The genesis of high ground temperature in the Long mountain road tunnel

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Abstract: Highway traffic increasingly extends to the mountainous area, requiring highway tunnels to be longer. Highway tunnel construction is risky and challenging, especially in the high ground temperature area of Western China. In this study, the Nige Tunnel of Yunnan Honghe Jian(ge) Yuan highway is the research object. By conducting numerous field temperature tests, geological surveys, water quality experiments, and other processes, the causes of high temperatures in the ground have been analyzed. The results show that the hot liquid or vapor from the earth’s crust deep area carries various chemical materials, passing through various channels (faults and fissures) to the superficial area and forms the geothermal of the tunnel. The thermal anomaly bodies in the deep crust move upward through faults Fn1 and Fn2. Some heat sources are exposed to the surface and form hot springs, and others are distributed through secondary channels after being transmitted to the shallow part of the crust. Among them, the entrance section of the Nige Tunnel is limestone, and the groundwater infiltrating the fracture channel is mixed in the conduction process, resulting in the overall low water temperature, and the rock wall temperature is lower than the water body temperature. The exit section of the Nige Tunnel is granite, the heat source is mainly conducted through structural fractures or rock mass, resulting in high rock temperature at the exit. By analyzing the causes of high ground temperature, this study provides a theoretical basis for developing the tunnel scheme.

1. Introduction

The rapid development of highway traffic has spread to farther and deeper mountain areas, and an increasing number of long mountain road tunnels have been built. Simultaneously, it is necessary to pass through complex geological units that are challenging to avoid and unfavorable geology, such as high ground temperature. The principal impacts of the tunnel passing through high ground temperatures areas are as follows: ① If the temperature exceeds the normal working range of workers, it affects the physical and mental health of workers and the working efficiency of machinery and equipment. It can easily lead to heatstroke, dehydration, and other safety hazards. ② The construction environment in the tunnel is damp, affecting the electrical safety of the tunnel. ③ The high...
temperature, humidity, and heat environment in the tunnel construction could affect the tunnel structure and related building materials and could even cause fundamental and permanent damage, affecting the normal operation of the tunnel.

Recently, numerous high geothermal tunnels have appeared in China, such as the Gaoligongshan Tunnel [1]. Because of the deep circulation of underground faults, the maximum water temperature reaches 50 °C. When the Sangzhuling Tunnel [2] of the Lalin Railroad passes through the active fault on the eastern edge of the Wakadachi, the rock and hot water temperatures are high, with the highest temperature reaching 89.9 °C. The entrance section of the Sangzhuling Tunnel [3] traverses the east side of the Woka graben. The magma condenses below the surface and forms igneous rock, and many hot springs are developed, with the highest temperature reaching 76 °C. The maximum hot water temperature of the diversion tunnel of Sichuan Xiangcheng Niangong Hydropower Station [4] is 78 °C. Wang Chujiao [5] studied the Tibet-entry line and concluded that high ground temperature only exists when special heat sources and groundwater convection and heat conduction coexist. Zhao Guobin [6] researched the diversion power tunnel in the Kara-Kunlun mountain area and concluded that high heat flow background value, the thermal conductivity of rock mass, and dense faults and fissures are the necessary conditions for creating high ground temperature. Yao Zhiyong [7] found that the heat sources of the China-Nigeria Railroad are the partial melting layer of granite at the bottom of the crust and magma sacs in the shallow part of the upper crust, dominated by medium and ultra-high-temperature zones. The geothermal distribution is in strips. When selecting the route, large-scale high-temperature areas must be avoided. If it is necessary to pass through, the sections in the geothermal marginal zone shall be selected to pass through bridges and subgrade projects. Therefore, studying the geological and hydrological characteristics of the Nige Tunnel and understanding the essential reasons for the formation of a high geothermal environment could provide good guidance for tunnel and operation construction. Simultaneously, it provides a theoretical basis for developing tunnel high ground temperature response schemes.

2. Overview of the Project

2.1. Overview of the tunnel

The Nige Tunnel is in the middle of the mountain near Kele Village, Jiasha Township, Gejiu City, and Honghe Prefecture. It has a split design and a two-way four-lane road 3,366 m long on the left and 3,351 m on the right. The maximum buried depth of the tunnel is 639 m, which is a deeply buried super long tunnel. The tunnel entrance is connected to the No. 2 bridge at Yashadi, and the exit is connected to the clear line base. The height difference between the entrance and exit is 67.9 m. The excavation line in the tunnel is 12.75 m high and 8 m wide.

The location of the tunnel has a south subtropical monsoon climate affected by seasonal and topographical changes. The results of the temperature measurements at the entrance and exit of the Nige Tunnel show that the temperature near the palm surface (within 30 m) of the exit section is 40 °C–45 °C. The temperature near the palm surface (within 30 m) of the entrance section is 25 °C–40.9 °C. Both are high geothermal tunnels.

During the tunnel construction, high-temperature surrounding rocks and groundwater cause air temperature in the tunnel to exceed 28 °C, affecting the safety of the construction and health of personnel. This is a high-temperature tunnel [8].
2.2. Main characteristics of tunnel ground temperature

(1) The entrance of the Nige Tunnel is predominantly characterized by high water temperature. Currently, the water temperature is 36 °C–53.8 °C, the water inflow is 0.5 L–6 L/s, and the air temperature is 30 °C–40.9 °C. The water temperature > rock temperature > air temperature. The air temperature is predominantly affected by water temperature and volume. Combined with ground temperature test results and analysis of geological conditions, the ground temperature of the imported limestone section is 35 °C–60 °C, and the temperature and water inflow of the water body near the contact zone could increase.

(2) The granite section at the exit of the Nige Tunnel is characterized by high rock temperature. Table 1 presents the current tunnel ground temperature test results.

Table 1. Tunnel ground temperature test results

| Palm surface temperature test | Advanced horizontal hole test | Second lining horizontal hole testing | Prediction of temperature in granite caves |
|------------------------------|-------------------------------|-------------------------------------|------------------------------------------|
| Rock wall temperature        | Air temperature               | 3–4 m                               | 20 m                                    |
| 44 °C–52 °C                  | 36 °C–45 °C                   | 52.4 °C–57.6 °C                     | 56 °C–60.5 °C                           |
| 44 °C–52 °C                  | 36 °C–45 °C                   | 32 °C–36 °C                         | 46.8 °C                                 |
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| 44 °C–52 °C                  | 36 °C–45 °C                   | 32 °C–36 °C                         | 46.8 °C                                 |
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| 44 °C–52 °C                  | 36 °C–45 °C                   | 32 °C–36 °C                         | 46.8 °C                                 |
| 44 °C–52 °C                  | 36 °C–45 °C                   | 32 °C–36 °C                         | 46.8 °C                                 |

3. Analysis of the Causes of Tunnel High Ground Temperature

3.1. Heat source investigation and cause analysis

3.1.1. Heat source investigation

(1) Investigation of possible heat sources

Three principal sources of hot spring heat source exist[9]. ① Hot spots form in the local upper-dome of the mantle asthenosphere, providing a powerful heat source for the overlying hydrothermal system (deep crustal thermal anomaly). ② Heat dissipation during the cooling process of the underground magma chamber, the high-temperature intrusive body in the crust, or surface ejection body in the underground provides a heat source for the near-surface water heating system (residual heat of magmatic rocks). ③ The frictional heat generated by the fracturing activity in the earth’s crust provides the heat source for the hydrothermal system and is often associated with the first and second heat sources.

(2) According to the investigation of residual heat sources of magmatic rocks, it is unlikely that the heat sources of high geothermal temperature in tunnels come from the active sources of magmatic rocks.

(3) Investigation and Analysis of Heat Sources of Thermal Anomalies in Deep Crust
To identify the heat sources causing the tunnel’s high temperature, a series of hot springs distributed around the Jian(g)e)yuan Expressway line were investigated, three hot springs near the Nige Tunnel were investigated and analyzed, namely the Nige Hot Spring (Q3), Laohutan Hot Spring (Q4), and Yashadi hot spring (Q1). Figure 1 shows the distribution map of each hot spring.

![Figure 1. Sketch map of hot spring distribution around the Nige Tunnel](image)

The three hot springs are distributed around the entrance and exit of the Nige Tunnel. The high ground temperature of the tunnel is consistent with the hot spring heat source, which is a geothermal heat source discharge outlet, connecting the underground heat source. Starting from the hot springs to identify the source is critical in tracing the heat source of the tunnel’s high ground temperature.

3.1.2. Analysis of water chemistry characteristics

Rock and water samples were taken at the entrance of the Nige Tunnel, the exit of the Feigu Tunnel, the Jiasha River, the Longcha River, and the surrounding hot springs for indoor testing. Table 2 shows the water quality analysis experiment.

**Table 2** Statistical table of water quality analysis experiment results

| Report  | Sampling position | $P(BZ±)$ mg/L |
|---------|------------------|---------------|
|         |                  | cation        | anion         | free | aggregate |
|         |                  | $K^+ + Na^+$  | $Ca^{2+}$     | $Mg^{2+}$ | $Cl^-$  | $SO_4^{2-}$ | $HCO_3^-$ | $CO_3^{2-}$ | $OH^-$ | $CO_2$ | $CO_2$ |
| 1       | Feigu Tunnel     | 26.91         | 11.02         | 3.03  | 7.92    | 42.81       | 29.31      | 11.53         | 0      | 0      | 0      |
| 2       | Nige Tunnel      | 20.7          | 69.11         | 7.89  | 5.45    | 43.53       | 240.32     | 0            | 0      | 8.88   | 0      |
| 3       | Water sample     | 22.08         | 51.08         | 4.25  | 6.44    | 44.97       | 167.06     | 0            | 0      | 3.33   | —      |
The analysis of the water quality experimental data shows that the water samples at the entrance of the Nige Tunnel, the exit of the Feigu Tunnel, and the three groups of hot spring water are HCO$_3^-$, Na·Ca type, belonging to weak alkali to alkaline water. Both have H$_2$S gas and the content of SO$_4^{2-}$ ions are similar, indicating that the hot spring and tunnel water have homology. The negative hardness (sodium and potassium hardness) and content of K$^+$ + Na$^+$ of the three groups of hot spring water were

| Report | Sampling position | mg/L (以CaCO$_3$计) | PH | Dissolved solids(mg/L) |
|--------|-------------------|---------------------|----|-----------------------|
|        |                   | hardness            |     |                       |
|        |                   | total               | temp | negati | perma | Bicarb | Carbonate | total |          |
| 1      | Feigu Tunnel      | 40.02               | 40.02 | 3.25  | 0      | 41.03  | 5.77    | 43.27  | 9.25  | 135     |
| 2      | Nige Tunnel       | 205.1               | 197.1 | 0      | 8      | 240.32 | 0       | 197.1  | 7.71  | 318     |
| 3      | Water sample of Jiasha River | 145.07 | 137.01 | 0 | 8.06 | 167.06 | 0 | 137.01 | 7.95 | 237     |
| 4      | Longcha River water sample | 95.05 | 95.05 | 1.1 | 0 | 117.23 | 0 | 96.15 | 8.05 | 300     |
| 5      | Guge on the left side of the Nige Tunnel | 182.59 | 170.66 | 0 | 11.93 | 199.29 | 4.32 | 170.66 | 8.54 | 243     |
| 6      | Nige hot spring water sample | 12.51 | 12.5 | 112.48 | 0 | 126.02 | 12.97 | 124.99 | 9.45 | 344     |
| 7      | Tiger Beach Hot Spring Water Sample | 17.51 | 17.51 | 121.9 | 0 | 152.4 | 8.65 | 139.41 | 8.42 | 388     |
| 8      | Yashadi hot spring water sample | 7.5 | 7.5 | 116.29 | 0 | 126.02 | 12.25 | 123.79 | 8.28 | 373     |
significantly higher than those at the entrance of the Nige Tunnel and exit of the Feigu Tunnel, whereas the content of Ca$^{2+}$ and Mg$^{2+}$ ions were significantly lower. The reasons are discussed below. A large number of sodium-bearing minerals are distributed in the acid magmatic rocks in the deep crust, carried to the surface with hot gas and hydrothermal fluid, forming ascending hot springs. The underground hydrothermal solution (or hot gas) containing sodium minerals passes through the shallow sedimentary rocks and mixes with the shallow water during ascending and diffusing. The formations at the entrance of the Nige Tunnel and exit of the Feigu Tunnel are composed of sedimentary carbonate rocks, and the main components are CaCO$_2$ and MaCO$_2$. The dissolution of CaCO$_2$ and MaCO$_2$ increases the Ca$^{2+}$ and Mg$^{2+}$ contents in the water at the entrance of the Nige Tunnel and exit of the Feigu Tunnel.

3.1.3. Radioactivity of granite analysis

Granite samples were taken from the palm surface of LZ5K47 + 053 at the exit of the Nige Tunnel for radioactivity testing. Table 3 shows the experimental test results, and Table 4 shows the analysis standards.

| Category         | Specific activity of $^{226}$Ra (Bq/kg) | Specific activity of $^{232}$Th (Bq/kg) | Specific activity of $^{40}$K (Bq/kg) | $I_{Ra}$ (inside) | $I_{r}$ (outside) | Testing institute                                           |
|------------------|---------------------------------------|---------------------------------------|-------------------------------------|------------------|-------------------|------------------------------------------------------------|
| Inside LZ5K47 + 053 | 253.2                                 | 372.6                                 | 1392.9                              | 1.3              | 2.4               | Kunming Mineral Inspection and Testing Center, Ministry of Land and Resources |

Table 4. Limit table of internal and external exposure index of building materials

| category | Building material | Decoration Materials |
|----------|-------------------|----------------------|
|          |                   | A                    | B                    | C                    |
| $I_{Ra}$ | ≤1.0              | ≤1.0                 | ≤1.3                 | —                    |
| $I_{r}$  | ≤1.0              | ≤1.3                 | ≤1.9                 | ≤2.8                 |

The radioactive levels of decoration materials specified in the Limit of radionuclides for building materials (GB6566-2010) shows that the radioactive test value levels of IRA and Ir of granite decoration materials are classified as class C. The radioactive report shows that the granite in the tunnel has little impact on the body of operators during construction.

3.1.4. Cause analysis of heat source

(1) Figure 2 shows the distribution of geothermal flow in Yunnan$^{[10]}$. The figure shows that the Niger Tunnel is in the southwest part of the VIII Youjiang block uplift. The measured or estimated values of
13 heat flows in the area are 45–68.8 MW/m², with an average of 56.1 MW/m², which is lower than the global average heat flow (61.6 MW/m²). Therefore, the area belongs to the low heat flow area.

Figure 2. Yunnan Earth Heat Flow Distribution etch map of hot spring distribution around the Nige Tunnel

I Tengchu plate, II Baoshan plate, III Lanpingsimao depression, IV Yanyuan-Lijiang epicontinental depression, V Dianzhong depression, VI Kangdiangu uplift, VII Diandong depression-folding zone, VII Youjiang uplift plate, F1 Nuijiang fault zone, F2 Beilancangjiang-Shuangjiang fault zone, F3 Red River fault zone, F4 Jianchuan-Lijiang fault zone, F5 Chenghai fault zone, F6 Yuanmou-lvzhijiang fault zone, F7 Xiaojiang fault zone, F8 Mile fault zone

(2) From the distribution law of geothermal (hot spring) in Yunnan Province, the Nige Tunnel area belongs to medium and low-temperature hot water distribution areas. Hot springs can be divided into three types, namely high-temperature hot springs above 75 °C, medium-temperature hot springs between 40 °C and 75 °C, low-temperature hot springs below 40 °C, and cold springs below 25 °C. The actual on-site water temperature measurement shows that the Nige and Laohutan hot springs are
medium-temperature, and the Yashadi hot spring is high temperature. In the area between the Ailao Mountain fault and the Shizong-Mile fault, the platform has a double-layered structure of the basement and caprock. The depression basin formed in the Cenozoic Period formed a huge thickness of Tertiary deposition, which made the foundation for the formation of a basin-type geothermal field.

(3) The investigation of the three hot springs shows that there is a small amount of egg odor and yellow sulfide (Figures 3–5) in the outlet of the hot spring. The composition of the substance is H\textsubscript{2}S, and the content of H\textsubscript{2}S depends on magma composition and gas migration conditions. Therefore, the content of H\textsubscript{2}S in magma is extremely unstable, and only under specific migration and storage conditions can it accumulate in the coal seam.

Research results \cite{11} show that many hot springs containing H\textsubscript{2}S gas and complex chemical components belong to the deep-circulated confined water-containing property. Below the continental sediment is a base composed of granite formed by the condensation of molten material \cite{12}; In igneous rock, granite represents a low melting point material and contains a large amount of crystalline quartz of free silica, which is separated from relatively basic rocks (such as basalt) deep in the earth. The compounds with low melting points (such as silica) remain in gaseous form or liquid in the late stage of igneous rock activity and can be sealed. In unusual cases (such as fracture), hot water or steam will be released, and various other substances will be removed by steam distillation. In this process, many rare elements could be enriched, elemental sulfur could be deposited, or gaseous sulfur, such as H\textsubscript{2}S and SO\textsubscript{2} could appear.

Given the above analysis, the heat source of hot spring water around the Nige Tunnel comes from the deep region of the earth’s crust. It carries various chemical components (predominantly characterized
by accumulating sulfur-containing substances) in the form of hydrothermal solution or steam, and transmits to the shallow section through various channels (faults and fissures), forming tunnel geothermal or hot springs. This type of heat source in the deep crust is called a deep crust thermal anomaly body.

3.2. Hydrogeological analysis

3.2.1. Stratigraphic lithology

Regional geological data and field geological investigation combined with drilling and geophysical results show that the strata of the Feigu and Nige Tunnels from top to bottom are the Quaternary residual slope accumulation layer ($Q_4^{el+dl}$), Yanshanian granite ($\gamma_5^{3(a)}$) (semi-impermeable rock mass), limestone (permeable rock mass) of Upper Triassic Gejiu Formation ($T_2^g$) of the Triassic system, and lime (permeable rock mass) of Triassic middle franc formation ($T_2f$).

3.2.2. Geological structure

The regional geological data show that the tectonic structure of the bridge site is at the southeast edge of the Sichuan-Yunnan Anticline (Kang-Dian axis) of the Yangtze quasi-platform. The southern Red River fault zone controls the intersection of the system. Since the Paleozoic, it has experienced many structural changes and complex geological structures.

(1) Fault

After the investigation, we found that a fault $F_{n1}$ developed along the Longcha River, a primary fault $f_{a1}$ developed along the gullies on the left side of the Nige Tunnel, and a fault $F_{n2}$ developed along the Jasha River.

(2) Limestone and granite contact zone

The geological mapping along the geological line (Figure 6) shows an M-shaped contact zone on the surface of the Nige Tunnel. There could be an unconformity contact zone between limestone and granite in the underground tunnel body. In the process of rising and condensing, the volume of magma shrinks rapidly, and a large fissure type groundwater passage easily forms near the contact zone.
3.2.3. Karst hydrogeology

(1) Surface water

A gully is developed in the tunnel area, and the overburden is widespread. After the rapid conversion of atmospheric precipitation into surface runoff, part of the precipitation converges into gullies and continues to discharge into the downstream gentle zone. The other part of atmospheric precipitation continues to enter the underground along the bedrock fissures after infiltrating through the surface soil mass. The Feigu and Nige Tunnels have developed the Jasha and Longcha Rivers (Figure 7). The surrounding springs are the Yashadi (Q1), Nige (Q3), and Laohutan hot springs (Q4). Table 5 shows the statistics of the properties of each hot spring.
Figure 7. Distribution of water systems in the Nige and Feigu Tunnels

Table 5. Spring water statistics

| Spring point number | Exposed location | Exposed stratum | Exposed height (m) | Flux (L/s) | Temperature (℃) | Feature description |
|---------------------|------------------|----------------|-------------------|------------|-----------------|---------------------|
| Yashadi hot spring (Q₁) | The left bank of the Jasha River (downstream) | T₂g Limestone | 940 | 2.20 | 87.9 | It is an ascending spring with stable flow and temperature. It does not dry up during dry seasons and the water flow is clear. It smells of rotten eggs, and there are yellow aggregates at the outlet. |
| Nigel Hot Springs (Q₃) | Longcha River left bank (upstream) | γ₅⁵(gr) granite | 908 | 1.06 | 67.9 | It is an ascending spring with a stable flow and temperature. It does not dry up during dry seasons. The water flow is clear and smells of rotten eggs. |
It is an ascending spring with a stable flow and temperature. It does not dry up during dry seasons and the water flow is clear. It smells of rotten eggs, and there are yellow aggregates at the outlet.

(2) Groundwater

Lithology, landform, and other factors control the groundwater in the tunnel site, and the recharge of groundwater is closely related to rainfall. The groundwater storage conditions in the limestone distribution area are poor, and is quickly discharged after atmospheric precipitation replenishment. The granite distribution area is predominantly aerated zone water, upper layer stagnation water, and there is no fixed groundwater level elevation. When excavating the limestone tunnel, most of the groundwater is dripping water and linear effluent. During the tunnel excavation in the limestone section, most of the groundwater is dripped and linear. In flooding season, water and mud gushing could occur along the structural contact zone, and groundwater affects tunnel excavation.

3.3. Investigation and cause analysis of deep circulation heat conduction channel

The heat conduction channels of the deep circulation of thermal anomaly bodies in the deep crust are faults and fissures. According to the length, scale, and influence range of the channel, it can be divided into the main and secondary channels. The main channel is deep with large faults. The secondary channels are secondary faults, structural fractures, dissolution fractures, karst pipelines, and contact zones.

The surrounding terrain of the Nige Tunnel is deep with developed valleys. Engineering geological survey and analysis show that geothermal channels are developed near the tunnel (Figure 8): fault F_{n1}, fault F_{n2}, fault f_{n1}, structural dominant fissure L_{G}, dissolution fissure and karst pipeline L_{R}, and limestone and granite contact zone L_{J}.
Figure 8. The analysis diagram of the geothermal conduction channel of the Nige Tunnel and the Feigu Tunnel

(1) Fault F_{n1} geothermal conduction channel

Several hot springs, such as the Longcha, Nige, and Laohutan hot springs, are developed along the Longcha River Valley from top to bottom. They are sulfur-containing hot springs formed by the deep circulation of underground thermal anomaly bodies. It is speculated that the connection between the river valley and hot springs develop a fault (F_{n1}), which is also a conduction channel for the hot spring heat source along the Longcha River.

(2) Fault F_{n2} geothermal conduction channel

The regional geological data show that the fault (F_{n2}) developed along the Jiasha River Valley at the entrance of the Nige Tunnel is a conduction channel for the heat source of the Yashadi hot spring.

(3) Secondary fault f_{n1} geothermal conduction channel

Figure 8 shows that a gully developed on the left side of the tunnel entrance, and the gullies at the exit section are deep cut. Combined with terrain analysis, the fault f_{n1} is a secondary fault of fault F_{n1}.

(4) Geothermal conduction channel L_G of structural dominant fracture
The granite fissures in the outlet section were measured, obtaining a clear set of dominant fracture surfaces. The appearance of the dominant fracture surfaces was \(133° < 65°\). This group of dominant fracture surfaces formed a secondary channel for geothermal conduction in the outlet section.

(5) Geothermal conduction channel \(L_R\) of dissolution cracks and karst pipeline

At the entrance of the Nige Tunnel, soluble rock strata developed, the lithology is limestone, and the rock mass is medium to thick. From the analysis of the dissolution principle of soluble rock, the inlet section is in the contact zone of limestone and granite, magma rises and condenses, and the volume shrinks, forming a large fissure groundwater passage near the contact zone. Under the action of groundwater, the original micro-cracks of limestone are continuously eroded and expanded, forming large karst fissures or pipelines, forming a secondary channel of geothermal conduction. From the analysis of the water inflow from the entrance of the tunnel (Figure 9), warm water gushes from the erosion fissure zone, verifying that the erosion fissure and karst pipeline in the inlet section are secondary channels for geothermal conduction.

![Figure 9. Water inflow along the erosion fissure zone at the tunnel entrance](image)

(6) Geothermal conduction channel \(L_J\) in the contact zone between limestone and granite

As mentioned above, the magma volume shrinks sharply during the ascent and condensation process, and large crack-shaped groundwater passages are likely to form near the contact zone. Cracks in the contact zone are also critical channels for geothermal conduction.

3.4. Analysis of hydraulic and thermal connection

Using the investigation and analysis of the geothermal heat source and conduction channel of the Nige Tunnel, a geological sketch of the Nige Tunnel region is obtained (Figure 10). The analysis in the above chapters reveals that the heat source in the Nige Tunnel is the high-temperature anomaly existing in the deep crust. The geothermal conduction channels include fault \(F_{n1}\), fault \(F_{n2}\), fault \(f_{n1}\),
structural dominant fracture $L_G$, dissolution fracture and karst pipeline $L_R$, and limestone granite contact zone $L_J$.

![Figure 10](image-url)

**Figure 10.** Geological sketch map of the Nige Tunnel and Feigu Tunnel.

T1g and $γ_{5(a)}$: Granite; T2g and T2g$^2$: Limestone

Figures 11 and 12 show the analysis diagrams of the hydraulic and thermal connections of the Nige Tunnel. The causes of the high ground temperature of the Nige Tunnel were analyzed. The thermal anomaly existing in the deep crust is conducted upward through fault $F_{a1}$ and $F_{a2}$. A part of the heat source moves to the surface and forms hot springs along the Longcha and Jiasha Rivers. The other part of the heat source is conducted toward the shallow surface of the earth’s crust and dispersedly conducted through secondary faults $f_{a1}$, contact zone fractures, structural fissures, erosion fissures, and secondary channels such as karst pipes or rock masses. The inlet section is limestone, and there is a contact zone between limestone and granite. The heat source transmitted to the shallow surface of the earth’s crust is predominantly conducted through secondary small faults, dissolved fissures, karst pipes, or contact zones.
During the conduction process, groundwater (cold water) infiltrating along the surface of the fissure channel was mixed, resulting in overall higher water temperature and lower rock wall temperature than the water body temperature. The outlet section is constructed of medium-weathered granite, a relatively water-resistant layer, and there is little rainfall infiltration. The heat source transmitted to the shallow surface of the crust is predominantly conducted through structural fissures or rock masses, resulting in high rock temperature at the outlet.

**Figure 11.** Sketch of the analysis of the cause of the formation of high ground temperature in the Nige Tunnel

(F_{n1} Geothermal conduction channel in Longcha River fault, F_{n2} Geothermal conduction channel in the fault of Jiasha River, f_{n1} Geothermal conduction channel on the left side of the inlet and gully fault at the outlet, L_{G} Exported granite tectonic fissure geothermal conduction channel, L_{R} Inlet dissolution cracks and karst pipeline geothermal conduction channel, L_{J} Geothermal conduction channel in the contact zone between limestone and granite)

**Figure 12.** The perspective views of the cause analysis of the formation of high ground temperature in the Nige Tunnel
4. Conclusion

Based on the evaluation of the characteristics of high ground temperature and investigation and analysis of the causes, this study draws the following conclusions:

(1) The above analysis reveals that the genesis of high ground temperature in the Nige Tunnel does not influence the heat generation of limestone, the waste heat of magmatic rock, and the radioactivity of granite. The cause of the formation is related to the formation of hot springs nearby, deep abnormal bodies, and geothermal conduction channels.

(2) The water quality experiments of the Nige and Feigu Tunnels and three hot springs were conducted, detecting the concentration of anions and cations, pH value, total hardness, alkalinity, and dissolved solids concentration in the water quality. From the experiment, the gases in the water contain H₂S, and the content of SO₄²⁻ ions is the same, which has homology and belongs to the deep circulation pressure-bearing property.

(3) The entrance section of the Nige Tunnel is limestone, and there is a contact zone between the limestone and granite, which is predominantly conducted through secondary small faults, dissolution fractures, karst pipelines, or contact zones. During the conduction process, groundwater (cold water) infiltrating along the fracture channel surface is mixed, resulting in overall high water temperature and high water temperature phenomenon. The exit section of the Nige Tunnel is moderately weathered granite, which is a relatively isolated water layer. The heat source is predominantly conducted through structural fractures or rock mass, resulting in high rock temperature at the outlet.

This study focused on the high ground temperature Nige Tunnel in Yunnan as a research object, evaluated the characteristics of high ground temperature, and investigated the causes of high ground temperature. It enriches the research of geothermal heat and has theoretical guiding significance for constructing the high ground temperature tunnel.

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