Research on the geological route selection of Sichuan-Tibet Railway passing through Eastern Himalayan syntaxis Areas

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Abstract. The eastern Himalayan syntaxis (EHS) area is characterized by complex topography due to the strong collision between the Indian and Eurasian Plates, developing deep fractures, active faults, and prominent high in-situ stresses. The designed Sichuan-Tibet railway passes through this area and connects Bome and Nyingchi on the east and west sides of the syntaxis. We encountered the following dilemma on railway route selection due to the large investment scale and the linear distribution of the railway: 1) the investment might skyrocket if the route runs outside the arc-shaped structure of the Namcha Barwa syntaxis in the Northwestern part of the EHS (detour syntaxis scheme); 2) the dynamic geological risk may increase if the route directly runs through the arc-shaped structure and Yarlung Zangbo Suture zone (crossing syntaxis scheme). Combined with a detailed field investigation, we comprehensively analyzed the regional deep structure, Holocene active faults and earthquakes, and regional in-situ stress and crustal deformation. The crustal stability in the Namcha Barwa syntaxis is extremely poor, having an uncontrollable risk. Concurrently, under topographic control, the tunnel’s bury depth of the crossing syntaxis route scheme is extremely deep, and the risk of rockburst, large deformation of soft rock, and water inrush is extremely high, severely affecting the construction period and potentially causing a significant increase in investment due to construction period delay. Therefore, the Sichuan-Tibet railway project is recommended to
1. Introduction

Tibet is a vast region with only about 3 million people. However, most of the population is concentrated in southeastern regions with relatively favorable natural conditions. Their major cities include Changdu City, Bome County, Nyingchi City, and Shannan City. It is also the most economically, socially, and culturally developed area in Tibet [1], as well as a key area for transportation construction in recent years, forming a transportation corridor construction area composed of railways, highways, and expressways. The Sichuan-Tibet railway, which is now under construction, is the most significant strategic high-speed transport channel [2-3].

The Sichuan-Tibet railway passes through large-scale plate junctions such as the Longmenshan fault zone, Jinshajiang junction zone, Lancangjiang junction zone, Nujiang junction zone, and Yarlung Zangbo Suture zone in the southeast of Tibet Plateau [1, 4-5] (Fig. 1a). With a total length of more than 500 km, the Yarlung Zangbo Suture zone is the longest crossing/parallel section of the planned route, stretching from Bome to Gongga County. The engineering geological condition of the Bome-Nyingchi section is the most complicated due to the arc structure of the eastern Himalayan syntaxis (EHS) [2-3]. The EHS is the easternmost margin of the compression collision between India and Eurasia. The region has undergone several episodes of severe tectonic deformation since the Cenozoic, eventually forming the current tectonic framework [6-7].

Fig. 1 Main in-situ stress trace map of East Asia (a, according to Xie et al., 2015 [8]), tectonic location map at the Bome-Nyingchi section of the Sichuan-Tibet Railway (b, according to Ding et al., 2001 [7]),
active faults in the EHS (according to Xie, 2018)⁹, historical earthquakes (according to Gu, 1983)¹⁰ and China’s seismic network, http://www.ceic.ac.cn/dataout), in-situ stress (according to the database of crustal stress environment in Chinese mainland) http://www.eq-netlab.com) and design railway route diagram (c).

The EHS comprises three secondary syntaxis formed in different stages. The Namcha Barwa syntaxis (NBS) at the northwestern end was formed at 65–42 million years ago (Ma), which is located between Bome county and Nyingchi city; the Siang and Assam syntaxis at the southeastern region, which was formed at 23–13 Ma and 13–3 Ma, respectively⁷. The deep structure in this area is active¹¹, with development active faults (Fig. 1b) and frequent earthquakes⁹, ¹³-¹⁴, remarkable crustal uplift and deformation¹⁵-¹⁷, high in-situ stress¹⁸-²⁰, and extremely broken rocks in the fault zones²¹, resulting in the current crustal instability.

Therefore, a detailed analysis of the crustal stability of the area from NBS to Gangdise magmatic arc is necessary, as well as the identification of a relatively suitable safety corridor for railway and other linear projects, to ensure the safety and feasibility of engineering survey, design, construction, and operation. In the geological route selection of the Bome-Nyingchi section of Sichuan-Tibet railway, two major strike schemes are considered: one is to bypass the NBS by passing through Bome to Lulang and then to Linzhi (detour syntaxis scheme); the other is the scheme that Bome reaches Lulang through NBS and connects Nyingchi (crossing syntaxis scheme). This study evaluates the characteristics of crustal stability in and around the EHS by analyzing regional crustal structure characteristics, active faults and earthquake development, crustal in-situ stress, and crustal deformation, to provide the basis for railway geological route selection.

2. Geological setting

The Bome-Nyingchi section of the Sichuan-Tibet railway is located in the mountainous and gorge landform area of Southeast Tibet. The mountain trend is mainly E–W (where E = East; W = West), with majestic mountains and deep valleys. Most of the mountains are over 5000 m high, with Namcha Barwa peak being the highest at 7782 m, and the relative height difference between the valley bottom and mountains is mainly 2000–3000 m. In the area, a tributary water system is densely distributed; the landform of glaciers, glacial lakes, moraines, and freeze-thaw landform are obvious, and the hillside vegetation is developed. The plateau marine climate and continental climate zone overlap in this region. Further, the annual average temperature is 9.6°C, the maximum temperature is 30.9°C, and the minimum temperature is −11.9°C due to the Indian Ocean’s warm current. The rainfall decreases from May to September, accounting for about 90% of the whole year.

The Gangdise magmatic arc encompasses the areas north of Lulang-Layue and east of Layue. The strata are mainly granite (γ62) and middle-lower Proterozoic gneiss (Pt12-3a). Namcha Barwa’s metamorphic body mainly developed the Proterozoic Namcha Barwa group (Pt2.3b), which is a set of extremely thick medium and high-grade metamorphic rock series, mainly composed of gneiss, quartzite, migmatite, granite gneiss, and marble, with a thickness of more than 10000 m.

3. Structural characteristics of crust

The N–S (where N = North; S = South) trend resistivity profile across the Namcha Barwa region (from Lhasa terrane to Yarlung Zangbo Suture zone, and then to Namcha Barwa syntaxis) in the west of the structural junction¹² shows the characteristics of high and low resistance (AA’ profile, Fig. 2).
High-resistivity bodies are developed in the Gangdise magmatic arc shallow crust (≤10 km), reflecting granite’s electrical characteristics. Large-scale high-resistivity bodies exist in the Namcha Barwa structural junction area, with the maximum value being 1584 Ωm. When the buried depth reaches 15 km, the resistivity gradually decreases to 100 Ωm at a depth of 25 km. This reflects the electrical characteristics of the Namcha Barwa metamorphic body (Paixiang Formation). The low resistivity body of the Yarlung Zangbo Suture zone extends to 25 km, reflecting the characteristics of the fault fracture zone. The low resistivity body in the south is about 30 km away from the low resistivity body in the north, which is distributed in the depth range of 5–30 km, reflecting the characteristics of the Duoxiongla formation fracture zone in a large bend near Paixiang. The northward subduction of the Namcha Barwa metamorphic body is reflected by the shape of the South and North low resistivity bodies.

Fig. 2 Structural model map of Namcha Barwa syntaxis. The location of the Yarlung Zangbo Suture zone is based on 1:250000 Regional Geological Map and Xu et al [22], and the duoxiongla migmatite fracture zone is based on Ding et al [7, 23]; The resistivity model of 2D electromagnetic inversion is referred in Jiang et al [12], and the receiver function CCP (common conversion point) stack profile is referred in Peng et al [11].

There are two types of disagreements over the actual location of the Yarlung Zangbo Suture zone, one in Lulang-Layue [22] and the other in Paixiang [7, 23], both of which are consistent with the location of
the low resistivity body in the north and south sides of the aforementioned AA' profile. Thus, the analysis shows that the aforementioned low resistivity bodies exhibit strong tectonic destruction, and their location has strong tectonic instability. Geomorphologically, the development of the Lulang and Yarlung Zangbo Rivers (Fig. 2) also confirms the deformation and destruction of surface rocks. The magnetotelluric near the EW trending section (BB' section, Fig. 2) also shows a low resistivity body 10–25 km below the Jiali fault[12], indicating its instability. Fig. 3 shows the rock characteristics of the corresponding area.

In addition, the NBS wave velocity disturbance image shows that a depth of 12 and 37 km in the NBS area presents high-speed disturbance. However, at a depth of 62 km, the velocity characteristics change abruptly, exhibiting an obvious low-speed disturbance, which may be related to deep fluid or melting [12]. From the CCP stack imaging map, obvious dislocation and elevation differences appear between the Moho surface of NBS, Himalayan terrane, and Gangdise magmatic arc. The crust thickness under NBS is rapidly thinning, about 5–10 km, with only about 55 km remaining, indicating significant uplift of this area [11] (Fig. 2). The active crust in the shallow layer corresponds to the location of the major fault zone, and the active position in the deep crust is located in the lower part of the NBS, based on the aforementioned geophysical data, which show strong activity in the deep part of the earth around the NBS.

4. Active faults and seismicity

4.1 Active faults

The Holocene active faults in the NBS and its vicinity include the Jiali fault, Milin fault, Xixingla fault, and Motuo fault [9] (Fig. 1c). The SEE-NWW trend Jiali fault comprises three segments, in which the Tongmai-Bome segment distributed along Palongzangbo river on the northeast side of the NBS is the middle segment [24]. The active time is about 2100 a [14], the strike-slip rate is 1.3–2.0 mm/a, and the extrusion rate is about 2.5 mm/a [25].

The seismogenic fault of the November 2017 Milin Ms 6.9 earthquake based on precise seismic array observations, is a nearly N–S strike reverse fault distributed in the east side of the NBS, and early aftershocks with larger magnitude after the 1950 Zayü Ms 8.6 earthquake also formed near the fault, the Holocene Active Xixingla fault [9, 25].

The Milin fault, which cuts across the Yarlung Zangbo River fault, is located in the west of the NBS. The fault runs from NE–SW to S–N and is made up of two parallel secondary faults. The fault’s northern segment is a Holocene active fault, which is characterized by thrust and left-lateral strike-slip
movement. Strong activity has occurred since the Holocene, with a vertical slip rate at about 0.17–0.27 mm/a\(^9\).

### 4.2 Historical earthquakes

More than 100 destructive historical earthquakes have been recorded in the East syntaxis area, including one earthquake with \(M_s \geq 8.0\) and more than 10 with \(M_s \geq 6.0–7.0\). These destructive earthquakes are distributed in two areas, one is near the Aparon River fault on the northeast region of the Siang and Assam syntaxis, such as the 1950 Motuo earthquake at \(M_s 8.6\) and several aftershocks with \(M_s 6.0\) or above\(^{20}\). The other area is located near the Xixingla and Julong Pangxin fault zones (Fig. 1c), including the 2017 Milin earthquake with \(M_s 6.9\) \(^{15}\). The earthquakes near the Jiali and Milin fault zones are relatively few, with relatively low magnitudes.

### 5. Regional in-situ stress, crustal uplift, and deformation

The Chinese mainland is located in the eastern part of the Eurasian plate. It is constrained by the Pacific, Indian Ocean, Siberian, and Philippines plates, resulting in a complex regional compressive in-situ stress field. Plate movement controls the direction of regional internal stress, and the major stress trace is around NE–SW \(^8\) (Fig. 1a). However, the eastern tectonic junction is at the eastward end of the India plate toward the Eurasian plate near the S–N direction, and is constrained by the SE–NW direction near the Philippine sea plate, forming unique arc characteristics of the in-situ stress on the Chinese mainland (Fig. 1a). These characteristics are consistent with the current surface displacement of the East Asian continent monitored using a global positioning system (GPS)\(^{27-28}\). The total direction of in-situ stress obtained in this area is between NEE–NWN from the obtained data (Fig. 1c).

#### 5.1 Late Cenozoic regional denudation

The Tibetan Plateau has experienced three periods of strong tectonic uplift since the Cenozoic, the latest of which was 3.4 Ma after the middle Pliocene\(^{29-30}\). Numerous thermochronological studies have been conducted on the NBS and its surrounding areas using \(^{40}\)Ar/\(^{39}\)Ar, fission-track, and (U-Th)/He methods. The spatial distribution characteristics indicate that the Namcha Barwa peak area has been the uplift center of the East syntaxis since 3 Ma, and the uplift rate is about 2–5 mm/a\(^{17, 31-34}\), which was significantly higher than that in the surrounding areas.

Based on the aforementioned chronological data, the NBS area’s denudation and uplift rate since the Quaternary is about 2.5–3 mm/a, which is significantly lower than that of 10 mm/a during 3.5–3.2 Ma\(^{17}\), and its stability has been improved. However, it is still significantly higher than its surrounding areas and other active tectonic development areas. The East and West sides of Liupan Mountain on the northeast margin of the Tibetan Plateau, for example, have uplift and denudation rates of only 0.172 mm/a and 0.397 mm/a, respectively\(^{35}\). Thus, the NBS is at its most stable stage since the previous Cenozoic, although it is still poor compared with the Gangdise magmatic arc on the north side, where uplift velocity differences are obvious. The rapid thinning of the crust beneath the NBS and the obvious uplift of the EHS might be the dynamic source of the uplift.

#### 5.2 In-situ stress
The maximum horizontal principal stress direction is about N60°E based on the measured in-situ stress of the Sejilashan tunnel. The maximum horizontal principal stress, $S_H$, can reach about 25–30 MPa when the buried depth is about 500–600 m, which is 13.5–16.2 MPa higher than the vertical principal stress, $S_V$, and the maximum measured $S_H$ is about 45 MPa/1410 m. This indicates a relatively strong compression in this area.

However, the measured in-situ stress value in the east structural section is higher, and the measured in-situ stress value of the water conservancy project in the Duoxiongla area is mainly $S_H > S_h > S_V$, in which $S_H$ is 8.12–37.64 MPa. Thus, the maximum stress in the rock body at 800-m depth is obtained, $S_H$ is 40–70 MPa [20], which is significantly higher than the stress level in the peripheral area of the Sejilashan tunnel and other EHS syntaxis. Moreover, the value of tectonic/vertical stresses is significantly higher than the average value at 1.39 (0.93–1.65) in Tibet Plateau and 0.95 (0.7–1.0) in China [18].

![Fig. 4 Comparison of measured maximum horizontal principal in-situ stress inside (red) and outside (blue) the Yarlung Zangbo Suture zone.](image)

5.3 Regional strain recorded by GPS

The GPS horizontal movement velocity field can directly reflect the characteristics of obvious tectonic differential movement in the study area, whereas the characteristics and properties of crustal fine deformation can be reflected in the GPS strain rate fields [15-16]. From the $1^\circ \times 1^\circ$ accuracy plane expansion and shear strain field diagram [15] (Fig. 5), the plane and shear expansion rates are observed to be extremely high in the area around the EHS, and the maximum value is located in the southeast of Motuo, about $-(60-160) \times 10^{-9}$ nanostrain/a in the NBS area. The value reduced significantly, from the NBS node to the NE and NW, and is only $-(20-60) \times 10^{-9}$ nanostrain/a in the Bome-Nyingchi Area. The maximum shear strain region is similar to that of the minimum expansion rate region [15-16]. These facts indicate that although this NBS surface deformation rate is lower than that of Assam and Siang syntaxis, it is higher than that of the Gangdise magmatic arc to the north.
In conclusion, as the Changdu Nyingchi segment is at the leading edge of the S−N compression collision between the Indian Ocean and Eurasian plates, the Bome-Nyingchi segment is characterized by strong tectonic stress on the whole, with the number of tectonic stress in the inner part of the East tectonic segment on the south side being significantly higher than that in the Gangdise magmatic arc on the north side of the East tectonic segment, with greater direction change.

6. Comprehensive comparison of regional stability and railway route selection

Three obvious low resistivity zones exist in the NBS shallow crust. In the low resistivity zone, which is considered a suture zone, faults are strongly developed and rocks are relatively broken. Concurrently, these low resistance zones of shallow crust are also the location of active faults. The Holocene active faults, such as the Milin, Xixingla, and Motuo fault zones are distributed in the Yarlung Zangbo Suture zone. The Jiali fault is also active in Holocene from Bome to Tongmai. The historical earthquakes are mainly distributed near the Xixingla fault, and the potential earthquake magnitude is about Ms 7.5. Few historical earthquakes occur near the Jiali and the Milin fault zones, and the potential earthquake magnitudes are moderately strong Ms 5.0–6.9 and Ms 7.2 [9], respectively.

NBS area surface expansion rate in $-(60–160) \times 10^{-9}$ nanostrain/a and shear strain rate are significantly higher than those of the Gangdise magmatic arc $-(20–60) \times 10^{-9}$ nanostrain/a. The uplift center of the NBS area is near the Namcha Barwa peak, with a rate of about 2.5–3 mm/a due to the Quaternary. The uplift rate in other areas is significantly lower, which may be related to the NBS active deep structure. The NBS regional tectonic stress is extremely high, and the tectonic stress value ($S_H/S_V$ is about 1.8–3.3) is significantly higher than that of the Gangdise magmatic arc ($S_H/S_V < 2$), with variable direction. Under the topographic control, the bury depth of the tunnel of the syntaxis-crossing route scheme is extremely deep, and the rockburst risk, large deformation of soft rock, and water inrush are extremely high. These factors will severely affect the railway construction and may significantly increase the investment due to construction delays.

The aforementioned facts show that the NBS has stronger regional crustal stability than the Siang and Assam syntaxis in the EHS. However, its stability is lower than that of the Gangdise magmatic arc in terms of deep geophysical field and lithologic petrofabric characteristics. Comprehensive analysis shows that the railway line should avoid the EHS and go through the Gangdise magmatic arc.

7. Conclusion

Sichuan-Tibet railway passes through the EHS in the Bome-Nyingchi area. The project’s geological risk is extremely high due to the complicated regional tectonic process. Thus, we investigated geological route selection based on this area’s crustal stability by reducing construction risk and investment to determine this section’s geological risk. Combined with a detailed field investigation,
we comprehensively analyze the regional deep structure, Holocene active faults and earthquakes, and regional in-situ stress and crustal deformation. The crustal stability inside the EHS is extremely poor and the engineering risk is uncontrollable, with a high rockburst risk, large deformation of soft rock, and water inrush. Therefore, it is recommended that the Sichuan-Tibet railway project avoids crossing the EHS and instead conduct a comprehensive scheme study based on the NBS detour and Gangdise magmatic arc.

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