

Article

Deformation History of the Heilongjiang Complex and Subduction Polarity of the Mudanjiang Ocean, NE Asia

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Abstract: During the Mesozoic, NE Asia experienced intense tectonic and magmatic activity, including the closure of the Mongol–Okhotsk Ocean (MOO), the subduction and demise of the Mudanjiang Oceanic Plate (MOP), and the continuous westward subduction of the Paleo-Pacific Plate (PPP). The evolution of the MOP remains highly contentious, particularly regarding its final closure timing and subduction polarity, and warrants further investigation. The Heilongjiang Complex (HLC), primarily distributed within the Mudanjiang Suture Zone (MSZ), which separates the Jiamusi and Songnen blocks, preserves key geological records of the Mudanjiang Oceanic subduction and closure. By employing detailed structural analysis, zircon U–Pb dating, and tomographic imaging, we reconstruct the tectonic history of the HLC and propose its five stages of deformation since the Mesozoic. The first stage, which occurs from the Late Triassic to the Early Jurassic, is characterized by SE-dipping schistosity within the HLC. Integrating the identification of the east-dipping remnants of the oceanic lithosphere west of the MSZ by tomographic imaging suggests an eastward subduction of the MOP underneath the Jiamusi Block during the Early Mesozoic. The second stage, spanning the Early Jurassic to the Late Jurassic, is characterized by E–W-striking tight folds associated with the MOO’s SSE-ward subduction and PPP’s NNW-ward subduction. The third stage of deformation, occurring from the Late Jurassic to Early Cretaceous, features S–N-striking box folds, indicative of the final amalgamation of the Jiamusi, Songnen, and Nadanhada terranes. The fourth stage, taking place in the late Early Cretaceous, is marked by near E–W-striking thrust faults that are associated with the closure of the eastern segment of the MOO. Finally, the fifth stage, which follows the Early Cretaceous, involves nearly NE-striking thrust faults related to NW-ward subduction of the PPP.

Keywords: Heilongjiang Complex; NE Asia; Mudanjiang Ocean; subduction polarity; Mesozoic



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1. Introduction

Northeast (NE) Asia lies within a convergent zone where the Pacific Plate, North China, and Siberian cratons meet, resulting in frequent seismic and volcanic activity [1,2] (Figure 1). The region is composed of several blocks, including the Songnen, Jiamusi, Khanka, and

Bureya blocks, as well as terranes such as the Nadanhada and Samarka (Figure 1). NE Asia has played a significant role in the evolution of several paleo-oceans, including the Paleo-Asian Ocean, the Mongol–Okhotsk Ocean (MOO), the Mudanjiang Ocean, and the Paleo-Pacific Ocean, all of which have undergone subduction and eventual closure [3–5]. Since the Mesozoic, the continuous convergence of various blocks and terranes has shaped the present-day continental configuration of the region [4–9]. The well-preserved geological records from diverse tectonic domains make this NE Asia a pivotal area for investigating the Mesozoic tectonic evolution of the region. These records provide critical insights into the convergence processes of tectonic blocks or terranes, driven by subduction and multi-directional orogenies along the continental margins (Figure 1).

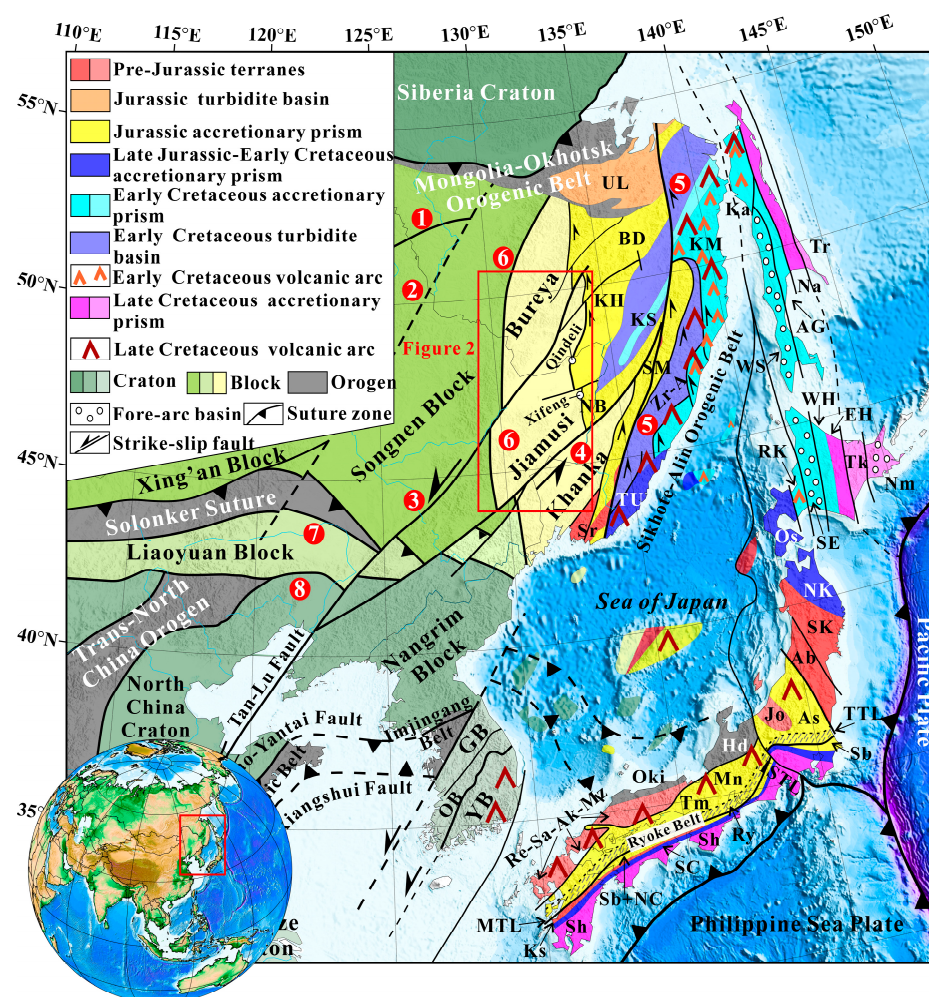


Figure 1. Tectonic division of the northeast Asia (modified after [2,7,10–15]. 1—Xinlin–Xiguitu Fault; 2—Hegenshan–Heihe Fault; 3—Yilan–Yitong Fault; 4—Dunhua–Mishan Fault (DMF); 5—Central Sikhote–Alin Fault; 6—Mudanjiang Fault/Mudanjiang Suture Zone; 7—Solonker–Xar Moron–Changchun–Yanji Fault; 8—Northern margin fault zone of North China. Abbreviations: UL, Ul’ban; BD, Badzhal; KH, Khabarovsk; NB, Nadanhada–Bikin; SM, Samarka; Zr-A, Zhuravlevka–Amur; KM, Kema; KS, Kiselevka–Manoma; TU, Taukhe; Sr, Sergeevka; Ka, Kamyshev; WS, Western Sakhalin; AG, Aniva–Gomon; Na, Nabil; Tr, Terpeniya; RK, Rebun–Kabato; SE, Sorachi–Ezo; WH, Western Hidaka; EH, Eastern Hidaka; Tk, Tokoro; Nm, Nemuro; Os, Oshima; NK, Northern Kitakami; SK, Southern Kitakami; Ab, Abukuma; As, Ashio; Jo, Joetsu; Hd, Hida; Sb, Sambagawa; Mn, Mino; Ry, Ryoike; Tm, Tamba; Sh, Shimanto; SC, Southern Chichibu; NC, Northern Chichibu; Ks, Kurosegawa; Re-Sa-Ak-Mz, Renge–Sangun–Akiyoshi–Maizuru; MTL, Median Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line; TTL, Tanagura Tectonic Line; GB, Gyeonggi Block; OB, Okcheon Belt; YB, Yeongnam Block.

Over the years, numerous studies have explored eastern NE Asia from various perspectives, including geochemistry [14,16–18], geochronology [1,12,19–22], petrology [23,24], paleontology [25], stratigraphy [26], and structural geology [27–30]. These studies have provided a robust framework for reconstructing the tectonic evolution history of north-eastern Asia. Despite significant progress, several unsolved issues continue to fuel debate. For instance, questions remain regarding how the Songnen and Jiamusi blocks were joined prior to the accretion of eastern terranes, such as the Nadanhada and Samarka terranes, onto the continental margin of East Asia [15,27]. This raises critical uncertainties about the timing of closure and the subduction polarity of the ancient ocean that once separated these blocks.

The amalgamation of the Jiamusi and the Songnen blocks occurred in multiple stages throughout the Paleozoic and Mesozoic. The two blocks initially merged to form the Jiamusi–Xingmeng (Jia-Meng) Block during the Early Paleozoic [26,31,32], with the collision occurring after approximately 445 Ma [33], or by 425 Ma [34]. The Heilongjiang Complex (HLC) is a blueschist-bearing, N–S trending high-pressure metamorphic belt, traditionally interpreted as the Mudanjiang Suture Zone. It has been regarded as evidence for the existence of an ancient ocean, referred to as the Mudanjiang Ocean. This ocean is thought to have formed through the breakup of the Jia-Meng Block between the Late Permian and Late Triassic [4,32]. However, recent studies challenge this interpretation [35,36], arguing against the existence of the Mudanjiang Ocean and disputing the characterization of the HLC as a suture zone. Instead, these studies propose that the HLC represents an underground, near-horizontal extension of the marginal continental accretionary wedge of the Nadanhada-Bikin terrane (flat subduction model), brought to the surface at the site of antiform bending [35]. Furthermore, Liu et al. [36], based on their analysis of mylonitic meta-sedimentary rocks in Huanan, located 85 km east of the Mudanjiang Suture Zone, suggest that complexes such as the HLC and the Zhangguangcai Range Complex may either be nappes displaced by post-exhumation thrusting or remnants of archipelagic oceanic crusts from the NW Paleo-Pacific region during the Early Mesozoic. These findings provide an alternative explanation for the formation of the HLC.

If the Mudanjiang Ocean did exist, as suggested by earlier studies, the exact timing of its final closure remains contentious. This is primarily due to the varying ages of blueschist metamorphism in the Heilongjiang Complex across different regions of the Mudanjiang Suture Zone, which marks the proposed closure location of the Mudanjiang Ocean. These inconsistencies have led to multiple interpretations of the closure period. Some scholars argue that closure occurred between the Late Triassic and Late Jurassic [32,37–39], based on $^{40}\text{Ar}/^{39}\text{Ar}$ ages of mica and glaucophane, as well as zircon U–Pb ages from mica schist and blueschist. Others propose an Early Jurassic closure [6,40–42], with some narrowing the timeframe to between 184 and 174 Ma, based on $^{40}\text{Ar}/^{39}\text{Ar}$ dating of biotite and phengite from the granitic gneiss and mica schist in the Luobei and Yilan areas [12]. Additionally, evidence suggests that the closure process may have extended into the Early Cretaceous, with estimated ages ranging from 150 to 140 Ma [9,43], supported by low-temperature thermochronological data from basement highs separating the eastern NE Asia basins, or as late as 145–146 Ma, corresponding to $^{40}\text{Ar}/^{39}\text{Ar}$ isochron ages of phengites in blueschists from the Yilan area [44].

Regarding the subduction polarity of the Mudanjiang Oceanic Plate (MOP), Zhang et al. [45] proposed that a west-dipping wedge-shaped reflection zone within the crust and mantle, observed in the Bayan–Huanan deep reflection seismic profile, indicates westward subduction of the Jiamusi Block lithospheric mantle beneath the Songnen Block. Recent research employing three-dimensional inversion of terrestrial magnetic profiles further supports this westward subduction model [46]. However, the inversion results reveal

that the high-conductivity zones dipping westward are located beneath the Yilan–Yitong Fault rather than directly under the Mudanjiang Suture Zone, while east-dipping high-conductivity zones are observed beneath the Mudanjiang Suture Zone.

Some researchers advocate for a bidirectional subduction model for the MOP, proposing eastward subduction beneath the Jiamusi Block and westward subduction beneath the Songnen Block. This model is supported by geochemical and petrological analyses of Late Permian basaltic intrusions in the Mudanjiang Suture Zone [47], as well as Early to Middle Paleozoic igneous rocks in the Lesser Xing'an–Zhangguangcai Range area [48,49]. The Jiamusi Block extends northward into the Bureya Block and southeastward into the Khanka Block in the Russian Far East, collectively referred to as the Bureya–Jiamusi–Khanka Block [12,50–52]. Li et al. [53] proposed that the Paleotethys Ocean, connected to the Qinling Ocean in the west, extended northeastward between the Bureya–Jiamusi–Khanka Block and the Songnen Block, with eastward subduction of the northern Paleotethys Ocean beneath the Bureya–Jiamusi–Khanka Block.

Based on the preceding analysis, it is evident that the amalgamation of the Jiamusi and the Songnen blocks remains a subject of ongoing debate, with relatively limited structural analyses available [54]. Consequently, this study focuses on the areas of HLC exposed within the Mudanjiang Suture Zone. By integrating field observations, detailed structural analysis, tomographic imaging, and zircon U–Pb geochronology, this study aims to investigate the deformation characteristics and evolutionary stages of the HLC. Additionally, it will examine the polarity of the Mudanjiang Oceanic subduction, explore the Mesozoic tectonic evolution history of NE Asia, and provide new insights into the ocean-continent convergence processes in East Asia.

2. Geological Setting

The Jiamusi Block is situated on the eastern margin of the Northeast Asian Continent, as shown in Figure 1. Its western boundary is defined by the Mudanjiang Suture Zone (Figure 1(6)), which separates it from the Songnen Block. To the north, the Jiamusi Block is separated from the Bureya Block by the Yilan–Yitong Fault (Figure 1(3)). The southern boundary is marked by the Dunhua–Mishan Fault (DMF) (Figure 1(4)), which separates it from the Khanka Block. To the east of the Jiamusi Block lies the Yuejinshan Complex and the Raohe Complex, also together referred to as the Nadanhaha Terrane. The boundary between the Jiamusi Block and the Yuejinshan Complex is identified by the Yuejinshan Fault, also known as the Tongjiang–Mishan Fault.

The Jiamusi Block is a microcontinent characterized by a typical double-layer structure comprising a basement and an overlying cover [4,8]. The main exposed units include the Mashan Complex, the HLC, the Paleozoic to the Mesozoic granitic rocks, and various sedimentary rock series [8,12]. The metamorphic crystalline basement comprises the Mashan Complex and the Early Paleozoic (541–484 Ma) granitic rocks [55,56]. The sedimentary cover is categorized into two structural layers. The lower layer consists of marine and marine-terrestrial interaction clastic sediments dating from the Lower Devonian to the Lower Carboniferous [25]. In contrast, the upper layer comprises clastic sediments and volcanic series spanning from the Upper Carboniferous to the Lower Cretaceous [4,8,12].

The Mashan Complex (formerly the Mashan Group) is mainly exposed in Jixi, Boli, Huanan, and Luobei (Figure 2). This complex consists of the khondalite series that have undergone a high amphibolite to granulite facies metamorphic process. It is characterized by abundant aluminum, along with phosphorus and graphite, and contains interbedded marbles, calc-silicate rocks, and quartz schists [4,56–58]. Initially, it was believed that the Mashan Complex formed during the Late Archean to the Early Proterozoic [55]. However,

more recent dating results indicate that the metamorphic age of the complex is approximately 500 Ma [57,59,60].

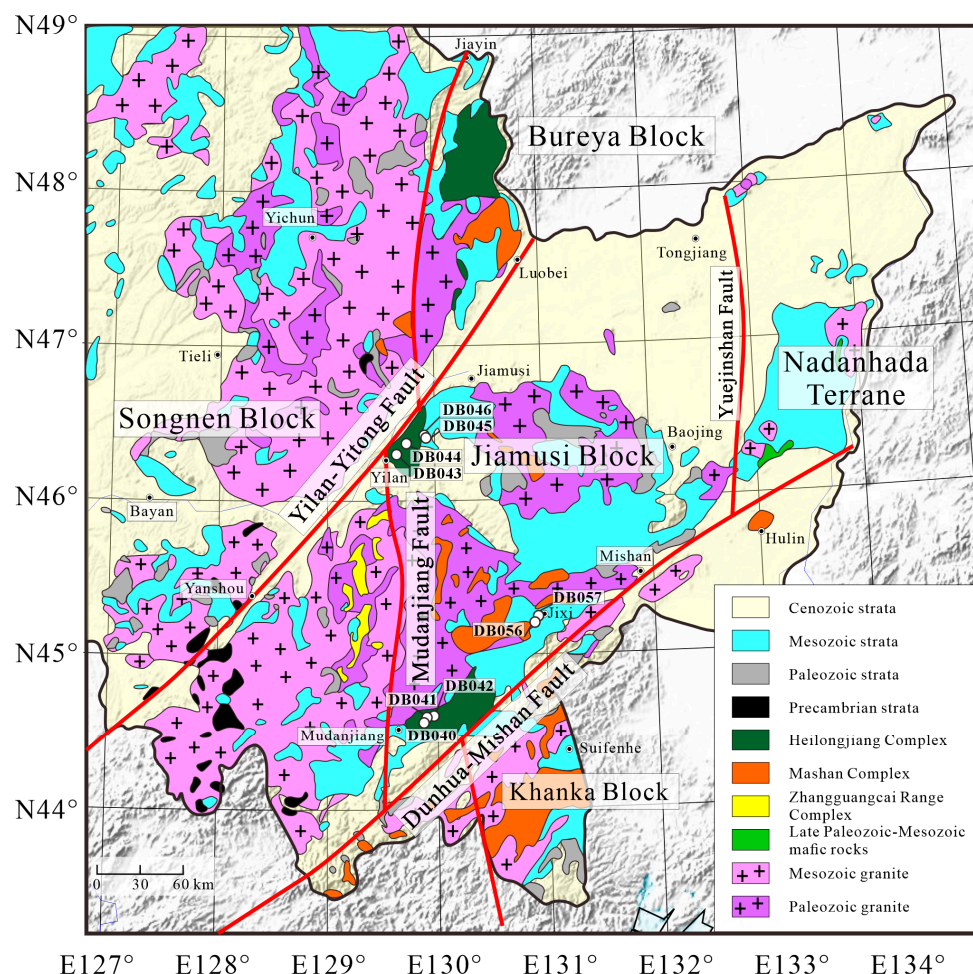


Figure 2. Geological map of the Jiamusi Block (modified after [47]). Red lines represent block boundaries, and white dots mark the sampling locations used in this study.

The HLC (formerly known as the Heilongjiang Group) is exposed along the western margin of the Jiamusi Block in a north–south orientation (Figure 2). It is observed in the regions of Mudanjiang (thicknesses > 6400 m), Yilan (thicknesses > 4000 m), and Luobei [61]. This complex comprises ultramafic rocks, blueschist-facies metamorphic basaltic rocks, greenschist, felsic schists, mica schists, and quartzites manifested as tectonic lenses or layers [62]. Geochemical analyses of selected blueschist samples indicate that their protoliths are associated with oceanic island basalt (OIB) or enriched Mid-Ocean Ridge Basalt (E-MORB) affinities, suggesting that they were generated in a rift setting or an ocean island setting [6,63].

Early studies classified the HLC as an Early to Middle Proterozoic metamorphic strata [55,64], and as a Precambrian greenstone belt [61,65–67]. However, more recent precise dating of zircons or micas from blueschists or meta-sedimentary rocks has revealed metamorphic ages ranging from the Late Triassic to the Early Jurassic [6,12,38,39,44,68,69].

The Jiamusi Block underwent four distinct phases of magmatic activity during the following periods: the Pan-African Period (541–484 Ma), the Late Carboniferous to Permian (305–250 Ma), the Late Triassic to Cretaceous (223–88 Ma), and the Cenozoic [4,62]. Granites from the Pan-African period are approximately 515 Ma [56,58] and are classified as I-type granites [60,70]. During the Late Carboniferous to Permian period, this region mainly

developed basaltic to acidic rocks, with widespread exposure to intrusive granites. Notable examples include the Chushan intrusion (256 Ma), which serves as a typical representative, along with the Qingshan (270 Ma), the Shichang (267 Ma), and the Chaihe (254 Ma) intrusions [1]. Volcanic rocks are primarily exposed in the eastern part of the block, featuring an assemblage of Early Permian basalt, basaltic andesite, andesite, and dacite, as well as a Middle Permian rhyolite-dacite assemblage. In the northern region of the Jiamusi Block, Mesozoic igneous rocks are developed, with predominantly intermediate to acidic compositions, including diorite, quartz diorite, lamprophyre, and granite porphyry. These rocks are commonly observed in columnar or vein-like formations with Cretaceous emplacement ages [50,71–73]. Cenozoic igneous rocks in this region are predominantly continental flood basalts distributed along the DMF and the Yilan–Yitong Fault. These basalts are likely the result of extensional processes within the Eurasian continent driven by the tectonic event of the Pacific Plate [74,75]. There are also granodiorites with the emplacement age of 54 Ma developed in the junction of the Jiamusi Block and the Nadanhada Terrane, intruding into the Upper Carboniferous to the Lower Permian strata [76].

The Yilan–Yitong Fault (Figure 1(3)) within the study area extends northeastward into the Russian Far East and represents the northern branch of the Tancheng–Lujiang Fault (Tan–Lu Fault) in NE China. Zhang and Dong [2] suggest that the Yilan–Yitong Fault formed during the late Early Cretaceous period, with associated oil and gas resources developing nearby [77]. The DMF (Figures 1(4) and Figure 2), also referred to as the Mishan–Fushun Fault, is the southern branch of the Tan–Lu Fault in NE China, extending northeastward over 900 km from Shenyang to Fushun, Dunhua, and Mishan, ultimately reaching into the Russian Far East while intersecting with the Mudanjiang Fault [78] (Figure 1(6)). These faults, including the DMF, have undergone significant strike–slip movement [77,79]. Geological evidence indicates a 170 km sinistral displacement along the DMF fault [80], which has played a key role in shaping the landscape of NE Asia.

3. Structural Observations of the Heilongjiang Complex

The deformation in the Jiamusi Block is characterized by its intensity and complexity, often manifested as schistosity, cleavages, folds, and faults [54]. This study primarily aims to analyze representative structural sections within the HLC, with the distribution of sampling points illustrated in Figure 2.

3.1. Field Characteristics

The outcrop DB040 ($44^{\circ}33'35.50''$ N, $129^{\circ}52'5.28''$ E, H: 318 m) is located in the southern part of the Jiamusi Block, near Modaoshi Town, Mudanjiang City, Heilongjiang Province (Figure 2). The primary rock unit exposed at this section is the HLC, which comprises fine-grained two-mica schist (Figure 3A(a)), biotite granulite (Figure 3A(b)), and an intrusive dike that has weathered to a light-yellow color (Figure 3A(c)). Except for the intrusive dike, each rock unit exhibits significant deformation, characterized by pronounced schistosity, particularly in the fine-grained two-mica schist, which displays distinct black-and-white stripes (Figure 3A(1)). This schistosity indicates that tectonic stress has significantly influenced these rocks, resulting in intense structural transposition, manifested as the $S_1 // S_2$ (where the first-stage schistosity parallels the second stage). The recorded occurrences (dip direction/dip angle) include $355^{\circ} \angle 38^{\circ}$, $000^{\circ} \angle 35^{\circ}$, $005^{\circ} \angle 35^{\circ}$. These N-dipping schistosity indicates that the N–S-directed compression formed the second-stage deformation. Following these stages of deformation, the complex was intruded by a dike, which provide a temporal constraint on the end time of the second-stage tectonic event. Subsequently, another phase of the tectonic event occurred, forming a left-lateral transpressive fault with

an occurrence of $100^{\circ}/80^{\circ}$. This fault cuts through the dike (Figure 3A(2)), indicating that it developed after the dike intrusion.

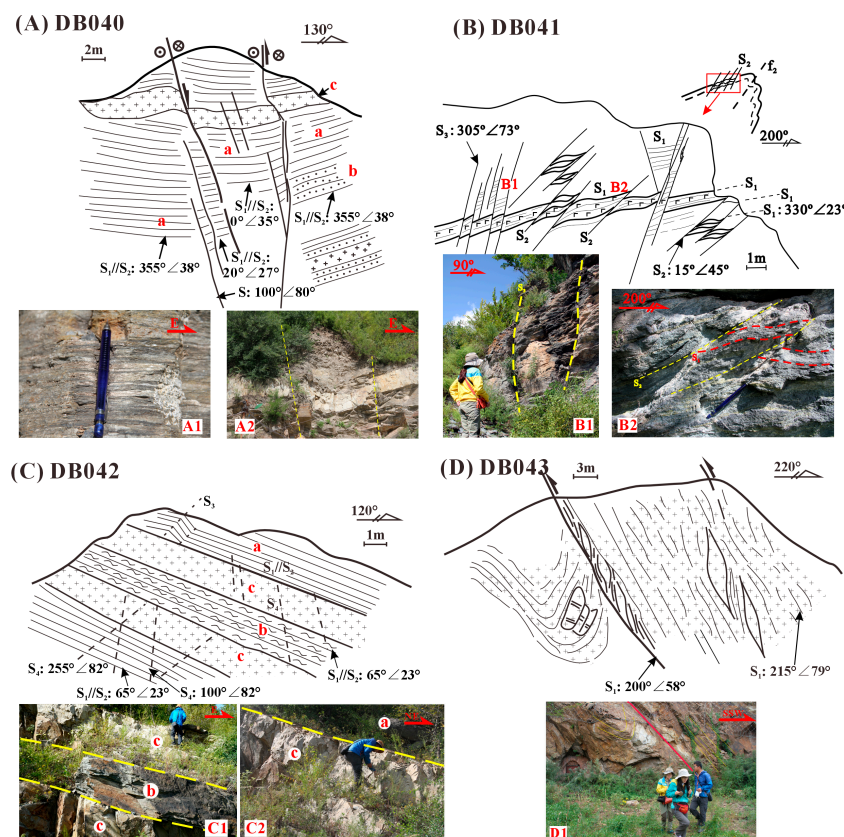


Figure 3. Sketch maps and field photographs of the outcrops DB040 (A), DB041 (B), DB042 (C), and DB043 (D). (A1), black-and-white stripes; (A2), left-lateral transpressive faults and an intrusive dike; (B1), cleavage S_3 ; (B2), schistosity S_1 and cleavage S_2 ; (C1), greyish-green epidote-chlorite schist and off-white aplite dikes; (C2), blue-black blueschist and off-white aplite dike; (D1), thrusting fault.

The outcrop DB041 ($44^{\circ}34'40.98''$ N, $129^{\circ}53'1.01''$ E, H: 398 m) is situated in the southern region of the Jiamusi Block, within Modaoshi Town (Figure 2). The predominant rock type exposed in this section is blueschist, characterized by the blue-grey hue and significant deformation. The original bedding, designated as S_0 , has become obscured, with three sets of schistosity or cleavage now observable.

The first set of schistosity S_1 intersects with the cleavage S_2 , as illustrated in Figure 3B(2). The second set of cleavage S_2 dips to the north, with a dip angle of 45° , representing the axial surface of the second-stage fold (see sketch in Figure 3B). This cleavage S_2 is located on the northern limb of an N-dipping overfold. S_2 has transformed earlier schistosity S_1 (Figure 3B(2)), and the overfold f_2 may be the product of an N-S-directed compression event.

Subsequently, schistosity set S_1 and cleavage set S_2 were cut by the cleavage formed during the third-period tectonic event (Figure 3B(1)). The third set of cleavage, S_3 , dips to the WNW with a dip angle of 73° . It can be inferred that the third tectonic event produced a near east-west compression.

The outcrop DB042 ($44^{\circ}35'4.62''$ N, $129^{\circ}55'49.73''$ E, H: 405 m) is located in the southern part of the Jiamusi Block, Shandi Village, Modaoshi Town (Figure 2). Three distinct rock types are identified in this outcrop: blue-black blueschist (Figure 3C(a)), greyish-green epidote-chlorite schist (Figure 3C(b)), and off-white aplite dikes (Figure 3C(c)). The blueschist and epidote-chlorite schist exhibit schistosity manifested as the S_1/S_2 . Subse-

quently, the area experienced a third phase of deformation, manifested as a kink structure in the schist, which was later intruded by the dike. Both the dikes and earlier schists were then affected by a later tectonic event, resulting in the formation of conjugate shear fractures S_4 , cutting through dikes. The occurrences of the fractures S_4 are $255^\circ \angle 82^\circ$ and $100^\circ \angle 82^\circ$. The direction indicated by the acute angle of the joint sets suggests that the principal stress direction is nearly north–south, indicating that the fourth tectonic event resulted in a near north–south compression. In addition, the age of the dike constrains the end time of the third-stage tectonic event.

The outcrop DB043 ($46^\circ 19' 39.71''$ N, $129^\circ 35' 2.84''$ E, H: 164 m) is situated in the northern region of the Jiamusi Block, east of Yilan County (Figure 2). This section mainly exposed banded biotite plagioclase gneiss, part of the Mashan Complex, interbedded with off-white marble lenses. A thrusting fault has developed in this area (Figure 3D(1)), with fault plane occurrences of $200^\circ \angle 58^\circ$, indicating an NNE-ward thrust under the north–south compression environment, representing the fourth deformation stage.

The outcrop DB044 ($46^\circ 22' 47.67''$ N, $129^\circ 41' 11.26''$ E, H: 119 m) is in the northern part of the Jiamusi Block, Yangjiaogou Village, Hongkeli Town, Yilan County (Figure 2). The exposed rock types include biotite felsic gneiss (Figure 4A(a)) and blueschist (Figure 4A(b)). These rocks show significant deformation, with pronounced schistosity resulting in intense structural transposition, manifested as the S_1 / S_2 with the occurrences of $355^\circ \angle 80^\circ$ and $348^\circ \angle 75^\circ$. The schistosity mainly dips to the north (Figure 4A(5)).

Remnants of folds from the second-stage deformation, labeled f_2 , can also be observed (Figure 4A(1,2)). Some f_2 folds exhibit plunging vertical structures (Figure 4A(1)), suggesting that they have experienced deformation after their formation. Additionally, box folds, representing the third-stage deformation (f_3), are developed (Figure 4A(4)).

Furthermore, a series of E–W-trending reverse faults cut through the rock, indicating the fourth-stage deformation in this region. The fault plane occurrence is $350^\circ \angle 62^\circ$, with visible drag structures (Figure 4A(3)).

The outcrop DB045 ($46^\circ 22' 59.01''$ N, $129^\circ 52' 25.00''$ E, H: 101 m) is in the northern part of the Jiamusi Block, Yongquan Village, Hongkeli Town (Figure 2). The main rock type is glaucophane aegirine-augite schists from the HLC, which has experienced varying degrees of deformation across different sections of this outcrop (Figure 4B). In areas of relatively weak deformation, the original structures are well-preserved, such as pillow structures (Figure 4B(4)) and amygdaloidal structures. In these weakly deformed zones, the rock exhibits an imbricate arrangement. It retains the early-stage deformation-induced schistosity S_1 , which predominately dips to the SE (130° , 135° , 145°), suggesting an NW-ward thrusting movement. This represents the first-stage deformation in the study area.

In the more intensely deformed sections, the intruding rock veins were affected by the second-stage deformation, along with the pre-existing schistosity S_1 , leading to the formation of fold f_2 . The southern limbs of overturned fold f_2 generally dip to the south (180°), while the hinge of some folds f_2 dips westward (255° , Figure 4B(1)). The f_2 fold exhibits a nearly E–W-striking tight fold, consistent with the overall structural pattern of the region. In the areas with more intense deformation, S_1 / S_2 and the subsequent cleavage, S_3 (Figure 4B(2)), indicate the third-stage deformation, confirming that the region has undergone at least three phases of tectonic events.

Furthermore, a nearby tuff outcrop has been identified, cut by an NNE-striking reverse fault with an orientation of $105^\circ \angle 67^\circ$. The blueschists are entirely thrust over the tuff, as depicted in Figure 4B(3), representing the fifth-stage deformation in the region. The age of the tuff provides a key constraint to define the onset of the fifth tectonic event in this region.

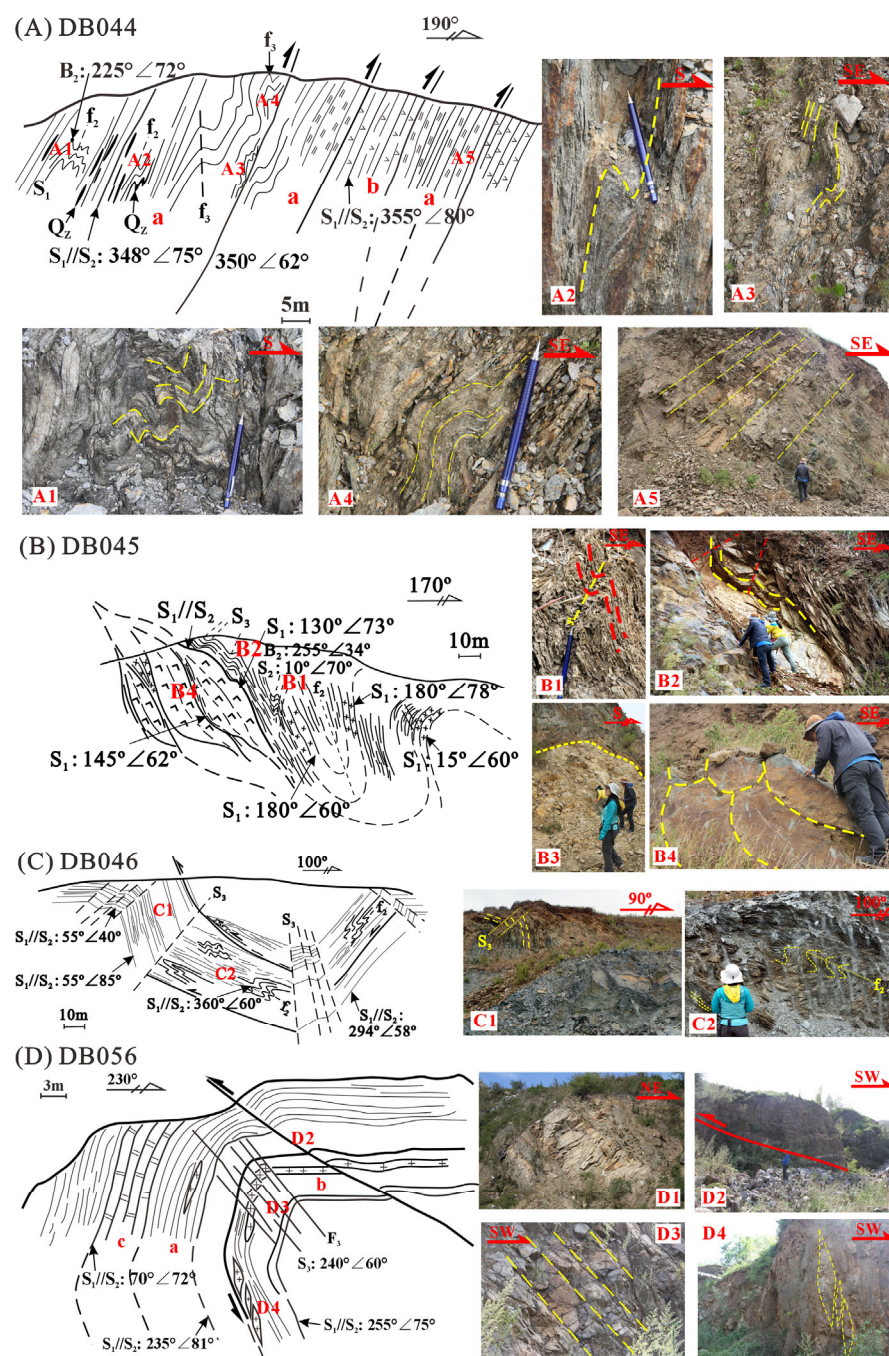


Figure 4. Sketch maps and field photographs the outcrops DB044 (A), DB045 (B), DB046 (C), and DB056 (D). (A1), plunging vertical structures; (A2), folds f_2 ; (A3), drag structures; (A4), folds f_3 ; (A5), S_1/S_2 ; (B1), folds f_2 ; (B2), cleavage S_3 ; (B3), blueschists over the tuff; (B4), pillow structures; (C1), the western limb of the box fold; (C2), the core of the box fold; (D1), banded biotite-plagioclase gneiss interbedded with off-white marble; (D2), reverse fault; (D3), cleavage, S_3 ; (D4), lenticular aplite.

The outcrop DB046 ($46^\circ 23' 3.01''$ N, $129^\circ 52' 50.37''$ E, H: 109 m) is located southeast of Yongquan Village in Hongkeli Town, in the northern part of the Jiamusi Block (Figure 2). The blueschist and greenschist of the HLC are visible here (Figure 4C), both exhibiting schistosity, manifested as S_1/S_2 (Figure 4C(1,2)). The entire profile is characterized by a large box fold, f_3 , which correlates with the third-stage deformation observed at DB044. In the core of fold f_3 , remnants of fold f_2 (Figure 4C(2)), related to the second-stage deformation, are present, with the axial cleavage of f_2 dipping northward (360°), indicating that this region has experienced N–S compression.

In the two limbs of the box fold, the schistosity S_1 / S_2 shows varying occurrences: the western limb towards the ENE (55°), while the eastern limb dips toward the WNW (294°). These variations indicate the third-stage compressional event in an E–W direction.

The outcrop DB056 ($45^\circ 14' 7.51''$ N, $130^\circ 49' 1' 3.62''$ E, H: 289 m) is situated in the central part of the Jiamusi Block, near the Liulin concentrating mill in Hengshan District, Jixi City (Figure 2). The primary rock type belongs to the Mashan Complex and consists of the banded biotite-plagioclase gneiss (Figure 4D(a)), interbedded with off-white marble (Figure 4D(c)) and aplitic dikes (Figure 4D(b)). These rocks exhibit significant deformation and well-preserved schistosity, manifesting as S_1 / S_2 , with occurrences of $70^\circ \angle 72^\circ$, $235^\circ \angle 81^\circ$, $255^\circ \angle 75^\circ$.

In addition, an axial cleavage, S_3 (Figure 4D(3)), which cuts through the earlier schistosity, can be seen, with an occurrence of $240^\circ \angle 60^\circ$. This cleavage S_3 represents the axial plane of fold f_3 , suggesting an NNW strike. The fold f_3 was subsequently cut by a later reverse fault (Figure 4D(2)), indicating another phase of the tectonic event.

3.2. Division of Deformation Stages

Through extensive observations and analysis, this study categorizes the sequence of deformation of the HLC into five stages:

1. SE-dipping schistoses characterize first-stage deformation. These features are well-preserved in the weakly deformed zones of the blueschist, as shown by the outcrop DB045, which belongs to the HLC.
2. Second-stage deformation formed tight folds with a near E–W strike, indicating a significant N–S-directed compressional stress.
3. Third-stage deformation is produced near S–N-striking box folds, formed under E–W compressional stress. These are evident in the structural patterns observed in several field outcrops.
4. Fourth-stage deformation is characterized by a series of near E–W-trending thrust faults, indicating compressional forces along a near S–N strike.
5. Fifth-stage deformation introduced a series of NNE-trending thrust faults. These faults exhibit a sinistral transpressional component at a local scale, suggesting complex tectonic interactions during this phase.

Each of these deformation stages reveals a distinct phase of a tectonic event, offering insights into the HLC's complex structural evolution.

4. Timing of Deformation

4.1. Petrography of Samples

Sample DB040-2 was collected from a dyke at outcrop DB040 (Figure 2), with its intrusive relationship to the host rocks illustrated in Figure 3A. The diabase dike (Figure 5A) is mainly composed of plagioclase (approximately 70% of the total rock content) and pyroxene (30%), exhibiting a gabbroic and ophitic texture (Figure 5B) and a massive structure. The plagioclase occurs as euhedral plate crystal, with grain sizes ranging from approximately 0.12–0.23 mm by 0.20–0.34 mm. Despite extensive alteration, the plagioclase retains its plate shape, having been replaced by zoisite. The pyroxene appears as subhedral columnar crystals, which, due to intense alteration, have largely transformed into chlorite. In addition to the early zoisitization of plagioclase and chloritization of pyroxene, the rock underwent later-stage silicification, resulting in cryptocrystalline silica.

Sample DB042-1 was collected from a dyke at outcrop DB042 (Figure 2), which demonstrates an intrusive relationship with the host rocks, as shown in Figure 3C. The hornblende aplite dike (Figure 5C) features an aplitic texture and a massive structure. The rock is mainly composed of feldspar (65%) and quartz (20%), with a small amount of mica (8%), horn-

blende (5%), and dark, opaque minerals (Figure 5D). The predominantly microcline feldspar appears as hypidiomorphic granular grains with a wide range of grain sizes, from 0.1 to 0.6 mm. These feldspars have undergone significant clayization and sericitization. Quartz shows undulatory extinction and fractured edges, indicating that the rock underwent multiple stages of metamorphism. Biotite exhibits an irregular plate shape and undergoes chloritization. The hornblende undergoes chloritization. This mineralogical alteration suggests that the rock underwent significant post-intrusion metamorphic processes.

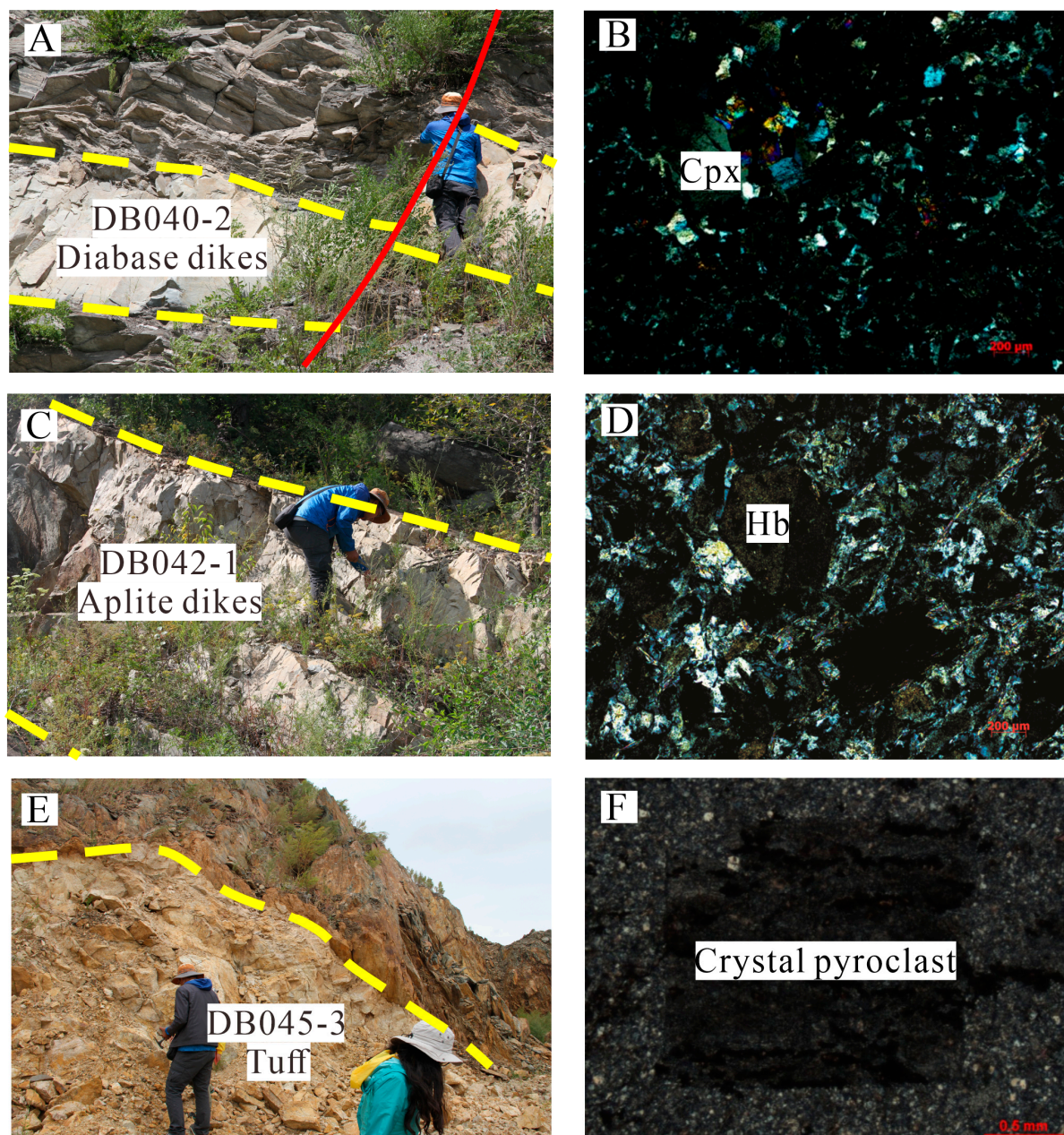


Figure 5. Field and Petrographic photographs of the samples: diabase dike DB040-2 (A,B), hornblende aplite dike DB042-1 (C,D), and rhyolitic crystal-vitric tuff DB045-3 (E,F). Abbreviations: Cpx, clinopyroxene; Hb, hornblende.

Sample DB045-3 was collected from the tuff layer at outcrop DB045 (Figure 2), which reveals a fault contact relationship as illustrated in Figure 5E. The rhyolitic crystal-vitric tuff has a porphyritic texture, with phenocrysts consisting of alkali feldspar (30%) and quartz (10%). The matrix mainly comprises cryptocrystalline feldspar, quartz, and mica, with

grain sizes less than 0.08 mm, contributing approximately 55% of the total rock content (Figure 5F). The rock exhibits a massive structure.

The feldspar phenocrysts are euhedral or subhedral plates in shape with irregular cracks, and their grain size ranges from 1.03 to 4 mm. It exhibits strong clayization and epidotization. The mineral grain size shown in Figure 5F is $0.17 \times 1.59 \text{ mm}^2$, with a wide variation in overall grain size within the sample. Quartz phenocrysts are xenomorphic and range in diameter from 0.8 to 2 mm. Their surfaces are relatively clean, but the edges are often eroded, creating bay-like boundaries. Post-deposition, the rock experienced low-temperature hydrothermal alteration processes, such as clayization and silicification. The matrix has mostly been altered into carbonate, clay minerals, and opaque metal minerals, reflecting significant secondary alteration after the initial formation.

4.2. Zircons U-Pb Dating

4.2.1. Analytical Methods

The monomineral separation and target preparation for zircon grains, as well as their imaging through transmission and reflection photography and cathodoluminescence (CL) photomicrography, were carried out at Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd, Nanjing, China. The samples were first subjected to crushing, sieving, heavy liquid extraction, and magnetic separation before being mounted in epoxy and polished to expose the grain centers. CL images were captured using a TESCAN scanning electron microscope to visualize the internal structures of the zircon grains. A Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) was utilized at the State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University for in situ zircon U-Pb dating. The laser sampling was performed with a GeoLas 200 M, while ion-signal intensities were acquired using an Agilent 7500a ICP-MS instrument. Zircon standard 91,500 and NIST610 glass served as external standards, and the laser ablation crater had a diameter of 32 μm . The analyzed data were processed using Glitter 4.0 software with ^{29}Si as the internal standard for correcting trace elements in zircon. Zircon U-Pb concordia and weighted mean age diagrams, and kernel density estimates were completed using the IsoplotR 3.3 software [81]. The correction method for the composition of common lead is described in Andersen [82].

4.2.2. Zircon U-Pb Geochronology

The zircon U-Pb dating results for the collected samples, including the diabase dike (DB040-2), hornblende aplite dike (DB042-1), and rhyolitic crystal-vitric tuff (DB045-3), are compiled in Table 1.

Zircons in sample DB040-2 are predominantly colorless, transparent, and euhedral to subhedral columnar crystals. Many grains are fragmented, and some exhibit alteration along their edges. The zircons display distinct oscillatory growth zoning, with length-to-width ratios ranging from 1.2 to 2 and lengths of 50–120 μm . Analyses of 21 zircon grains yielded Th/U ratios of 0.30–1.38, consistent with magmatic zircon characteristics. The $^{206}\text{Pb}/^{238}\text{U}$ ages of these zircons are widely dispersed, ranging from 157 to 526 Ma (Figure 6a). Kernel density estimates (Figure 6b) reveal four main peaks at 160 Ma, 180 Ma, 260 Ma, and 490 Ma. These ages do not conform to typical intrusive rock ages. The ages distribution includes characteristic components of the Heilongjiang Complex, indicating that the protolith captured zircon age information from the Mashan Complex (with a peak age of ~500 Ma), Late Permian to Early Triassic granitic rocks around the Jiamusi Block (with a peak age of ~250 Ma), and orogenic granitic rocks of the Jiamusi Block (with a peak age of ~185 Ma) [4]. The youngest single age component (see the blue box in Figure 6a,b), approximately 160 Ma, is interpreted as the crystallization age of the diabase intrusion.

Table 1. LA-ICP-MS zircon U-Pb dating results for the selected samples in the Jiamusi Block.

Sample Spot	Th/U	Concentration (ppm)			Isotopic Ratios						Age (Ma)						Concordance
		Pb	Th	U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	
DB040-2-1	0.30	15.4	87.4	289.2	0.0523	0.0007	0.3078	0.0037	0.0428	0.0009	296	28.1	273	2.9	270	5.2	0.99
DB040-2-2	0.72	20.8	265.3	370.3	0.0525	0.0009	0.2752	0.0044	0.0381	0.0008	306	37.3	247	3.5	241	4.8	0.98
DB040-2-3	0.49	32.5	157.3	319.8	0.0568	0.0007	0.6055	0.0069	0.0774	0.0015	484	25.8	481	4.4	480	9.1	1.00
DB040-2-4	0.79	18.3	150.6	191.6	0.0552	0.0009	0.4964	0.0077	0.0653	0.0013	420	35.2	409	5.2	408	7.9	1.00
DB040-2-5	0.33	24.9	162.5	487.2	0.0518	0.0007	0.2928	0.0039	0.0410	0.0008	277	31.2	261	3.1	259	5.1	0.99
DB040-2-6	0.43	12.6	125.4	292.1	0.0510	0.0018	0.2365	0.0079	0.0337	0.0008	242	78.5	216	6.5	213	4.7	0.99
DB040-2-7	0.52	9.5	130.7	249.0	0.0500	0.0010	0.1955	0.0036	0.0284	0.0006	196	43.8	181	3.1	180	3.6	0.99
DB040-2-8	0.30	10.3	83.6	274.5	0.0504	0.0010	0.1897	0.0037	0.0273	0.0006	213	46.6	176	3.2	174	3.5	0.99
DB040-2-9	0.57	34.9	179.8	314.6	0.0573	0.0007	0.6307	0.0073	0.0800	0.0016	501	26.2	497	4.6	496	9.4	1.00
DB040-2-10	0.58	15.7	213.1	370.7	0.0510	0.0008	0.2159	0.0033	0.0307	0.0006	240	35.6	199	2.7	195	3.9	0.98
DB040-2-11	0.56	27.9	352.6	632.4	0.0514	0.0007	0.2190	0.0029	0.0309	0.0006	257	31.4	201	2.4	196	3.9	0.98
DB040-2-12	0.73	20.3	340.5	467.0	0.0509	0.0010	0.1961	0.0037	0.0280	0.0006	237	44.5	182	3.1	178	3.6	0.98
DB040-2-13	0.52	35.5	174.6	339.0	0.0585	0.0007	0.6852	0.0080	0.0850	0.0017	549	25.9	530	4.8	526	10.0	0.99
DB040-2-14	0.76	34.9	594.0	786.5	0.0506	0.0006	0.2274	0.0025	0.0326	0.0006	221	25.5	208	2.0	207	4.0	1.00
DB040-2-15	0.50	7.2	102.6	203.9	0.0502	0.0009	0.2101	0.0035	0.0304	0.0006	203	39.1	194	2.9	193	3.8	1.00
DB040-2-16	1.38	22.2	794.7	574.6	0.0503	0.0007	0.1703	0.0023	0.0246	0.0005	211	31.7	160	2.0	156	3.1	0.98
DB040-2-17	0.54	24.5	353.3	650.5	0.0507	0.0006	0.1955	0.0024	0.0280	0.0006	227	28.3	181	2.0	178	3.5	0.98
DB040-2-18	0.45	27.2	354.7	791.5	0.0502	0.0006	0.1877	0.0021	0.0272	0.0005	202	26.8	175	1.8	173	3.4	0.99
DB040-2-19	0.69	13.5	274.5	400.0	0.0501	0.0008	0.1705	0.0025	0.0247	0.0005	198	35	160	2.2	157	3.1	0.98
DB040-2-20	0.76	7.3	99.8	130.6	0.0526	0.0009	0.2861	0.0045	0.0395	0.0008	313	36.2	256	3.5	250	4.9	0.98
DB040-2-21	0.83	8.9	177.5	214.2	0.0504	0.0009	0.2108	0.0035	0.0303	0.0006	215	39.0	194	2.9	193	3.8	0.99
DB042-1-1	0.34	9.8	120.0	349.5	0.0509	0.0012	0.1320	0.0031	0.0188	0.0004	235	54.7	126	2.7	120	2.5	0.96
DB042-1-2	0.76	20.9	588.9	773.4	0.0508	0.0008	0.1342	0.0020	0.0192	0.0004	232	35.0	128	1.8	122	2.4	0.96
DB042-1-3	0.14	5.3	31.6	229.5	0.0491	0.0010	0.1443	0.0028	0.0213	0.0004	153	46.0	137	2.5	136	2.7	0.99
DB042-1-4	0.12	34.9	214.9	1746.4	0.0487	0.0006	0.1188	0.0013	0.0177	0.0004	131	26.7	114	1.2	113	2.2	0.99
DB042-1-5	0.78	11.5	333.9	427.0	0.0490	0.0008	0.1311	0.0020	0.0194	0.0004	148	36.2	125	1.8	124	2.5	0.99
DB042-1-6	0.35	17.9	260.9	745.2	0.0505	0.0007	0.1461	0.0020	0.0210	0.0004	217	33.1	139	1.8	134	2.7	0.97
DB042-1-7	0.16	11.0	78.5	481.3	0.0485	0.0008	0.1253	0.0019	0.0187	0.0004	124	36.9	120	1.7	120	2.4	1.00
DB042-1-8	0.51	15.6	320.8	632.9	0.0489	0.0007	0.1287	0.0017	0.0191	0.0004	143	30.7	123	1.5	122	2.4	0.99
DB042-1-9	0.83	10.1	293.6	354.8	0.0496	0.0011	0.1377	0.0030	0.0201	0.0004	178	51.3	131	2.6	129	2.6	0.98
DB042-1-10	0.08	18.1	69.0	856.5	0.0505	0.0006	0.1286	0.0016	0.0185	0.0004	218	29.0	123	1.4	118	2.3	0.96
DB042-1-11	0.76	4.9	143.7	190.1	0.0498	0.0009	0.1327	0.0023	0.0194	0.0004	185	41.7	127	2.1	124	2.5	0.98
DB042-1-12	1.64	18.2	850.0	517.9	0.0490	0.0008	0.1222	0.0020	0.0181	0.0004	149	39.1	117	1.8	116	2.3	0.99
DB042-1-13	0.19	9.9	86.4	445.5	0.0493	0.0007	0.1291	0.0017	0.0190	0.0004	162	31.9	123	1.6	121	2.4	0.98
DB042-1-14	0.18	5.3	41.8	232.5	0.0484	0.0013	0.1186	0.0031	0.0178	0.0004	119	62.6	114	2.8	114	2.4	1.00
DB042-1-15	0.45	14.3	250.9	559.7	0.0499	0.0006	0.1397	0.0017	0.0203	0.0004	192	28.8	133	1.5	130	2.6	0.98
DB042-1-16	0.24	8.7	75.6	317.9	0.0514	0.0007	0.1440	0.0019	0.0203	0.0004	259	30.7	137	1.7	130	2.6	0.95
DB042-1-17	1.39	18.4	831.7	599.8	0.0486	0.0006	0.1345	0.0017	0.0201	0.0004	131	30.7	128	1.5	128	2.5	1.00
DB042-1-18	0.09	7.8	24.8	277.9	0.0497	0.0008	0.1380	0.0021	0.0202	0.0004	179	36.2	131	1.9	129	2.6	0.98
DB042-1-19	1.14	7.5	295.7	259.8	0.0488	0.0008	0.1315	0.0021	0.0196	0.0004	137	37.6	126	1.9	125	2.5	1.00
DB045-3-1	0.46	12.1	253.1	549.3	0.0490	0.0007	0.1121	0.0016	0.0166	0.0003	147	33.1	108	1.4	106	2.1	0.98
DB045-3-2	0.40	13.6	267.8	664.1	0.0494	0.0007	0.1120	0.0015	0.0164	0.0003	168	31.3	108	1.3	105	2.1	0.97
DB045-3-3	0.67	18.6	589.3	884.6	0.0485	0.0010	0.1003	0.0020	0.0150	0.0003	123	48.9	97	1.9	96	2.0	0.99
DB045-3-4	0.80	14.0	517.4	642.8	0.0510	0.0007	0.1145	0.0015	0.0163	0.0003	241	30.7	110	1.4	104	2.1	0.95
DB045-3-5	0.55	9.6	243.7	441.7	0.0485	0.0007	0.1103	0.0016	0.0165	0.0003	122	34.8	106	1.5	106	2.1	0.99
DB045-3-6	0.61	22.9	609.8	1006.8	0.0491	0.0007	0.1118	0.0015	0.0165	0.0003	153	32.5	108	1.4	106	2.1	0.98
DB045-3-7	0.56	14.3	392.9	696.5	0.0481	0.0009	0.1069	0.0018	0.0161	0.0003	105	41.1	103	1.7	103	2.1	1.00
DB045-3-8	0.54	16.7	448.2	825.5	0.0481	0.0007	0.1056	0.0014	0.0159	0.0003	103	31.7	102	1.3	102	2.0	1.00
DB045-3-9	0.46	14.3	319.9	702.4	0.0496	0.0007	0.1141	0.0015	0.0167	0.0003	178	31.6	110	1.4	107	2.1	0.97

Table 1. Cont.

Sample Spot	Th/U	Concentration (ppm)			Isotopic Ratios						Age (Ma)						Concordance
		Pb	Th	U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	
DB045-3-10	0.50	16.1	370.5	746.9	0.0494	0.0007	0.1149	0.0017	0.0169	0.0003	167	34.2	111	1.5	108	2.2	0.98
DB045-3-11	0.31	11.0	80.8	260.0	0.0523	0.0007	0.2773	0.0037	0.0385	0.0008	300	31.1	249	3.0	243	4.8	0.98
DB045-3-12	0.46	14.4	316.4	694.8	0.0482	0.0007	0.1105	0.0014	0.0166	0.0003	111	31.4	106	1.3	106	2.1	1.00
DB045-3-13	0.65	23.4	731.2	1130.1	0.0481	0.0008	0.1067	0.0016	0.0161	0.0003	104	36.8	103	1.5	103	2.1	1.00
DB045-3-14	0.51	15.2	271.8	536.5	0.0499	0.0008	0.1104	0.0018	0.0161	0.0003	188	38.9	106	1.7	103	2.1	0.97
DB045-3-15	0.42	14.4	302.0	714.0	0.0499	0.0007	0.1121	0.0015	0.0163	0.0003	191	31.2	108	1.4	104	2.1	0.97
DB045-3-16	0.46	19.9	84.8	183.6	0.0592	0.0007	0.7511	0.0090	0.0920	0.0018	575	26.4	569	5.2	567	10.9	1.00
DB045-3-17	0.54	12.7	255.3	468.6	0.0491	0.0007	0.1444	0.0019	0.0213	0.0004	152	31.1	137	1.7	136	2.7	0.99

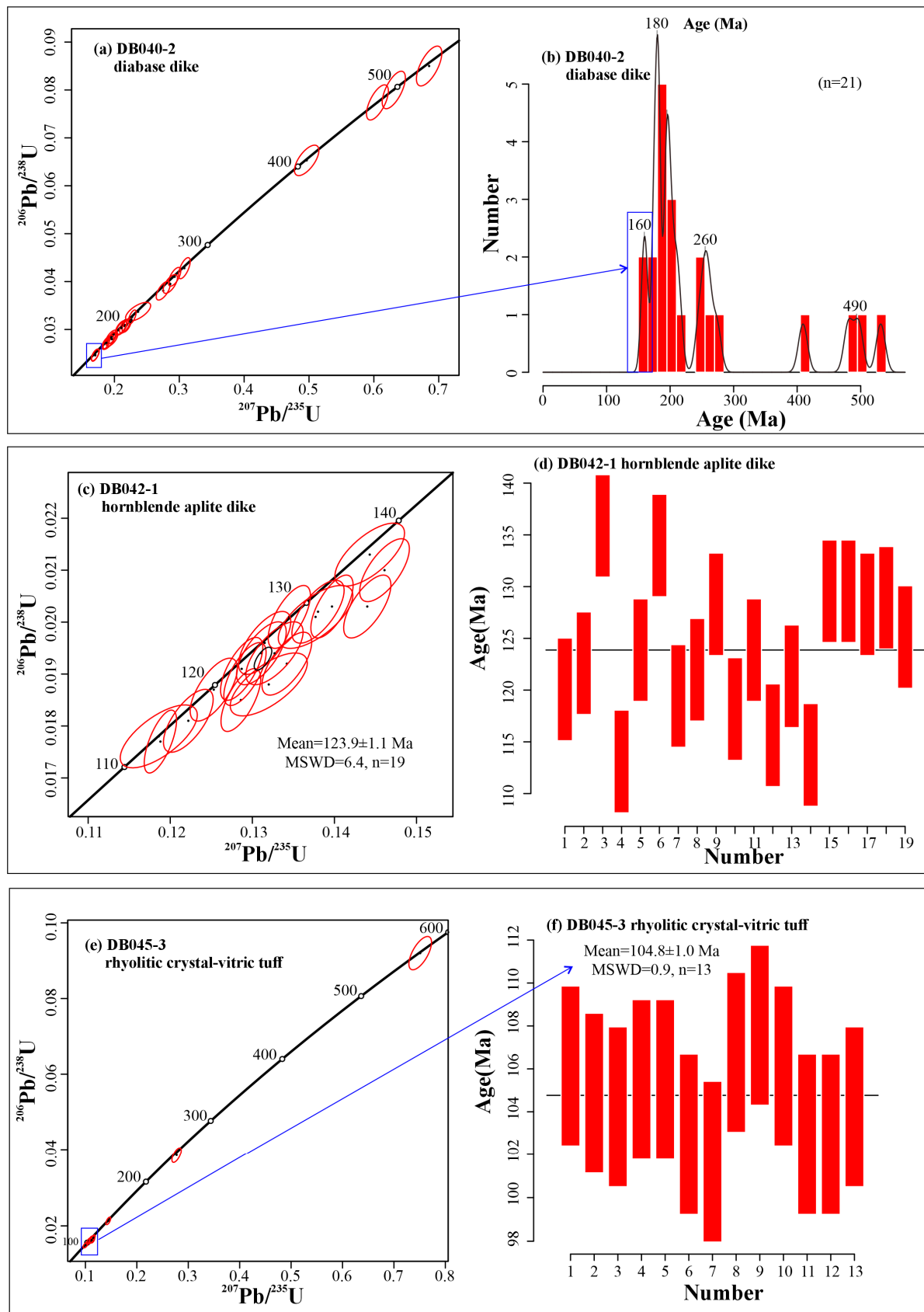


Figure 6. Zircon U–Pb concordia diagrams for the diabase dike (a), hornblende aplite dike (c), and rhyolitic crystal-vitric tuff (e); weighted mean age diagrams for the hornblende aplite dike (d) and rhyolitic crystal-vitric tuff (f); and kernel density estimate diagram for the diabase dike (b).

The zircons in sample DB042-1 are euhedral columnar crystals with length-to-width ratios of 2–5 and lengths of 100 μm . They exhibit well-developed oscillatory growth zoning, with relatively uniform interiors and narrow zoning at the margins. Analyses of 19 zircon grains yielded Th/U ratios of 0.08–1.64, consistent with magmatic zircon characteristics. 19 analyses of the zircon grains yield concordant or nearly concordant ages ranging from 113 Ma to 136 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 123.9 ± 1.1 Ma (MSWD = 6.4) (Figure 6c,d). We interpret this as the crystallization age of the hornblende aplite dike.

The zircons in the sample DB045-3 exhibit relatively good crystal forms, though some grains are fragmented. Grain sizes are variable, with most grains being prismatic and measuring 30–50 μm in length. Some can extend as long as 100 μm . Analyses of 17 zircon grains revealed well-developed oscillatory growth zoning in most cases. Th/U ratios range from 0.31 to 0.80, indicating magmatic zircon characteristics. The $^{206}\text{Pb}/^{238}\text{U}$ ages of 13 zircon grains are highly concentrated and young (see the blue box in Figure 6e), ranging from 96 Ma to 107 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 104.8 ± 1.0 Ma (MSWD = 0.9) (Figure 6f). This age is interpreted as the crystallization age of the rhyolitic crystal-vitric tuff.

4.3. Zircon $^{206}\text{Pb}/^{238}\text{U}$ Age Constraints for Deformation Stages

Using the zircon data mentioned earlier, along with zircon $^{206}\text{Pb}/^{238}\text{U}$ ages and the relationships among dikes, strata, and faults analyzed in this study, the period of the five stages of deformation in the HLC can be accurately determined.

The diabase dike (DB040-2) was emplaced at 160 Ma. The contact relationships illustrated in the outcrop DB040 profile (Figure 3A) indicate that the intrusion of this dike occurred after the second-stage deformation. Therefore, it can be inferred that the second-stage of deformation in the HLC took place before 160 Ma, which corresponds to the Late Jurassic period.

The hornblende aplite dike (DB042-1) formed in 123.9 ± 1.1 Ma. The contact relationship between the dike and the strata in the outcrop DB042 profile (Figure 3C) indicates that its emplacement occurred after the third-stage deformation in this area and was affected by the fourth-stage tectonic event. Therefore, the age of this dike indicates that the third-stage deformation occurred before 124 Ma, which falls within the Early Cretaceous, with the fourth-stage deformation occurring subsequently.

The rhyolitic crystal-vitric tuff (DB045-3) formed in 104.8 ± 1.0 Ma. The contact relationship between the tuff and the fault observed in the outcrop DB045 profile (Figure 5E) indicates that the fifth-stage tectonic deformation led to the thrusting of earlier metamorphic strata over the tuff. This suggests that the fifth-stage deformation occurred after 105 Ma.

Furthermore, previous studies on the blueschist in Jiamusi Block indicate that the protolith of the blueschist from HLC formed between 250 Ma and 210 Ma. In comparison, the metamorphic age ranges from 190 Ma to 180 Ma [40]. Therefore, this paper posits that the first phase of deformation occurred after the formation of the blueschist protolith, specifically during the interval of 210–180 Ma.

In summary, the HLC experienced five stages of deformation. The initial stage exhibited a schistosity dipping towards the southeast, which developed between 210 and 180 Ma (Late Triassic to Early Jurassic). The second stage was characterized by nearly E–W-striking tight folds, formed from 180 to 160 Ma (Early to Late Jurassic). The third stage displayed nearly S–N-striking box folds between 160 and 124 Ma (Late Jurassic to Early Cretaceous). The fourth stage revealed an almost E–W-trending thrust fault that emerged between 124 and 105 Ma (late Early Cretaceous). Finally, the fifth stage presented a set of NNE-trending thrust faults, with a sinistral transpressional component in some regions, forming after 105 Ma.

5. Discussion

5.1. Subduction Polarity of the Mudanjiang Oceanic Plate

Based on the structural analysis for the HLC of the Jiamusi Block in Section 3 of this paper, typical outcrops such as the DB045 profile show that the first phase of deformation is well preserved in the blueschist. In the foliated blueschist, residual protoliths, namely basic rock blocks, can be arranged in an imbricate form. These blocks are in contact with the schistosity S_1 . The occurrence of the S_1 generally dips to the southeast (130° , 135° , 145°), suggesting that the first phase of deformation was likely under the NW-ward thrust, indicating that the Mudanjiang Oceanic Plate (MDP) between the Jiamusi and the Songnen blocks might have undergone eastward subduction.

We also analyzed the seismic tomography images of the study area. As shown in the regional geological map (Figure 7A), the Mudanjiang Suture Zone extends approximately along the longitude of $E 130^\circ$. To investigate the characteristics of this suture zone at various depth, we selected four profiles: Profile A-A' ($N 47^\circ$, $E 125^\circ$ – $E 135^\circ$), Profile B-B' ($N 46^\circ$, $E 125^\circ$ – $E 135^\circ$), Profile C-C' ($N 45^\circ$, $E 125^\circ$ – $E 135^\circ$), and Profile D-D' ($N 44^\circ$, $E 125^\circ$ – $E 135^\circ$). The depth range of these profiles is set at 0 km–1000 km, focusing on specific depths of 200 km, 400 km, 600 km, and 800 km to analyze their planar structural characteristics.

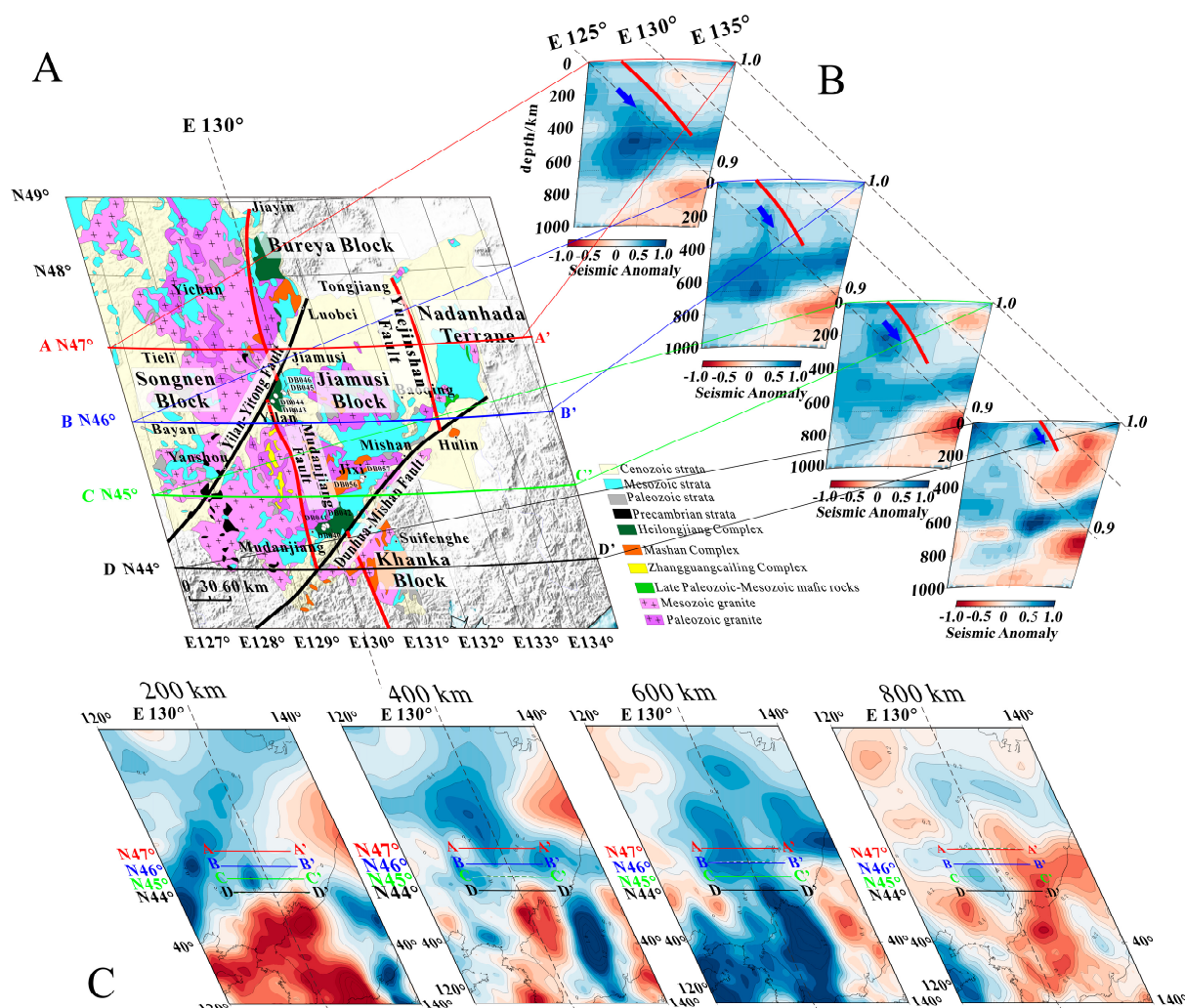


Figure 7. The tomographic images of the Mudanjiang Suture Zone (A), including cross-sectional images (B) along the lines A-A', B-B', C-C', and D-D', and planar images (C) at different depths of 200 km, 400 km, 600 km, and 800 km.

Figure 7 illustrates that blue color represents positive seismic velocity anomalies, typically linked to high-velocity bodies of cold, subducted oceanic crust materials. Conversely, red color signifies negative seismic velocity anomalies, indicating low-velocity bodies commonly associated with hot mantle material. The planar distribution maps of seismic anomaly values at different depths (Figure 7C) reveal that at a depth of 600 km beneath the Mudanjiang Suture Zone, the range of positive velocity anomaly values is the most extensive, accompanied by relatively high anomaly values. This suggests a significant presence of subducted oceanic crust in this region. Across different depth planes, the high-velocity anomalous bodies in the area where the profile is situated are distributed approximately in a north–south direction, indicating that the Mudanjiang subduction zone extends predominantly along this orientation.

In Figure 7B, profile A-A' (N 47°) traverses the northern part of the Mudanjiang Suture Zone. The west side generally exhibits positive velocity anomalies, and the high-velocity anomalous body on the west side dips to the east (marked by the red lines in Figure 7B), which might be the remnant oceanic lithosphere in the upper mantle, indicating that the eastward subduction of the now-vanished MOP. Meanwhile, the high-velocity anomalous body on the east side stays nearly horizontally at a depth ranging from 400 km to approximately 660 km, which may correspond to the Paleo-Pacific Plate (PPP) or Pacific Plate that underwent westward subduction.

Profiles B-B', C-C', and D-D' are similar to profiles A-A', where the subducted oceanic lithosphere remaining in the upper mantle can be identified. On the eastern side, the high-velocity anomalous body dips to the west, indicating that the PPP or Pacific Plate is subducted from east to west and remains in this region. Conversely, the high-velocity anomalous body on the west side dipping to the east (marked by the red lines) indicates the eastward subduction and disappearance of the MDP.

Furthermore, the geochemical analysis for the gabbro from the Taiping intrusion in the Jiamusi Block suggests a correlation with the eastward subduction of the MDP [47]. Additionally, the development of gneissic granodiorite within the Jiamusi Block exhibits I-type granite characteristics, indicating that its magma source is derived from a subducted slab [17,83]. This may be associated with the eastward subduction of the MDP beneath the Jiamusi Block.

5.2. Evolution of the Heilongjiang Complex

The evolution history of the HLC is summarized below based on the structural analysis and zircon U-Pb geochronology data presented in this study.

From the Late Triassic to the Early Jurassic (210–180 Ma), the MDP, located between the Songnen Block and the Jiamusi Block, underwent eastward subduction. During this process, first-stage deformation of the HLC in the Jiamusi Block occurred, characterized by schistosity dipping to the southeast. Furthermore, the dating evidence of blueschists in the HLC reveals that the metamorphic age in the southern Mudanjiang region is older [40], while that in the northern Yilan region is relatively younger [44,84]. It is hypothesized that the south part of the Mudanjiang Ocean might have closed earlier, leading to an initial collage of the southwestern part of the Jiamusi Block onto the Songnen Block first, resulting in a scissors-like closure.

During the period from the Early Jurassic to the Late Jurassic (180–160 Ma), the subduction of the MDP was completed. Concurrently, the Mongol–Okhotsk Oceanic Plate in the north was subducting towards the SSE [85], while the PPP was moving northward [86]. Consequently, the Jiamusi region was under a strong compressive environment in a near north–south direction. This led to the second deformation phase in the HLC, manifested

as nearly E–W-striking tight folds. Similar structural features can also be observed in the Yuejinshan Complex [15], located east of the Jiamusi Block.

Subsequently, from the Late Jurassic to the early stage of the Early Cretaceous (160–124 Ma), during the westward subduction of the PPP, the Jiamusi Block was completely combined with the Songnen Block to the west and the Nadanhada Terrane to the east. Consequently, this led to forming the third phase near N–S-striking box folds in the HLC.

In the late stage of the Early Cretaceous (124–105 Ma), with the closure of the easternmost section of the Mongol–Okhotsk Ocean [87], this region was under north–south compression, leading to a nearly E–W-trending reverse fault, which represented the fourth phase of deformation of the HLC.

After the late stage of the Early Cretaceous (105 Ma), the HLC underwent the fifth-stage tectonic event due to the NW-ward subduction of the PPP, resulting in a series of nearly NE-trending reverse faults.

6. Conclusions

In the areas HLC exposed on the Jiamusi Block, five distinct phases of deformation occurred during the Mesozoic, characterized as follows:

1. The presence of SE-dipping schistosity in the Late Triassic to Early Jurassic indicates the eastward subduction of the MDP.
2. In the Early to Late Jurassic, near E–W-trending tight folds developed, associated with the SSE-ward subduction of the Mongol–Okhotsk Oceanic Plate and the NNW-ward subduction of the PPP.
3. Near N–S-trending box folds formed in the Late Jurassic to early Early Cretaceous, indicating the final amalgamation between the Jiamusi Block and the Songnen Block in the west and the Nadanhada Terrane in the east.
4. During the late Early Cretaceous, near E–W-trending, reverse faults developed, linked to the final closure process involving the Mongol–Okhotsk Ocean.
5. After the Early Cretaceous, nearly NE-trending reverse faults appeared, corresponding to the NW-ward subduction of the PPP.

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