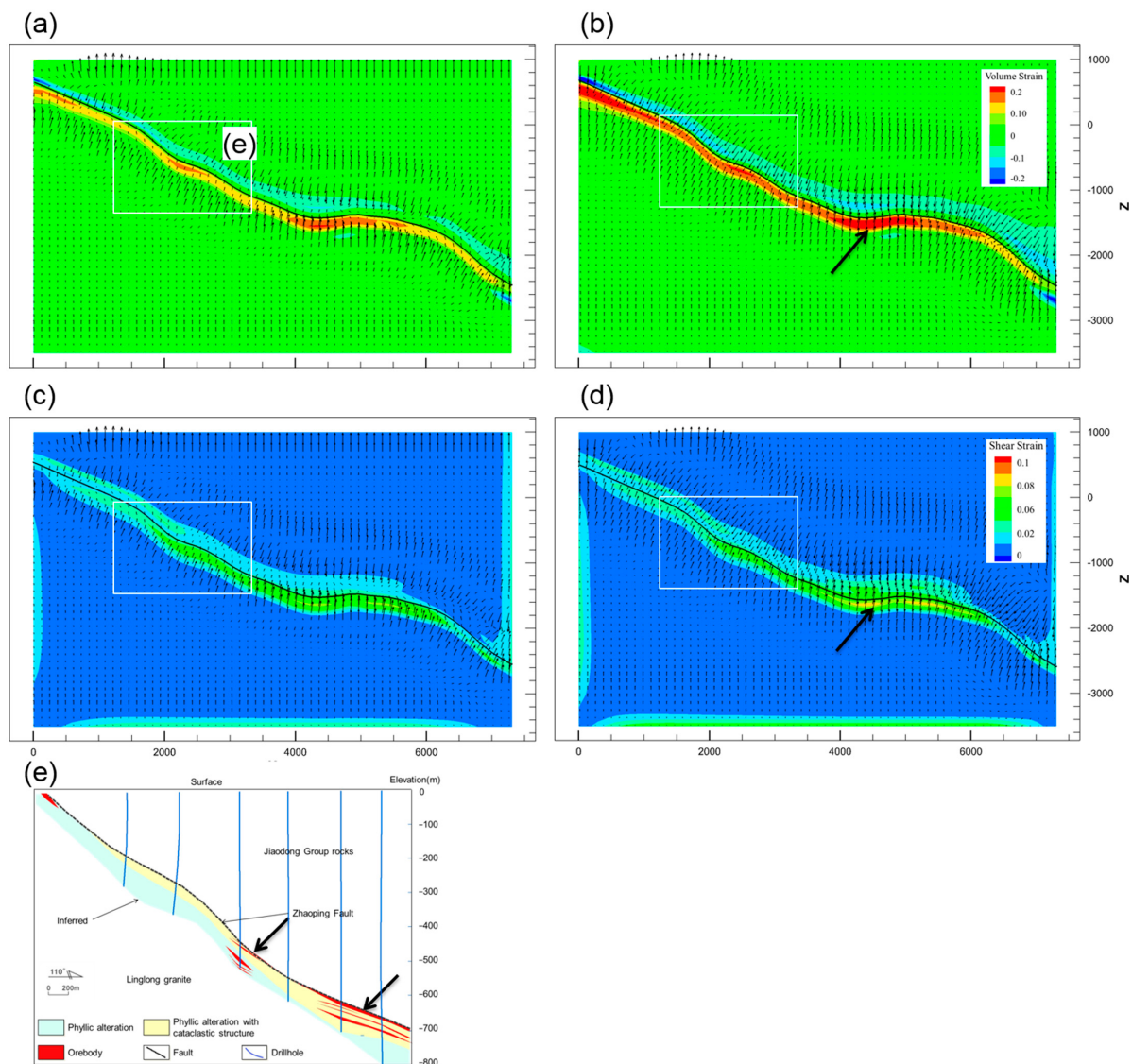


Figure 9. The volumetric strain, shear strain distribution, and detailed fluid flow vectors at a strain rate of 10^{-11} s^{-1} . In the figure, the rectangular box is the scope of the cross-sections; thick arrows indicate areas of intense strain or mineralization; the vector arrows represent the Darcy flux and are used to indicate the direction of flow. (a) 0.5% volumetric strain, (b) 1.0% volumetric strain, (c) 0.5% shear strain, (d) 1.0% shear strain, and (e) corresponding geological section.

4.4. Model 4: Extension in NW–SE Direction with Dextral Strike-Slip

Compared to Model 3, we applied tensile stress instead of compressive stress in Model 4. The volumetric strain, shear strain, and fluid migration distribution are shown in Figure 10. The modeling results suggest that the structural morphological differences of the fault significantly enhanced the control of strain after 0.5% bulk shortening (Figure 10a,b). Due to the inhomogeneous action of tectonic stress, the dilation deformation in the fault zone was discontinuous and the deformation distribution ranged from the surface to −2500 m in the narrow dip angle of the fault. The maximum volumetric strain and fluid velocity of the fault zone were 1.6×10^{-2} and 2.8×10^{-5} m/yr, respectively.

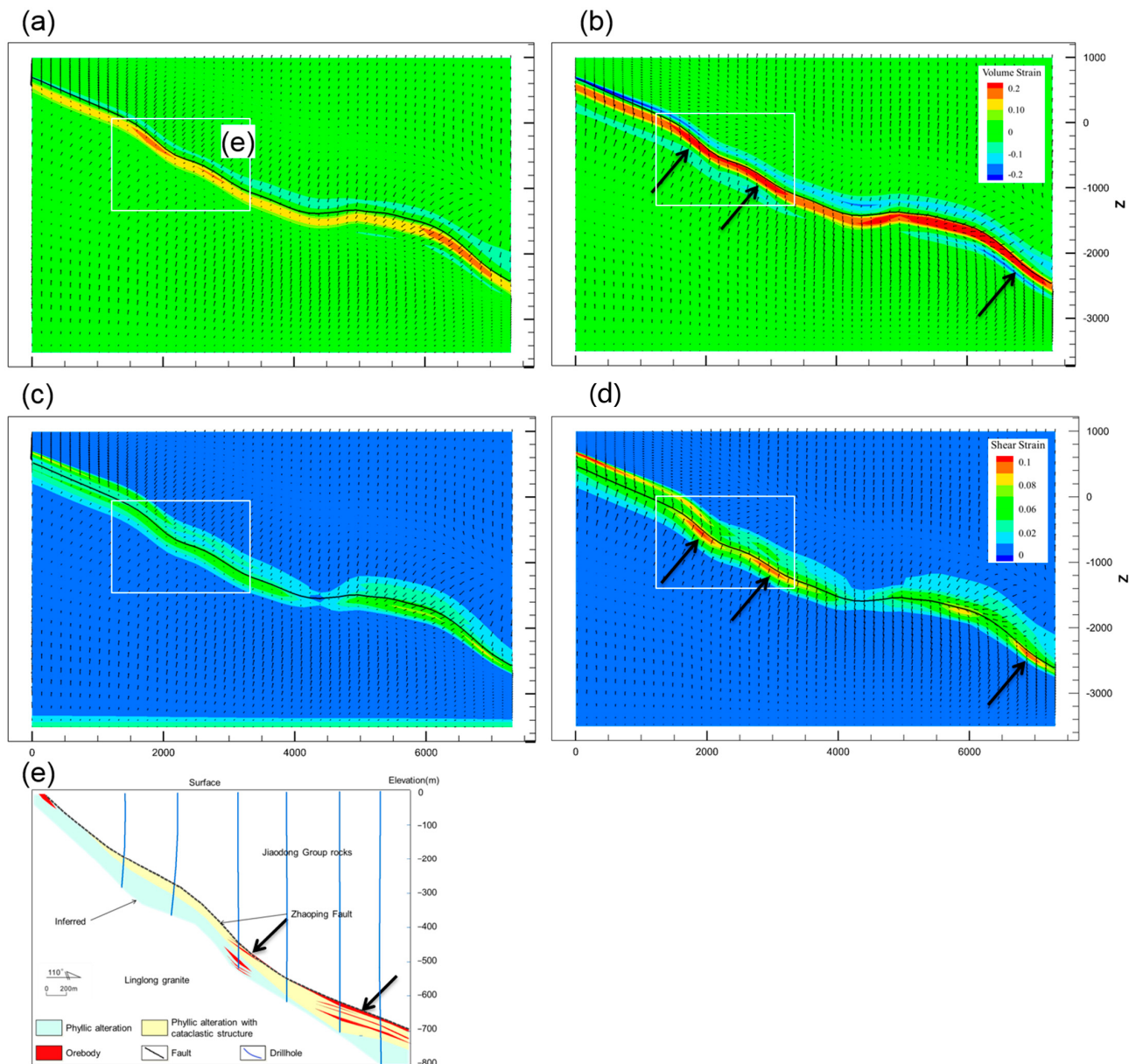


Figure 10. The volumetric strain, shear strain distribution, and detailed fluid flow vectors at a strain rate of 10^{-11} s^{-1} . In the figure, the rectangular box is the scope of the cross-sections; thick arrows indicate areas of intense strain or mineralization; the vector arrows represent the Darcy flux and are used to indicate the direction of flow. (a) 0.5% volumetric strain, (b) 1.0% volumetric strain, (c) 0.5% shear strain, (d) 1.0% shear strain, and (e) corresponding geological section.

As extension progressed (1% of bulk shortening), the strains were more regularly distributed on relatively narrow and thick faults (Figure 10c,d). The distribution of the dilation deformation and fluid flow patterns in the model were consistent with the mineralization pattern (Figure 10b,d). The fault zone was a high-speed channel for conveying fluid from depths toward the surface; the maximum velocity was 5.7×10^{-5} m/yr, and the velocity decreased to 2.7×10^{-5} m/yr in locations with gentle dip.

According to the cross-sections (Figure 11), the expansion deformation zone appeared at the sites with dip angles of $35^{\circ}\sim 60^{\circ}$ in the footwall. The expansion deformation zones of section Nos. 82, 86, and 90 extended along with the NE-trending distribution from shallow to deep levels and were consistent with the distribution of the known orebodies. The fluid inflow was significant in zones with a steep fault dip angle.

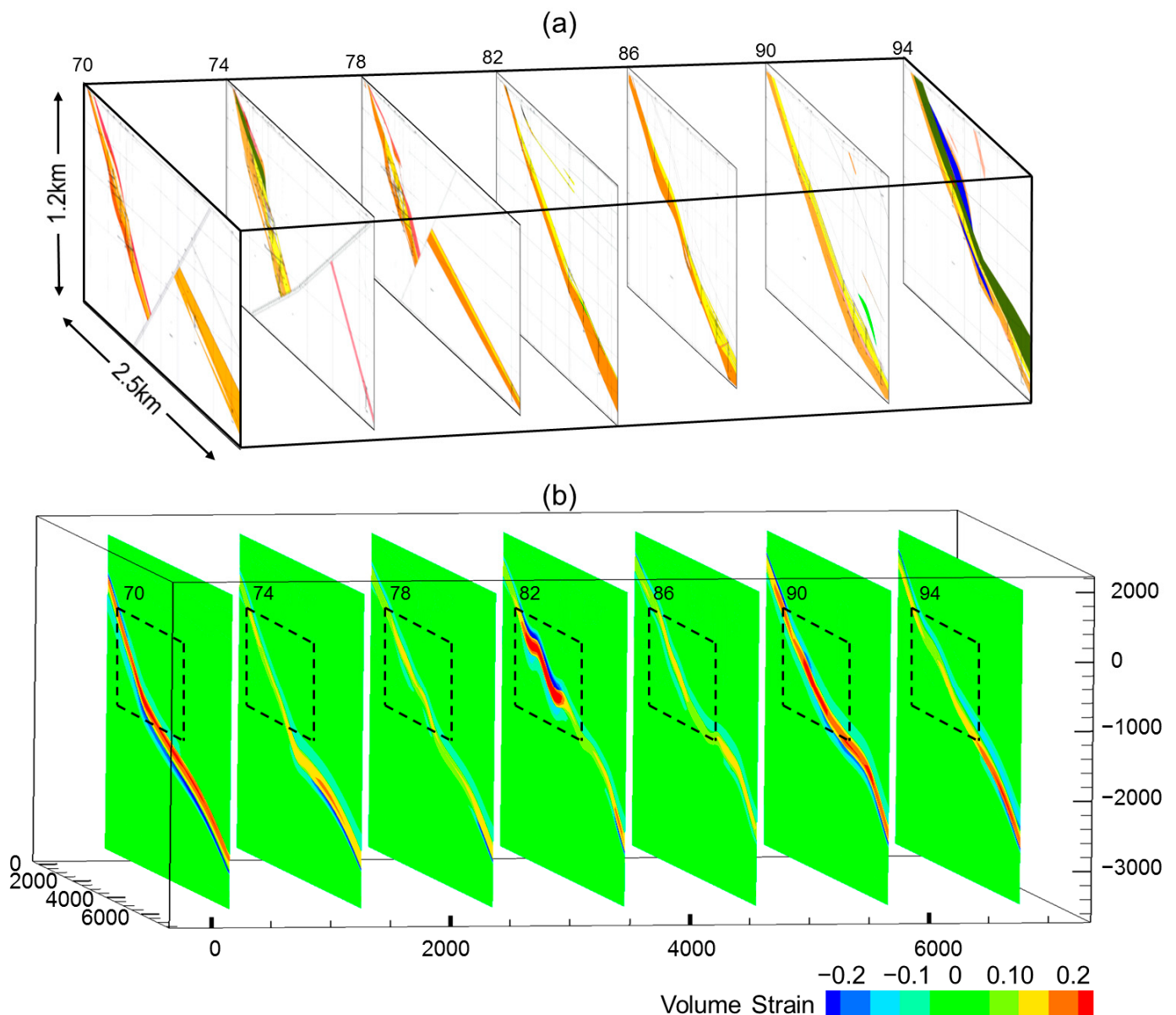


Figure 11. Cross-section of volume strain corresponding to exploration line with 1% bulk shortening. The rectangular box is the scope of the cross-sections. (a) Nos. 70~94 geological cross-sections; (b) cross-section of 1% bulk shortening in Model 4.

5. Discussion

5.1. Paleostress Regimes in the Dayingezhuang District

Rock deformation provides channels and facilitates ore-forming fluid flows to form various hydrothermal deposits [71–73]. In hydrothermal systems, the sites of shear strain and the related local dilation tend to increase the fluid flux, often resulting in favorable locations for mineral precipitation [18,24,27,29,74]. Based on the Mohr–Coulomb plasticity criterion, shear induces dilatancy, which increases the pore volume of the rock [18,75], and thus, we carried out several experiments to determine the deformation with tectonic stress in various directions (Figures 7–10) to better understand the relationship of fluid flow and shear strain, as well as related dilation. A series of numerical simulation experiments, described above, show that in our models, the obvious dilation zones occur in the fault zone (Figures 7–10) and vary according to the stress regime.

The fluid flow is related to compression or tension stress in the context of simple mechanical compression and tension, and compressive and extensional deformation leads to fluid flow upward or downward along the fault (Figures 7 and 8). The compression in Model 1 resulted in an overpressure state of the whole system [22,24,27,29]. The compression deformation occurred at the shallow interface between the hanging wall and the fault and extended to deeper levels. Compared to the Jiaodong Group, the low permeability granites were subject to a faster pressure increase (Figure 7), and therefore, the hydraulic head gradient was formed between the granite and Jiaodong Group. The difference between the pore pressure and hydrostatic pressure increased with the increase in strain. In contrast, the extension deformation in Model 2 occurred in the granite at depth on the fault, and the low permeability of the granite [76] experienced a faster pressure decrease than the Jiaodong Group (Figure 8). Fluids migrated downward from the high-permeability fault zone into the underpressure granite. With the increase in the strain rate, the underpressure became more and more significant. Thus, the fluid migration pattern and expansion deformation locations indicate that the stress conditions of Models 1 and 2 are inconsistent with the known distribution of mineralization for the Dayingezhuang gold deposit.

The tensile stress and strike-slip activity of the stratum seem to be crucial factors controlling the expansion deformation at specific parts of the fault in the Dayingezhuang deposit based on our results. In Model 3, the shear stress was distributed in the gentle dip sites of the fault, and the expansion deformation occurred in the geometric depression sites of the fault within the range of $-400\sim-1000$ m (Figure 9b), where fluid migrated towards the fault slowly. However, the expansion deformation caused by the compressed state is inconsistent with the known distribution of mineralization. In Model 4, the shear stress was distributed in the sites where the fault is steeply–gently transformed. The continuous expansion zone appears at the position of a $35^{\circ}\sim 60^{\circ}$ dip angle in the contact between the hanging wall and footwall (Figure 10b), which extends deep along the NE direction, where the fluid slowly migrates towards the footwall of the fault. The dilational zones in our modeling, in this case, are consistent with the distribution of known orebodies in the Dayingezhuang deposit. The location of the high-grade mineralization of orebody Nos. 1 and 2 in the Dayingezhuang deposit is closely related to dilation under the fault (Figure 10).

5.2. Metallogenic and Exploration Implications

The sites of tectonic deformation can effectively be used to locate the mineralization sites in the fault and indicate the directions and locations of fluid migration. The Zhaoping fault zone has developed along the NE direction, and the tensile and strike-slip activities have led to the increase in shear stress and rock deformation along the fault strike. Deformation increases the permeability of the rock and facilitates hydrothermal fluid flow [77,78] into the highly permeable fault zone [5]. In Model 4 (Figure 10), the variation of the fault dip angle shows a great influence on the strain distribution and fluid flow patterns. Most of the orebodies in the Dayingezhuang deposit and their controlling faults share similar specific dip angles [79]. The steep dip segments of the fault are open, with lower pressure at the top, resulting in the ore-bearing fluid rapidly migrating along the fault. On the contrary, the

gentle segments of the fault are relatively closed, with higher pressure at the top areas, so the ore-bearing fluids diffuse slowly in the lateral direction and are prone to deposition [4]. The sections of the model show (Figure 12) that ore-forming fluids tend to flow to the site of dilation deformation during the migration and pooling processes. Mineralization is highly focused on the footwall of the regional detachment fault zones (Figure 10b) and displays a staircase geometry [4,5] with inhomogeneous spatial distribution.

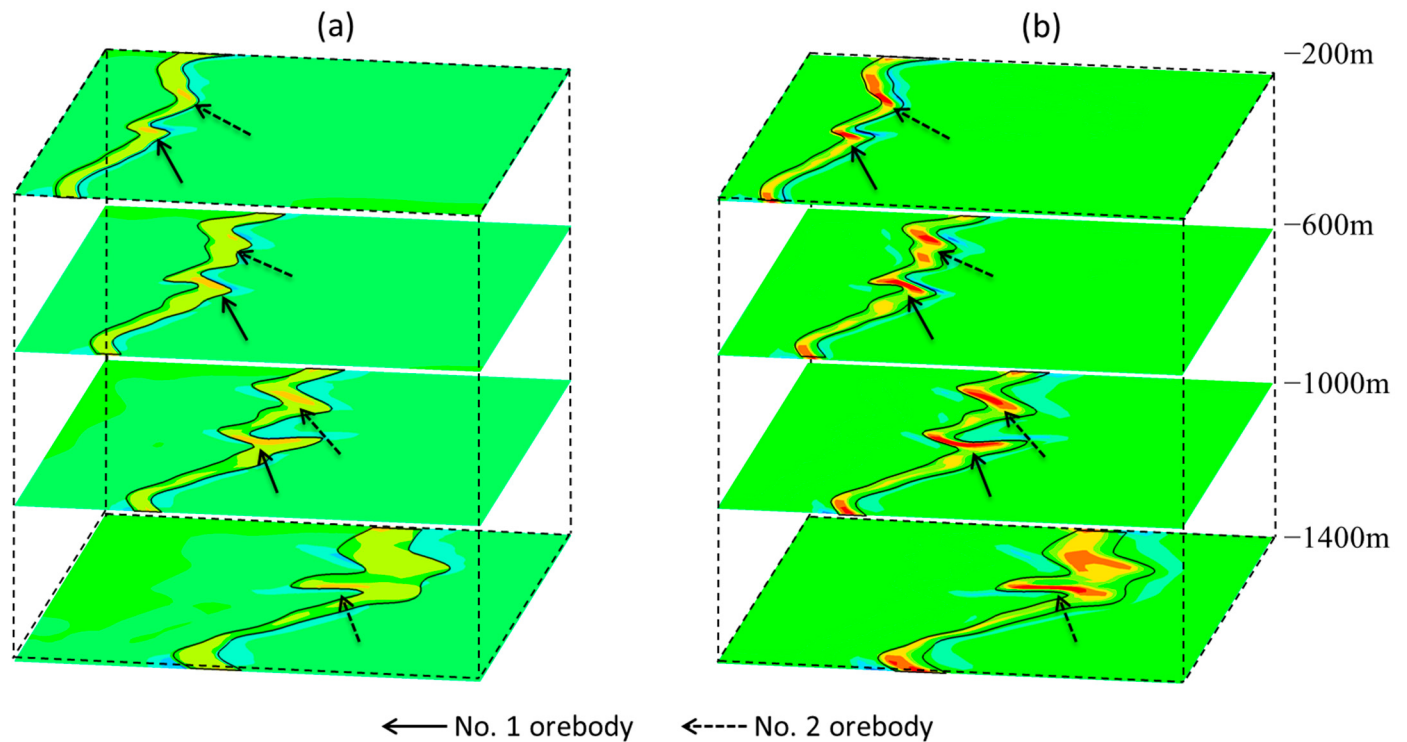


Figure 12. Spatial distribution of dilation deformation on horizontal planes. (a) after 0.5% and (b) 1% of bulk shortening.

Structural controls of fluid flow and infiltration are closely related to fault morphology. Tectonic stress is a crucial factor in the fluid migration mechanism, promoting the rapid fluid migration from deep to shallow levels [1,4]. Therefore, when the fluid rises to the dilation sites of the fault, which are the pooling centers for fluids [74,80], the flow of the fluid slows down significantly, and gold may be precipitated during this process (Figure 13). Structural controls in the Dayingezhuang deposit are represented by strain localization and the formation of shear zones and fractures, which eventually influence fluid activity and mineral precipitation [30]. The Zhaoping fault is the only known conduit for the deep auriferous fluid to migrate to the shallow crust [37]. The deformation caused by tectonic stress drives the migration of high-pressure fluid from deep to shallow levels, resulting in fluid accumulation and mineralization in the expansion area (Figure 12). The results of Model 4 show that the most favorable locations for mineralization have a slope range from 15° to 45° and dip angle changes of -10° (Figures 10 and 11). Inhomogeneous tensile tectonic stress leads to discontinuous expansion space, strong and weak variation in mineralization, variation in the orebody grade, and the tendency of gold deposits to pinch out and reappear, as well as to branch and recombine [81]. All of these features indicate the importance of dilation deformation and related fluid activity in the formation of the Dayingezhuang gold deposit.

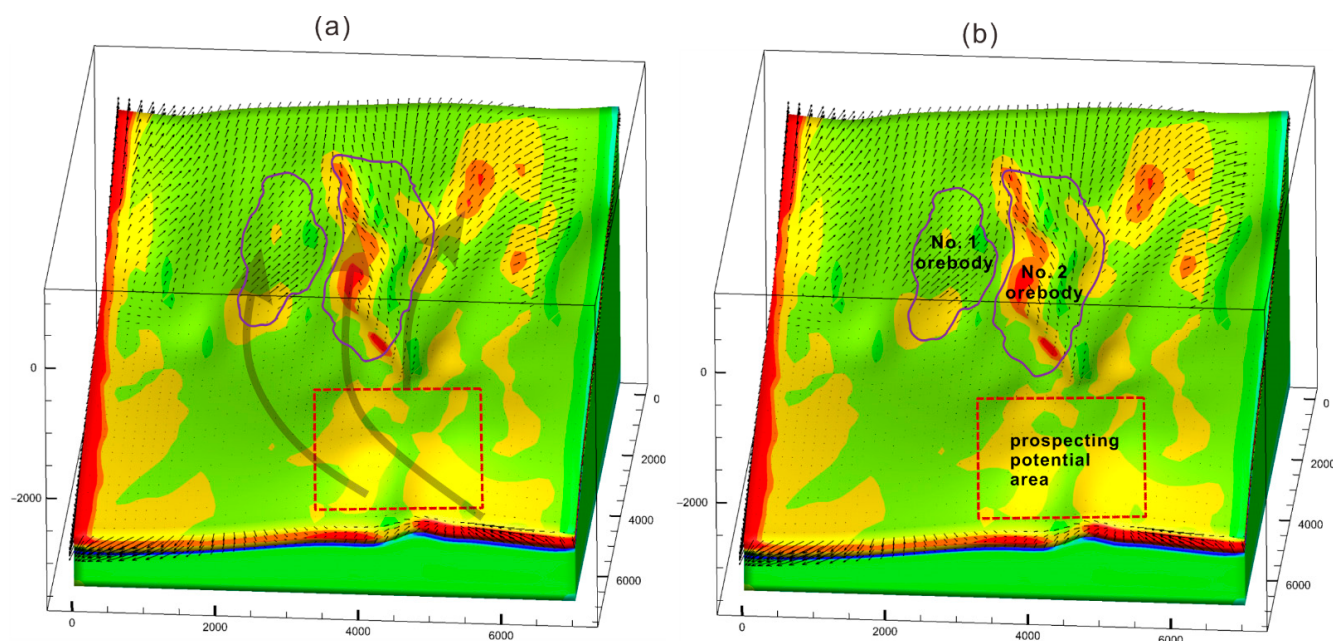


Figure 13. (a) Fluid migration model and (b) deep potential prospecting area at Dayingezhuang.

Our simulation results show the close correlation between the dilational zones and sites of known mineralization in the Dayingezhuang deposit and suggest that the dilational zones may be an effective tool for identifying exploration targets. The No. 2 orebody of the Dayingezhuang deposit extends to deeper levels, which may have contained pooling areas for ore-forming fluids and, thus, has good prospecting potential (Figure 13). The simulation results not only provide reasonable explanations for the formation of the Dayingezhuang deposit in northwest Jiaodong but also highlight the effective utility of numerical simulation for the exploration of tectonic-controlled hydrothermal gold deposits.

6. Conclusions

We present the coupled deformation–fluid flow model of the Dayingezhuang deposit, demonstrate how numerical modeling can be used to determine paleostress background, identify favorable structures for gold mineralization, provide further insight into the mineralizing processes, and highlight areas for future exploration. The numerical modeling results demonstrate that the paleostress orientation of the Zhaoping fault that hosts the Dayingezhuang deposit was NE–SW tensile stress (σ_1 NE–SW, σ_2 vertical, σ_3 NW–SE) with strike-slip deformation during the ore-forming stage. The expansion deformation at specific parts of the fault can effectively locate the mineralization sites and indicate the directions and locations of fluid migration. The direction of fault movement controls the scale and scope of fluid migration. Inhomogeneous extensional tectonic stress leads to discontinuous expansion space, and the NE dilation zone serves as a channel for the migration of gold-bearing fluids. Ore-forming fluids tend to flow to sites of dilation deformation during migration. There is the potential for fluid pooling at a NE depth of the No. 2 orebody, and we suggest this as a future prospecting area. The computational method used in this research is limited with respect to chemical reactions, large-scale deformation, and the phase change method. We suggest that future simulation experiments might improve the numerical simulation results by incorporating these components as well as large-scale deformation simulation experiments for the northwestern Jiaodong Peninsula, which may provide new constraints for the paleostress and help us better clarify the stress background.

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