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A Review of Research on the Pillow Basalts of the Second Member of the Liushugou Formation in the Bogda Mountains

Senyu Wang

School of Resources and Environment, Henan Polytechnic University, Jiaozuo 454003, China

ABSTRACT

The Bogda orogenic belt, located in the eastern segment of the East Tianshan Mountains, is a key component of the Central Asian Orogenic Belt. Its Late Paleozoic tectonic evolution is closely related to the final closure of the Paleo-Asian Ocean. The Upper Carboniferous Liushugou Formation (C2l) is a widely distributed marine volcanic-sedimentary rock series in the Bogda region. The second lithological member ($C2l^2$) is characterized by the development of typical pillow basalts and serves as an important window for exploring the Late Carboniferous tectonic attributes of this area and the timing of the Paleo-Asian Ocean closure. This paper systematically reviews the regional tectonic background, petrological and geochemical characteristics of the pillow basalts of the second member of the Liushugou Formation in the Bogda Mountains, with a focus on sorting out the main academic viewpoints, core debates, and controversial focal points regarding their tectonic setting. It also summarizes current research status both domestically and internationally, aiming to provide a reference for an in-depth understanding of the Late Paleozoic tectonic evolution of the southern margin of the Central Asian Orogenic Belt.

KEYWORDS

Geochemistry; Petrology; Bogda Mountains; Tectonic setting; Pillow basalt.

1. REGIONAL GEOLOGY

1.1. Geotectonic Position

The Bogda Mountains are located in the central part of the Xinjiang Uygur Autonomous Region, situated in the eastern segment of the Tianshan Orogenic Belt. They form an approximately E-W-trending arcuate mountain system between the Junggar Basin and the Turpan-Hami Basin, extending for more than 400 km. The mountain range is 90–100 km wide at its eastern and western ends, and narrower in the middle (30–60 km). In terms of geotectonic position, it borders the East Junggar Basin to the north, adjoins the Turpan-Hami Basin to the south, connects with the Yilinhalga Orogenic Belt to the west, and extends toward the Kalamaili-Harlik Orogenic Belt to the east. It occupies a critical position at the convergence of multiple units, including the Siberian Block, the Tarim Plate, and the Junggar Terrane[1-4]. (Fig. 1: Regional tectonic background of the Bogda Orogenic Belt and stratigraphic distribution of the Liushugou Formation). The regional geological evolution of the Bogda Mountains records multi-stage tectonic processes, including the closure of the Paleo-Asian Ocean, continental-continental collision, and intracontinental orogeny since the Mesozoic, making it one of the important areas for studying the tectonic evolution of the eastern segment of the Central Asian Orogenic Belt[5].

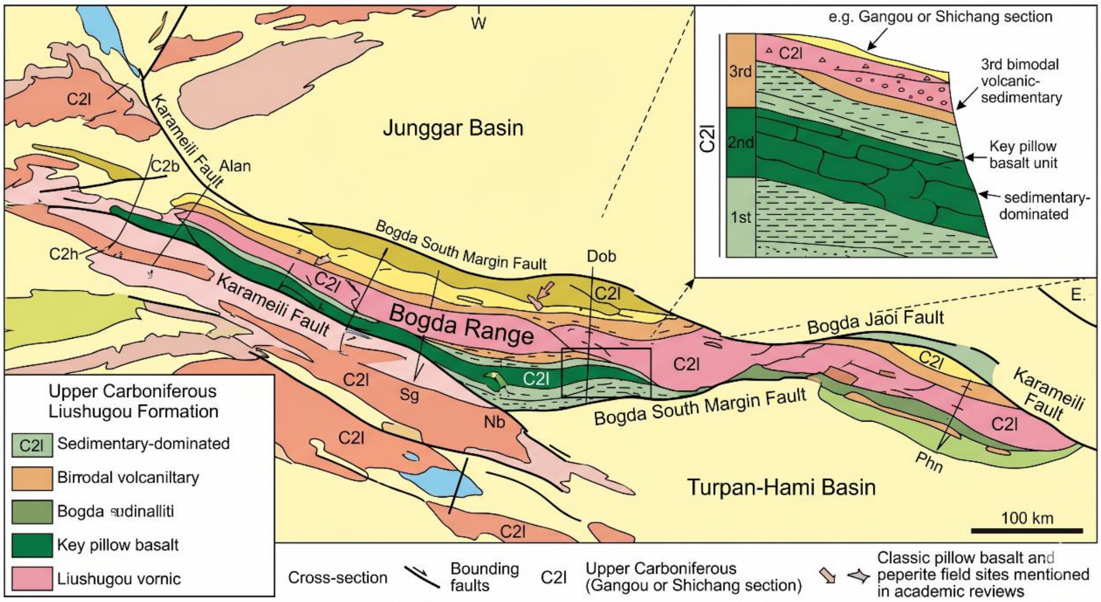

Fig 1: Regional tectonic background of the Bogda Orogenic Belt and stratigraphic distribution of the Liushugou Formation

1.2. Regional Stratigraphy and Rock Characteristics

The Carboniferous stratigraphic sequence in the Bogda region mainly comprises, from bottom to top, the Lower Carboniferous Qijiaojing Formation (C1q), the Upper Carboniferous Liushugou Formation (C2l), Qijiagou Formation (C2q), and Aertu Formation (C2a). The lithological development of the Liushugou Formation differs significantly between the eastern and western segments of the Bogda Mountains: the eastern segment is dominated by clastic rocks, whereas the western segment is more developed in volcanic lavas and volcanic breccias, with typical marine volcanic rock features such as pillow structures and vesicular-amygdaloidal structures observed. The second member of the Liushugou Formation (C2l2) is the core interval of the Upper Carboniferous Liushugou Formation, widely exposed in the Bogda tectonic belt, and generally distributed in an approximately E-W direction. It is mostly in conformable contact with the underlying first member and the overlying Qijiagou Formation, with local fault contacts[6-8]. The thickness of this member varies considerably, with a known thickness greater than 444.66 m. The lithological assemblage is dominated by volcanic rocks, intercalated with marine sedimentary rocks, recording the tectono-magmatic evolution from intense volcanic activity to relatively quiet sedimentation in a Late Carboniferous rift basin. Its typical stratigraphic sequence is divided from bottom to top as follows:

(1) The first member (C2l1): A set of intermediate-basic volcanic clastic rocks and volcaniclastic sedimentary rocks, intercalated with minor volcanic lavas and occasionally carbonate rock lenses. The main lithologies are gray-green tuffaceous sandstone, gray-black thick-bedded tuff, gravel-bearing coarse sandstone, gray-green crystal tuff, gray-black tuffaceous siltstone, intercalated with gray-green andesite, and gray to gray-white massive limestone lenses. The main rock types include: light gray-green crystal tuff, variegated lithic breccia tuff, gray-green vitroclastic-lithic tuff breccia, light gray-green andesitic lithic tuff, gray-green amygdaloidal basaltic andesite, blue-gray epidotized basalt, gray-green basaltic andesite porphyrite, gray-green amygdaloidal andesite, and gray-green cleaved basaltic andesitic crystal tuff. Overall, it constitutes a set of intermediate-basic volcanic clastic rocks with intercalated volcanic lavas[9].

(2) The second member (C2l2): The focus of this review, representing a marine-terrestrial transitional volcanic-sedimentary rock assemblage. The main rock types are: light gray silty-microcrystalline limestone, gray-green tuffaceous lithic sandstone, gray-green tuffaceous lithic feldspathic graywacke, gray gravel-bearing lithic tuff, light gray-green andesitic volcanic breccia tuff, epidotized andesite,

gray-green basaltic andesite, gray-black amygdaloidal basaltic andesite, and variegated amygdaloidal basalt. It is dominated by intermediate-basic volcanic lavas, intercalated with volcanic clastic rocks and volcaniclastic sedimentary rocks. The lithologies include gray-green to gray-purple andesite, gray-green amygdaloidal andesite, dacite, rhyolite, andesite porphyrite, pyroxene andesite porphyrite, volcanic agglomerate, volcanic breccia, and tuff. Typical rock characteristics are as follows: ① Amygdaloidal basalt, exhibiting aphyric-intersertal texture and amygdaloidal structure. It is composed of a framework of elongated plagioclase, with interstitial volcanic glass and metallic minerals. Plagioclase is approximately 0.04–0.15 mm in size, and the volcanic glass has been devitrified into crystallites. Amygdules are occasionally seen, occurring as rounded and irregular shapes, filled with chlorite, carbonate, epidote, and other minerals. ② Volcanic breccia lava, exhibiting breccia-lithic texture and massive structure, mainly composed of volcanic breccia (50%–55%) and interstitial material (40%–50%). The volcanic breccia is basaltic in composition, and the interstitial material is lava, with minor tuffaceous material; the lava exhibits porphyritic texture, and the matrix exhibits hyalopilitic texture. ③ Tuff, exhibiting tuffaceous texture and massive structure. The rock is composed of clasts (60%–80%) and cement (20%–30%). The clasts are lithic and crystal clasts, predominantly tuff, with minor andesite; the cement is volcanic ash. ④ Pyroxene andesite porphyrite, dark gray, exhibiting porphyritic texture and interstitial texture in the matrix, with massive structure. The phenocrysts are plagioclase, accounting for approximately 20%–25%, occurring as subhedral to euhedral tabular crystals, 0.7–1.5 mm in length, mostly as glomerocrysts with well-developed polysynthetic twinning. The matrix is dominated by plagioclase, accounting for approximately 50%–55%, with subordinate chlorite (10%–15%), pyroxene (10%–15%), and minor calcite (2%–3%).

(3) The third member (C2l3: Dominated by carbonate rocks, representing a relatively stable shallow marine environment. The main rock types are: brownish-red andesitic tuff, purplish-red andesite porphyrite, light gray andesitic tuff, gray-green andesitic tuff, gray-white medium-grained lithic feldspar sandstone, gray-white calcareous siltstone, and light gray limestone. The overall characteristics are that the base is dominated by brownish-red andesitic tuff, and the top contains minor terrigenous clastic rocks intercalated with limestone lenses. (Fig. 2: Stratigraphic columnar schematic diagram of the Liushugou Formation in the Bogda Mountains)

In the areas of Baiyanggou, Qijiaojing, Cheguluquan on the southern slope of the Bogda Mountains, and Baiyanghe, Tianchi, and other areas in the western segment, the basalts of the Liushugou Formation are extensively exposed, often exhibiting pillow structures and vesicular-amygdaloidal structures. Locally, plagioclase-phyric basalts (with plagioclase phenocryst content up to 40%) are developed, with considerable thickness and stable stratigraphic horizons, and can serve as regional marker beds for correlation[10].

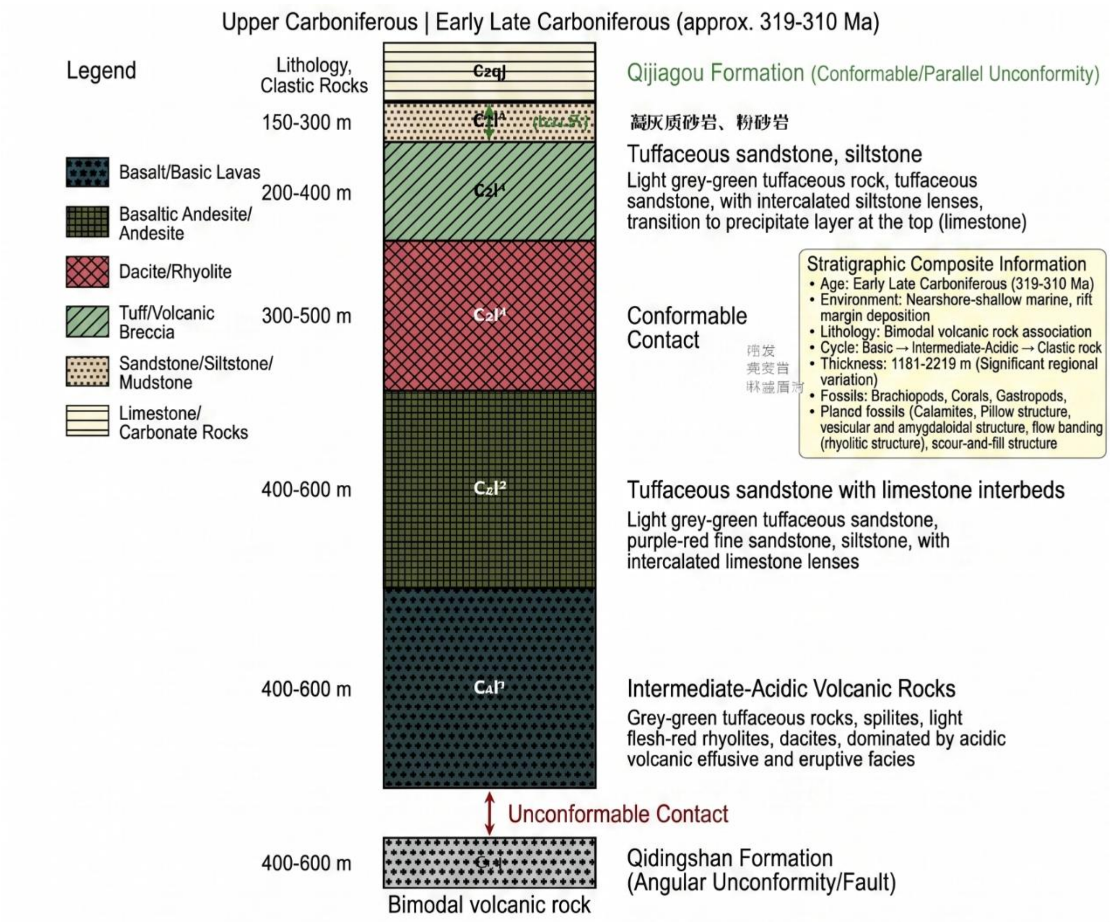

Fig 2: Stratigraphic columnar schematic diagram of the Liushugou Formation in the Bogda Mountains

2. PETROLOGICAL AND GEOCHEMICAL CHARACTERISTICS

2.1. Petrological Characteristics

Macroscopic Occurrence and Structure. In outcrops, the rocks are mainly gray-green, dark gray, or gray-purple. The most representative feature is the development of typical pillow structures; some rock bodies exhibit massive or amygdaloidal structures. This member of rocks is usually intercalated with minor amounts of volcanic clastic rocks and terrigenous clastic rocks[11, 12].

Microscopic Texture. Under the microscope, the rocks mainly exhibit porphyritic texture, with the matrix mostly showing intersertal-intergranular texture. The chilled margins (hyaline texture) display extremely fine, acicular, or even skeletal plagioclase microlites formed by extremely rapid cooling, recording extreme temperature gradients. The cores of the pillow bodies (intergranular-intersertal texture) show relatively slower cooling, with porphyritic texture visible, including plagioclase phenocrysts and pyroxene and Fe-Ti oxides in the matrix[5,13,14]. (Fig. 3: Microstructural comparison of chilled margins and pillow cores)

Mineralogical Composition. Phenocrysts account for approximately 10% to 12% of the rock, mainly composed of subhedral tabular plagioclase (approximately 10%) and subhedral short-columnar augite (approximately 2%). The matrix content is relatively high (approximately 88%), mainly composed of fine plagioclase microlites (approximately 48%), granular or fascicular augite (approximately 35%), and minor glass (approximately 5%). The plagioclase microlites often interlock to form a framework, with pyroxene and glass filling the interstices, constituting a typical intersertal-intergranular texture.

Amygdules and Accessory Minerals. Amygdules are mostly sub-rounded to elliptical in shape, generally ranging from 0.2 to 2 mm in size, with a content of approximately 4% to 10%. A small amount of anhedral granular magnetite is also visible, scattered between plagioclase grains.

Alteration Characteristics. Affected by later tectonism and hydrothermal fluids, the rocks have generally undergone varying degrees of secondary alteration. Mafic minerals (such as pyroxene) and glass are mostly devitrified, altered, or metasomatized, forming scaly chlorite and cryptocrystalline epidote aggregates. Plagioclase exhibits slight to moderate sericitization, argillization, and carbonatization [7,15-17].

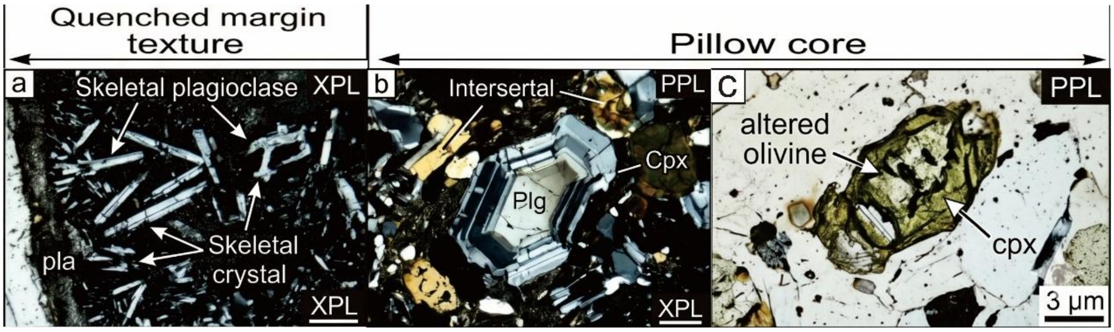

Fig 3: Microstructures of chilled margins and pillow cores

2.2. Geochemical Characteristics

2.2.1. Major Element Geochemistry

The pillow basalts of the second member of the Liushugou Formation exhibit typical continental rift tholeiitic basalt characteristics in terms of major elements. The Al2O3 content is greater than the sum of K2O + Na2O + CaO, belonging to the peraluminous type. At the same time, the total iron content is relatively high (with a relatively high average FeO content), and the magnesium index (Mg#) is relatively low (mostly between 33.98 and 48.40), belonging to the ferrous basic rocks. The alkali metal content is relatively high, and the rocks exhibit the characteristic of Na2O content being significantly greater than K2O (with a high Na2O/K2O ratio), belonging to medium-potassium, sodic rocks[11,13,18-20]. According to the TAS diagram and the AFM discrimination diagram, these pillow basalts mainly belong to the tholeiitic basalt series of the subalkaline series, with a small number of samples possibly showing an evolutionary trend of alkaline basalt. This high-aluminum, low-magnesium characteristic is highly consistent with the magma composition formed under rapid extension of relatively thin continental crust.

2.2.2. Trace and Rare Earth Element Geochemistry

The total rare earth element content (ΣREE) is relatively low (approximately 61.2 to 275.6 ppm). In the chondrite-normalized distribution pattern diagram, the curve is overall relatively flat but shows a gently right-inclined pattern with light rare earth elements (LREE) enriched relative to heavy rare earth elements (HREE) (LREE/HREE ratio and (La/Yb)N both greater than 1). The europium (Eu) anomaly is not obvious, mostly showing weak negative to slight positive anomalies (δEu values between 0.68 and 1.19), reflecting that the fractional crystallization of plagioclase during magma evolution was not intense. Cerium (Ce) shows a weak negative anomaly, indicating formation in a relatively reducing submarine environment.

Trace Element Characteristics. In the primitive mantle-normalized spider diagram, the rocks are obviously enriched in large ion lithophile elements (LILE, such as K, Rb, Ba, Sr). High field strength elements (HFSE, such as Nb, Ta, Zr, Hf, Ti) show relatively flat or moderately depleted patterns. This characteristic of LILE enrichment and relative HFSE depletion, combined with high (Th/Nb)N ratios, low Nb values, and Nb/U ratios, strongly suggests that the basaltic magma underwent assimilation and contamination by middle-lower crustal materials during its ascent[3, 12, 21-25]. (Fig.

4: Whole-rock geochemical classification (TAS) and primitive mantle-normalized spider diagram of the basalts of the second member of the Liushugou Formation)

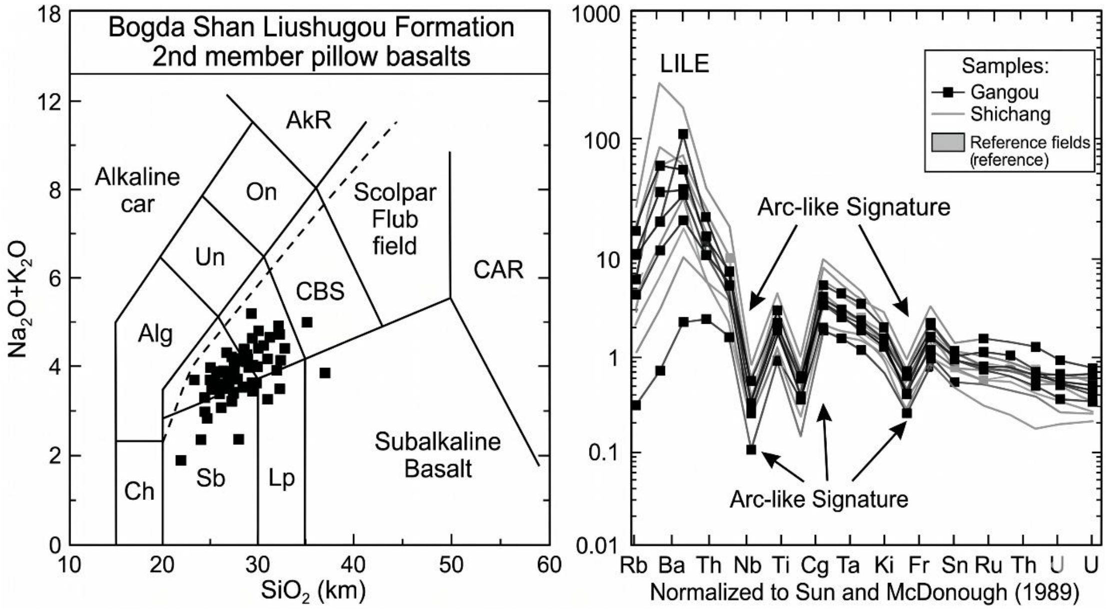

Fig 4: Whole-rock geochemical classification (TAS) and primitive mantle-normalized spider diagram of the basalts of the second member of the Liushugou Formation

2.3. Magma Genesis and Tectonic Evolution Significance

Integrating the above petrological and geochemical characteristics, the tectono-magmatic evolution model of this region during the Late Carboniferous can be established.

2.3.1. Magma Source Region

The incompatible element (such as Zr, Y, Nb) ratio characteristics (e.g., Zr/Nb vs. Ce/Y relationships) indicate that the parent magma generating the pillow basalts of the second member of the Liushugou Formation originated from relatively high degrees of partial melting of spinel peridotite in a depleted mantle[13].

2.3.2. Tectonic Environment

Trace element tectonic discrimination diagrams (such as Zr-Zr/Y, Zr-TiO2, etc.) show that these samples mainly fall into the within-plate basalt or continental rift basalt fields, distinctly different from island arc basalts or typical mid-ocean ridge basalts at convergent plate margins[11].

2.3.3. Evolutionary Process

In the early Late Carboniferous, the Bogda region was in a strong regional extensional setting. Crustal thinning triggered upwelling of mantle material (passive continental rift). As the faulted basin further expanded and seawater intruded, the underplated basaltic magma erupted along fissures onto the seafloor and rapidly cooled, forming large-scale pillow lava constructions. During the ascent and eruption of the magma, crustal contamination accompanied the process, ultimately forming tholeiitic bimodal volcanic rock assemblages with both depleted mantle source characteristics and crustal contamination imprints[14, 15].

3. VIEWPOINTS, DEBATES, AND CONTROVERSIES ON THE TECTONIC BACKGROUND

The determination of the Late Carboniferous tectonic attributes of the Bogda region is central to understanding the final closure process of the Paleo-Asian Ocean. Academic circles have long engaged in fierce debate regarding the genetic environment of the pillow basalts of the Liushugou Formation, which can be mainly summarized into the following three levels of controversy:

3.1. Controversy over the Timing of the Paleo-Asian Ocean Closure

The closure time of the Paleo-Asian Ocean directly determines whether the Bogda region was in an ocean-continent evolution stage or an intracontinental evolution stage during the Late Carboniferous. Currently, there are three main viewpoints: the Late Devonian-Early Carboniferous closure hypothesis, the end of Early Carboniferous closure hypothesis, and the end of Permian-Early Triassic closure hypothesis.

3.1.1. Late Devonian-Early Carboniferous Closure Hypothesis

Xia Linqi et al. (2004, 2008) proposed that, based on evidence such as the angular unconformity between the Devonian and Carboniferous systems and the fact that ophiolites mainly formed before the Carboniferous, the main ocean of the Paleo-Asian Ocean had basically closed by the end of the Devonian, and the Carboniferous entered a post-collision continental extension stage[26].

3.1.2. End of Early Carboniferous Closure Hypothesis

Li Jinyi et al. (2006) advocated that the South Tianshan Ocean basin closed at the end of the Early Carboniferous. Their evidence includes the Andean-type active continental margin characteristics of Early Carboniferous volcanic rocks in the Ili area, and the continental within-plate characteristics of Late Carboniferous Yishijilike Formation volcanic rocks in the West Tianshan. They believe that the development of large amounts of Carboniferous island arc volcanic rocks supports this timing.

3.1.3. End of Permian-Early Triassic Closure Hypothesis

Xiao et al. (2004, 2010) argued that the Paleo-Asian Ocean existed throughout the Paleozoic. Based on the presence of Early Permian ophiolites, they proposed that it closed in the Early Triassic. However, an increasing amount of chronological and geochemical evidence has challenged this viewpoint[14].

3.2. Core Debate on the Carboniferous Tectonic Background: Island Arc vs. Rift

3.2.1. Continental Rift Viewpoint

Gu Lianxing et al. (2000) were the first to systematically demonstrate the continental rift attributes of Carboniferous volcanic rocks in the Bogda region. They proposed that both the Qijiaojing Formation and the Liushugou Formation are bimodal volcanic rock constructions (basalt-rhyolite assemblages). The basalts originated from a depleted mantle, and the rhyolites were products of fractional crystallization of basaltic magma. The Bogda rift began in the Early Carboniferous and closed in the Middle-Late Carboniferous[2, 3]. Subsequent studies further classified the Liushugou Formation as a product of a continental rift environment, believing that it experienced an evolutionary process of initial faulted basin (first member), middle continental rift (second member), and late rift stage (third member)[21,27]. Key evidence supporting the rift viewpoint includes: the bimodal lithological assemblage lacks intermediate components; the basalts exhibit within-plate geochemical characteristics (enriched LILE, depleted HFSE, but with Nb-Ta depletion weaker than typical island arcs); the rhyolites exhibit A-type granite characteristics; and regionally, large-scale extensional structures developed synchronously [18].

3.2.2. Volcanic Island Arc/Back-Arc Basin Viewpoint

Some scholars, based on calc-alkaline series volcanic rock-volcaniclastic rock constructions, Nb-Ta negative anomalies, and LILE enrichment and other "arc imprints," have judged that the Bogda region during the Late Carboniferous was still in a subduction-consumption environment, and that the Liushugou Formation volcanic rocks formed in a volcanic island arc or back-arc basin. Ma et al.

(1997) and Xiao et al. (2004) regarded the Bogda-Harlik belt as an arc system on the southern margin of the Paleo-Asian Ocean, believing that it represents the volcanic island arc of the Paleo-South Tianshan Ocean, with a characteristic of gradual extinction from west to east[1, 12, 14].

3.2.3. Volcanic Island Arc/Back-Arc Basin Viewpoint

In recent years, an increasing number of scholars have proposed a "post-collisional rift basin" model, attempting to reconcile the above contradictions. This viewpoint holds that the Bogda region completed the ocean-continent transition by the end of the Early Carboniferous, and that the Late Carboniferous Liushugou Formation volcanic rocks formed in a post-collisional rift basin related to local strike-slip faults. The basalts may have originated from a depleted mantle source modified by fluids and sediment melts from the subducted slab, and the rhyolites originated from partial melting of juvenile continental crust, reflecting the dynamic process of lithospheric delamination and asthenospheric upwelling after collision [16]. (Fig. 5: Sr-Nd-Hf isotopic variation diagrams and genetic model schematic diagram of the basalts of the second member of the Liushugou Formation)

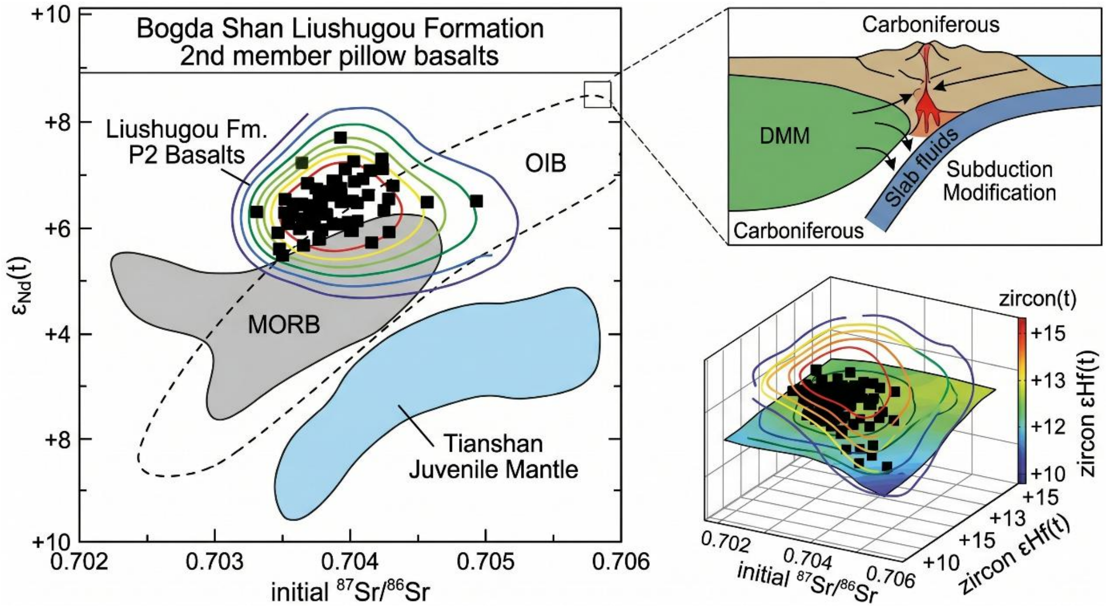

Fig 5: Sr-Nd-Hf isotopic variation diagrams and genetic model schematic diagram of the basalts of the second member of the Liushugou Formation

3.2.4. Subduction-Tear Type Rift (Back-Arc Spreading) Viewpoint

In response to the opposition between traditional rift and island arc models, some scholars have proposed the concept of a subduction-tear type rift. This viewpoint holds that the formation of the Bogda rift is related to the oblique subduction of the Paleo-Asian Oceanic crust toward the Southeast Junggar-Turpan-Hami block. The friction of the subducting plate or mantle upwelling caused back-arc spreading, forming a special type of back-arc tear rift. This model explains why the Bogda volcanic rocks simultaneously possess the lithological assemblage characteristics of within-plate rifts and the geochemical imprints related to subduction (such as Nb-Ta depletion) [28].

3.2.5. Rear-Arc/Back-Arc Environment Viewpoint

Xie et al. (2016), through comparative study of Late Carboniferous high-alumina basalts (HAB, 315–319 Ma) and pillow basalts (~311 Ma) in the Bogda region, proposed that the Chinese North Tianshan was in a rear-arc or back-arc environment during the Late Carboniferous, possibly related to the southward subduction of the Paleo-Tianshan Ocean [13, 15]. They found that both types of basalts exhibit MORB-like isotopic compositions (Sr-Nd-Hf-Pb) and arc-like trace element characteristics, highly similar to the Izu-Bonin back-arc basalts, indicating that they originated from a depleted mantle metasomatized by subducted sediment melts, and formed in an extensional environment related to subduction, rather than a mantle plume-related large igneous province.

3.3. Controversy over the Specific Genetic Environment of the Pillow Basalts

Regarding the specific genesis of the pillow basalts of the second member of the Liushugou Formation, the focus of controversy centers on the submarine eruption environment, the nature of the mantle source region, and the degree of crustal contamination.

Submarine Eruption Environment. Pillow structures clearly indicate submarine eruption, but whether it was a shallow marine environment within a rift basin, a deep-water environment in a back-arc basin, or a lacustrine environment in a post-collisional intracontinental stage remains subject to different interpretations [23, 29].

Nature of the Mantle Source Region. Early studies suggested that the basalts originated from a depleted asthenospheric mantle; recent research has revealed that they may have originated from a lithospheric mantle metasomatized by subducted fluids/melts, or from partial melting of a transitional phase from spinel lherzolite to garnet lherzolite [2].

Degree of Crustal Contamination. Some basalts show obvious crustal contamination signals ($Th/Nb > 1$, $Nb/La < 1$), but the coupling relationship between the degree of contamination and the tectonic environment (rift extensional thinning crust vs. back-arc basin) remains unclear [3].

4. CURRENT RESEARCH STATUS DOMESTICALLY AND INTERNATIONALLY

4.1. Advances in Geochronology

Precise geochronological constraints are the foundation for limiting tectonic evolution stages. Domestic and international scholars have carried out systematic zircon U-Pb and whole-rock Rb-Sr dating on the pillow basalts of the Liushugou Formation and their associated acidic volcanic rocks. Among them, the zircon U-Pb age of the basalts of the second member of the Liushugou Formation is 312.5 ± 6.5 Ma, the rhyolitic tuff is 316.2 ± 1.4 Ma, the quartz keratophyre is 314.9 ± 1.2 Ma, and the volcanic rocks of the Liushugou Formation in the Xishan area are 311.2 ± 1.7 Ma, consistently limiting their formation to the Late Carboniferous (Pennsylvanian) [21]. In addition, the Rb-Sr isochron ages of basalt and rhyolite from the bimodal volcanic rocks in the Qijiaojing area are 342.0 ± 3.2 Ma and 340.3 ± 3.4 Ma, respectively; the Rb-Sr age of rhyolite in the Xidi-Yiqi-Xiaohongliuxia area is 296 ± 2 Ma; and the Early Permian Kalagang Formation rhyolite is 278 ± 2 Ma, indicating that rift magmatism continued from the Late Carboniferous to the Early Permian [24].

4.2. Geochemical and Petrological Research

Domestic scholars have conducted extensive analyses of major, trace, and rare earth elements on the Liushugou Formation volcanic rocks in different sections of the Bogda Mountains. The main results include:

Bimodal Volcanic Rock Assemblage. It has been confirmed that the Liushugou Formation is composed of basalts (dominant) and rhyolites forming a typical bimodal volcanic rock assemblage, lacking intermediate components such as andesite, with a basalt/rhyolite ratio of approximately 5:1 to 7:1 [12].

Rock Series Classification. The basalts belong to the tholeiitic series ($THI > 1$), and the acidic volcanic rocks belong to the high-K calc-alkaline to subalkaline series, with some rhyolites exhibiting A2-type granite characteristics [16].

Geochemical Discrimination. Using tectonic discrimination diagrams such as Ti-Zr-Y, Nb-Zr-Y, and Th-Hf-Ta, most samples fall into the within-plate/rift or back-arc basin fields, with a few showing island arc characteristics, reflecting the complexity or multi-stage superposition of the tectonic environment [2, 19, 23, 30, 31].

4.3. Isotopic Geochemical Research

Nd-Sr Isotopes. The basalts in the eastern segment of the Bogda Mountains exhibit positive εNd(t) values (+5.63 to +5.89), with $(^{143}Nd/^{144}Nd)_I$ = 0.512927–0.512944 and $(^{87}Sr/^{86}Sr)_I$ = 0.703–0.707, indicating a magma source from depleted mantle with crustal contamination; the rhyolites have $(^{87}Sr/^{86}Sr)_I$ = 0.7051–0.7052 and $\delta^{18}O$ = 11.6‰, indicating partial melting of crustal material.

Zircon Hf Isotopes. Chen et al. (2011) studied the zircon Hf isotopes of the Liushugou Formation basalts and rhyolites from the Baiyanggou, Qijiaojing, and Cheguluquan areas on the southern slope of the Bogda Mountains. The results show that the basalts have εHf(t) = 8.0–15.6, originating from a metasomatized lithospheric mantle; the rhyolites may have originated from two distinctly different source regions, suggesting frequent transitions of tectonic stress from extension to compression during the rift closure period [18, 28].

4.4. International Research Progress and Regional Comparison

Accretionary Evolution of the Central Asian Orogenic Belt Sengör, Windley, Xiao Wenjiao, and others have emphasized that the Bogda Mountains are an important component of the accretionary complex on the southern margin of the Paleo-Asian Ocean, having experienced multi-stage subduction-accretion-collision processes. Xiao et al. (2004, 2013) proposed that the Bogda region was a back-arc basin or accretionary wedge environment during the Carboniferous, and transitioned to post-collisional evolution in the Permian [14].

Comparison with Global Rift/Back-Arc Systems. Xie et al. (2016) compared the Bogda basalts with the Izu-Bonin back-arc basalts, the Siberian Large Igneous Province, and the Emeishan Large Igneous Province, confirming that they show significant differences from mantle plume-type basalts, but are highly consistent with a back-arc extensional environment [13, 15].

Post-Collisional Rift Basin Model. International scholars such as Laurent-Charvet and Yuan et al. support the interpretation of the Bogda region during the Late Carboniferous as a post-collisional extensional environment, emphasizing the role of strike-slip faults in controlling the formation of rift basins [16].

4.5. Comprehensive Tectonic Evolution Model

Integrating domestic and international research, the Late Carboniferous tectonic evolution of the Bogda region can be summarized into the following stages:

(1) Early Carboniferous (347–326 Ma): Qijiaojing Formation eruption period, initial rift formation, represented by bimodal volcanic rocks (massive/pillow basalt + rhyolite), with magma originating from depleted mantle [6].

(2) Early Late Carboniferous (319–311 Ma): Pillow basalt eruption period of the second member of the Liushugou Formation, the rift entered its peak stage or back-arc extensional stage, with intense submarine volcanic activity, forming pillow structures and bimodal assemblages [21].

(3) Late Late Carboniferous (310–300 Ma): Rift activity weakened or closed, with the Qijiagou Formation dominated by shallow marine carbonate platform deposition, accompanied by minor pillow basalt eruptions; subsequently, the Aertu Formation transitioned to deep-water turbidite fan deposition, reflecting enhanced rift activity or tectonic inversion.

(4) Early Permian (298–288 Ma): Post-collisional intracontinental rift period, with the development of slump structures, deep-water turbidite fans, and bimodal volcanic rocks, marking the end of the Paleo-Asian Ocean plate tectonic regime and the beginning of the intracontinental evolution stage.

5. EXISTING PROBLEMS AND PROSPECTS

Although abundant research results have been achieved on the pillow basalts of the Liushugou Formation in the Bogda Mountains, the following key issues remain:

(1) Multi-solution of tectonic attributes: Existing geochemical discrimination diagrams have overlapping fields for rift, back-arc basin, and post-collisional environments, making it difficult to clearly distinguish them using a single indicator. Comprehensive constraints combining sedimentology (such as the paragenetic relationships of pillow lavas with carbonate rocks and siliceous rocks), paleontology (paleoecological indicators such as radiolarians and corals), and structural analysis (kinematics of contemporaneous faults) are needed.

(2) Precise constraints on the timing of the Paleo-Asian Ocean closure: The closure times of the South Tianshan Ocean basin and the Junggar Ocean basin may not be synchronous. The Bogda region is located at the junction of multiple units, and its closure timing may be controlled by the scissor-like closure of ocean basins in different directions. High-precision zircon U-Pb, muscovite Ar-Ar, and high-pressure to ultra-high-pressure metamorphic rock geochronology studies need to be strengthened.

(3) Genesis mechanism of the pillow basalts: Currently, research on the eruption water depth, eruption rate, and marine-terrestrial transition process of the pillow basalts of the second member of the Liushugou Formation is weak. Analysis of the individual morphology of pillow lavas, chilled margin thickness, and associated sedimentary lithofacies can provide direct evidence for paleo-water depth and paleogeographic reconstruction.

(4) Deep dynamic processes: Whether under a rift model or a back-arc model, the deep dynamic mechanism for the large-scale magmatism during the Late Carboniferous needs to be explained. The geophysical responses of lithospheric delamination, asthenospheric upwelling, and subducted slab rollback/tearing still lack verification from deep seismology or magmatic thermodynamic modeling.

(5) Differences between the eastern and western segments: The pattern of the eastern segment of the Bogda Mountains being dominated by clastic rocks and the western segment by volcanic lavas reflects asymmetric subsidence or segmented evolution of the rift basin. The controlling factors (such as the activity of boundary faults and differences in crustal thickness) await further investigation.

6. CONCLUSION

The pillow basalts of the second member of the Liushugou Formation in the Bogda Mountains are an important component of the Late Carboniferous (approximately 319–311 Ma) marine bimodal volcanic rock assemblage. Their formation is closely related to the dramatic transformation of the Late Paleozoic tectonic framework on the southern margin of the Paleo-Asian Ocean. Regarding their tectonic background, academic understanding has evolved from a "single rift" to a "single island arc," and then to diversified perspectives including "post-collisional rift," "subduction-tear type rift," and "rear-arc/back-arc environment." Existing research indicates that the Liushugou Formation pillow basalts possess both the lithological assemblage characteristics of within-plate rifts and the geochemical imprints related to subduction (Nb-Ta depletion, LILE enrichment). They most likely formed in a complex tectonic environment superimposed by intracontinental extension after the closure of the Paleo-Asian Ocean and residual subduction effects, namely a post-collisional rift or back-arc spreading environment.

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