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Crustal-upper mantle velocity structure from the North Qilian Shan to Beishan Block Beishan Orogenic Collage: and the tectonic significance of the crustal deformation

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Abstract The Qilian Shan constitutes represents a Cenozoic fold-thrust belt characterized by multi-stage tectonic deformation since the Paleozoic. North of it lies the The Hexi corridor basins and the Beishan Block orogenic belt, which constitute, located north of the Qilian Shan, are the southern segment of the Central Asian Orogenic Belt. The crustal-mantle structure of the study area, serves as a transition zone, is crucial for comprehending to understanding the deep processes of accretion and crustal deformation. This study introduces presents a newly acquired 460-km seismic wide-angle reflection and refraction profile spanning traversing from the North Qilian Shan to the Beishan Block Beishan Orogenic Collage (BOC). The P-wave velocity structure of the crust and upper mantle indicates reveals a 47.5–60 km thick crust crustal thickness between 47.5 km and 60 km, segmented divided into five stratalayers. The deepest Moho (60 km) lies beneath the central Jiuquan basin displays the most substantial crust, measuring 59.5–60 km in thickness. The Average crustal velocities (6.24–6.43 km s⁻¹) varies between 6.24 and 6.43 km/s, while the and Pn values velocity (ranges from 7.7 km/s to 8.1 km/s km s⁻¹) reveal strong lateral. The considerable variance in crustal velocity indicates heterogeneity. North-dipping velocity contours from 20 km to the uppermost mantle beneath the Qilian Shan, coupled with a lower-crust-upper-mantle low-velocity corridor beneath the Hexi Basin, support early Paleozoic north-dipping subduction of the Qilian Ocean. A positive upper-mantle anomaly (8.0–8.3 km s⁻¹, 45–70 km depth) aligns with the Hongliuhe–Xichangjiang ophiolite mélangé likely represents a fossil break-off slab broken off after north-dipping subduction of the Beishan Ocean. Crustal velocity contrasts across the southern margin fault of the Beishan affirm its role as a regional strike-slip structure. Integrating geological and geophysical evidence, we suggest that the Altyn Tagh Fault does not terminate at the Qilian Shan front but rather extends east-northeast along the southern margin of the BOC into the Beishan and Alxa Block.

in the crustal composition of the Qilian Shan and Beishan block. The southern edge fault of the Beishan block delineates the area, where northward and southward thrusting induces upper crustal deformation on opposing sides. The crust of the southern Beishan block is weaker than that of the bordering regions. Additionally, we propose a north-direction subduction polarity of the Qilian Ocean based on the northward-tilted velocity contour in Paleozoic.

Keywords: North Qilian; Beishan Block Beishan Orogenic Collage; Altyn Tagh fault; Crustal-upper mantle velocity structure; crustal deformation

The NW-SE-trending Qilian Shan, situated in the NE Tibet, is bounded by the Altyn Tagh fault (ATF) to the west, the northern Qaidam thrust system to the south, the Haiyuan fault to the east, and the north Qilian Shan fault to the north (Fig. 1b). The present-day Qilian Shan exhibits a Cenozoic fold-thrust belt with enduring multi-stage tectonic deformation prior to the Cenozoic (Yin and

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Harrison 2000; Gehrels et al. 2003; Song et al. 2014; Wu et al. 2016; Zuza et al. 2017; 2019). The Qilian Shan exhibits a Cenozoic fold-thrust belt with multi-stage tectonic deformation since Paleozoic. North of the Qilian Shan, the Hexi corridor basins and the Beishan block Beishan Orogenic Collage (BOC) form the southern section of the Central Asian Orogenic Belt (CAOB, Xiao et al., 2010; Li et al., 2023; Xiong et al., 2024). As the middle of the South Tianshan-Beishan-Solonker suture zone, the BOC underwent multi-stage breakup, subduction, collision, and amalgamation during the closure of the Paleo-Asian Ocean (PAO) AO, mainly in the Paleozoic (Fig. 1; Zuo et al. 1991; Liu 1995; Yue and Liou 1999; Wang et al. 2010; Xiao et al. 2010; Zuo and Li 2011; Şengör 2015; Liu 1995; Yuan et al. 2015; He et al. 2018; Li et al. 2023). The geological history of the BOC is further complicated by regional extension, subsequent intracontinental overthrusting, and strike-slip faulting since Mesozoic (Zheng et al. 1996; Meng et al., 2003; Xiao et al. 2010; Zuo and Li 2011; Zhang and Cunningham 2012; Li et al. 2023). is inside the middle of the South Tianshan-Beishan-Solonker suture zone (Fig. 1b). Particularly in the Cenozoic, the far-field effect of the Indian-Eurasian collision led to the outward expansion of the NE Tibetan Plateau, and reactivated the Qilian Shan, causing stress to propagate across the Hexi corridor basins into the BOC, and extending even further north to the Mongolian Plateau (Cunningham 2013; Zheng et al. 2017; Wang et al. 2022).

The Qilian Shan is become an important part of the Tibetan plateau, playing a significant role in accommodating researching the intracontinental convergence, thrusting-folding and the northern extension of The NE Tibetan Plateau (Meyer et al. 1998; Yuan et al. 2013; Zuza et al. 2017). As the southernmost CAOB, the BOC acted as a major zone area for examining the for the reactivation of inherited structures the ancient crust during and the transmission of compressional stress leading to the uplift outward exhumation of the NE Tibetan and the Mongolian Plateaus in Cenozoic. Therefore, acting as a the transition zone between the NE Tibetan Plateau and CAOB, the crustal-mantle structure of the studied study area is crucial for comprehending understanding the regional evolution and interaction of including the Qilian Shan and Beishan block operates as the contact zone between the northeastern Tibetan plateau Tibetan Plateau, (NE-Tibet) and the southern CAOB. This region acts as the transition zone between part of the Tethys tectonic domain, and the Paleo-Asian ocean PAO ie (PAO) tectonic domain (PAO) since the Paleozoic (Fig. 1a; Li et al. 1982; Yin and Harrison 2000; Xiao et al. 2009; Zhao et al. 2018; He et al., 2025; Xiong et al., 2025).

Previous geophysical studies across the Qilian Shan–BOC transition zone, have provided valuable insights into the subduction polarity, continental extension, lithospheric foundering and magmatic activity (Xiao et al. 2012; Huang et al. 2014; Wei et al. 2017; Xu et al. 2019; Shen et al. 2020; Huang et al. 2021; Wang et al., 2023; Xiong et al., 2024; Yang et al. 2024). Nevertheless, the crustal-upper mantle velocity structure remains ambiguous because of the wide shot and receiver spacing and the relatively weak explosive sources inherited from the earlier, lower-resolution acquisition design (Cui et al., 1995). In this study, we present a 460-km-long, SW-NE-trending wide-angle reflection and refraction profile that traverses the North Qilian Shan, Hexi corridor (containing the Jiuquan basin and the Huahai basin), and the entire BOC. The new data yield a high-quality crustal-upper mantle velocity structure of the study area. Combined with existing geological and geophysical evidence, we discuss the tectonic significance of the transition zone, provide new constraints of the subduction polarity of the Qilian Ocean and the southern PAO, elucidate the crustal deformation mechanism across main regional faults, and propose the eastern termination and extension of the ATF. The NW-SE-trending Qilian Shan, situated in NE-Tibet, is bordered by the Altyn Tagh fault to the west, the northern Qaidam thrust system to the south, the Haiyuan fault to the east, and the north Qilian Shan fault to the north (Figure 1b). The present-day Qilian Shan has witnessed Cenozoic reactivation as a fold-thrust belt (Zuza et al. 2017, 2019), enduring multi-stage tectonic deformation prior to the Cenozoic (Yin and Harrison 2000; Gehrels et al. 2003; Song et al. 2014; Wu et al. 2016; Zuza et al. 2017). The Beishan block, sometimes referred to as the Beishan orogenic belt (Liu 1995; Yuan et al. 2015; He et al. 2018; Li et al. 2023), is inside the middle of the South Tianshan-Beishan-Solonker suture zone (Fig. 1b). Experiencing multi-stage breakup, subduction, collision, and amalgamation during the closure of the PAO, mainly in the Paleozoic (Fig. 1; Zuo et al. 1991; Yue and Liou 1999; Wang et al. 2010; Xiao et al. 2010; Zuo and Li 2011; Şengör 2015), the geological history of the Beishan block is further complicated by regional extension overlap, subsequent intracontinental overthrusting, and strike-slip faulting since Mesozoic (Zheng et al. 1996; Xiao et al. 2010; Zuo and Li 2011; Zhang and Cunningham 2012; Li et al. 2023). The NE-trending grabens in the Gobi Altai, southeastern Mongolia and Beishan forms

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a rift system, associated with the termination of the final subduction of the PAO (Meng 2003; Donskaya et al. 2008; Cunningham et al. 2009; Davis and Darby 2010) or the Cenozoic Indian-Eurasian collision (Zhang et al. 2007, 2021; Buslov 2012). This study proposes a new-acquired 460-km-long seismic wide angle and refraction profile encompassing the North Qilian Shan to Beishan block. The crustal upper mantle P-wave velocity structure reveals the crustal thickness ranging from 47.5 to 60 km, divided into five layers. The central Jiuquan basin has the thickest crust at 59.5–60 km. Average crustal velocity ranges from 6.24 to 6.43 km/s, and Pn velocity of 7.7–8.1 km/s. Notably, the considerable variance in crustal velocity shows inhomogeneity non the crustal composition of the Qilian Shan and Beishan block. Bounded by the southern edge fault of the Beishan block, north direction and south direction thrusting contribute to upper crustal deformation to separate sides. The crust of the southern Beishan block is weaker than that of the bordering regions. Additionally, we propose a north direction subduction polarity of the Qilian Ocean based on the northward-tilted velocity contour in Paleozoic.

In Cenozoic, the far-field effect of the Indian-Eurasian collision led to the outward expansion of NE Tibet, spreading across the Hexi corridor basins into the Beishan block or the Mongolian Altai Mountains (Mts.) (Cunningham 2013; Zheng et al. 2017; Wang et al. 2022). The reactivated Qilian Shan finally became an important part of the Tibet plateau, playing a significant role in researching the intracontinental convergence, thrusting-folding and the northern extension of NE Tibet (Meyer et al. 1998; Yuan et al. 2013; Zuza et al. 2017). As the southernmost CAOB, the Beishan block also served as a major place for examining the reactivation of the ancient crust and the transmission of compressional stress arising from the outward exhumation of NE Tibet and the Mongolian plateau in Cenozoic.

While previous geophysical studies have been conducted in the Qilian Shan–Beishan block transition zone to comprehend the subduction polarity, continental extension, foundering and magmatic activities (Xiao et al. 2012; HUANG et al. 2014; Wei et al. 2017; Xu et al. 2019; Shen et al. 2020; Huang et al. 2021; Yang et al. 2024), the crustal upper mantle structure remains ambiguous due to limited resolution quality. In this study, a N-S trending 460-km-long seismic wide angle and refraction profile sweeps throughout the North Qilian, Hexi corridor (containing the Jiuquan basin and the Huahai basin), and the entire Beishan block was done. This profile reflects the high-quality crustal upper mantle velocity structure of the research area. Combined with other geological and geophysical datasets, we examined the tectonic consequence of the key characteristics of the velocity structure, hoping to throw light on the northern extension of the NE Tibet plateau, and the reactivation of the Beishan crust.

Geological Setting

The early Paleozoic Qilian Shan, recording the closure of the Qilian Ocean as part of the Proto-Tethys Ocean (Yu et al. 2021), has been is a typical orogen traditionally divided into three structural units: the North Qilian Shan Orogenic belt (NQS), the Central Qilian block, and the South Qilian thrust belt (Yin and Harrison 2000). The boundary between the former two units is delimited by the North Qilian fault (F9). The NQS principally comprises early Paleozoic ophiolite suites (Fig. 1c), blueschists, eclogites, greenschists, and arc-related magmatic and volcanic rocks (Xu et al. 2005; Zhang et al. 2007; Song et al. 2009; Xiao et al. 2009; Zhao et al. 2024). These strata are overlain by Silurian flysch, Devonian molasse and Carboniferous-Triassic sedimentary periods (Wang et al. 2023). In the Mesozoic, the extensional and transtensional basins evolved over the Qilian Shan from the Xining Basin in the south to the Hexi corridor in the north (Horton et al. 2004; Pan et al. 2004). In the Cenozoic, the Qilian Shan has been reactivated as a fold-thrust belt to accommodate the crustal deformation resultant from the Indian-Eurasian collision with development of massive thrusts and strike-slip faults (Tapponnier et al. 1990; Zuza et al. 2019).

The Hexi corridor, sandwiched between the BOC and the Qilian Shan by the southern margin fault of the Beishan (F5) and northern margin fault of the North Qilian (F8), is a Cenozoic foreland basin system (Fig. 1b; Li et al. 2002). The basement of the Hexi corridor consists predominantly Paleozoic rocks, covered by thick Mesozoic and Cenozoic deposits. In this study region, tThe Hexi corridor is divided into the Huahai basin in the north and Jiuquan basin in the south by the Kuantanshan-Heishan fault (F6). The Huahai basin is part of the Dunhuang block, traditionally assigned as a Precambrian cratonic block or a microcontinent (BGMGRP 1989; Che and Sun 1996;

Mei et al. 1997; Mei 1998; Yu et al. 1998; Ren et al. 1999; Xu et al. 1999; Lu et al. 2008; Liu et al. 2009; Zhang et al. 2011; He et al. 2013; Zong et al. 2013), and involved in the final closure collision of the Paleozoic Asian Ocean (PAO; Shi et al. 2022). The Jiuquan basin, a subbasin of the Hexi Corridor foreland basin, has deposited Cenozoic sediments since as early as ca. 40 Ma (Dai et al. 2005; Wang et al. 2016), and was subsequently influenced by the uplift of the NQS since the Cenozoic.

The Beishan block is positioned between the Mongolian Plateau collage system in the north and the Dunhuang Block in the south (Fig. 1; Zuo et al. 1991; Yue and Liou 1999; Wang et al. 2010; Xiao et al. 2010; Zuo and Li 2011). It is widely considered to encompass multiple different tectonic units, including the Queshan, Hanshan, Mazongshan, Shuangyingshan, and Shibanshan terranes. They are separated by four nearly parallel W-E-trending ophiolite melange zones, named Hongshishan-Baiheshan (F1), Shibanzhong-Xiaohuangshan (F2), Hongliuhe-Xichangjing (F3) and Liuyuan-Huitongshan-Zhangfangshan (F4) respectively (Fig. 1c; Zuo et al. 1991; Liu 1995; Wei et al. 2004; Ao et al. 2010, 2012, 2016; Xiao et al. 2010; Yang et al. 2010; Zuo and Li 2011; He et al. 2014; Wang et al. 2017; Wei et al. 2017; He et al. 2018; Wang et al. 2018; Li et al. 2022; Li et al. 2023). The Hongliuhe-Xichangjing suture zone (F3) is generally recognized as the final suture zone of the South Beishan Block and North Beishan Block in the middle to late Ordovician (Li et al. 2022, 2023).

The Hexi corridor, sandwiched between the Beishan block and the Qilian Shan by the southern margin fault of the Beishan (F5) and northern margin fault of the North Qilian (F8), is a Cenozoic foreland basin system (Fig. 1b; Li et al. 2002). The basement of the Hexi corridor consists predominantly Paleozoic rocks, covered by thick Mesozoic and Cenozoic deposits. In this study region, the Hexi corridor is divided into the Huahai basin in the north and Jiuquan basin in the south by the Kuantanshan-Heishan fault (F6). The Huahai basin is part of the Dunhuang block, traditionally assigned as a Precambrian cratonic block or a microcontinent (BGMGP 1989; Che and Sun 1996; Mei et al. 1997; Mei 1998; Yu et al. 1998; Ren et al. 1999; Xu et al. 1999; Lu et al. 2008; Liu et al. 2009; Zhang et al. 2011; He et al. 2013; Zong et al. 2013), and involved in the final collision of the PAO (Shi et al. 2022). The Jiuquan basin, a subbasin of the Hexi Corridor foreland basin, has deposited Cenozoic sediments since as early as ca. 40 Ma (Dai et al. 2005; Wang et al. 2016), and was subsequently influenced by the uplift of the North Qilian since Cenozoic. The early Paleozoic Qilian Shan, recording the closure of the Qilian Ocean as part of the Proto-Tethys Ocean (Yu et al. 2021), is a classic orogen traditionally divided into three structural units: the North Qilian Shan Orogenic belt (NQS), the Central Qilian block, and the South Qilian thrust belt (Yin and Harrison 2000). The previous two units are delimited by the North Qilian fault (F9). The NQS principally comprises early Paleozoic ophiolite suites (Fig. 1c), blueschists, eclogites, greenschists, and are related magmatic and volcanic rocks (Xu et al. 2005; Zhang et al. 2007; Song et al. 2009; Xiao et al. 2009; Zhao et al. 2024). These strata are overlain by Silurian flysch, Devonian molasse and Carboniferous-Triassic sedimentary periods (Wang et al. 2023). In Mesozoic, the extensional and transtensional basins evolved over the Qilian Shan from the Xining Basin in the south to the Hexi corridor in the north (Horton et al. 2004; Pan et al. 2004). In Cenozoic, the Qilian Shan has been reactivated as a fold-thrust belt to accommodate the crustal deformation resultant from the Indian-Eurasian collision with development of massive thrusts and strike-slip faults (Tapponnier et al. 1990; Zuza et al. 2019).

Data and Methods

Seismic Acquisition, Collection and Processing

In 2018, The Chinese Academy of Geological Sciences completed a SW-NE-trending seismic wide-angle reflection and refraction profile stretching from the North Qilian NQS to the Beishan block. The profile starts from Yanglong in Qinghai Province in the south, passing through Qingqing, Baiyanghe, Dongxiang Ethnic Town, Ganhaizi, Humuletu Wusu, Sharitola, Wutongjing, Heiyingshan, and Har Borogdyn Uul, before ending at the China-Mongolia border in the north. Nine TNT trinitrotoluene (TNT) blastshots, ranging from 1.5 to 3.0 tons, were detonated throughout the seismic profile at intervals of roughly 30–60 km (ZB0–ZB8, shown in red stars in Fig. 1c). To achieve thorough dense ray coverage, 250 portable

seismographs (depicted as blue circles in Fig. 1c) were ~~strategically distributed~~~~deployed~~ along the ~~whole-entire~~ seismic ~~lineprofile~~ at a spacing of 2–3 km. ~~This deployment sought to capture high-quality seismic data, and the specific-detailed~~ parameters of the shots are presented in Table 1.

Identification of ~~S~~Seismic ~~P~~Phases

Using the ZPLOT plotting package (Zelt, 1994), we performed trace editing, automatic gain control, band-pass filtering, velocity reduction, and phase picking for each shot. To ~~make the seismic records clearer~~improve the signal-to-noise ratio, we applied each trace was bandpass filtered up to 8 Hz and displayed the seismic sections ~~in reduced time using a reduction velocity of 6 km s⁻¹ based on a velocity of 6 km/s in the breadth~~over a time window of -5–10 s (e.g. Fig. 2, Fig. 3).

Uncertainties in phase picking primarily arise from challenging signal-to-noise conditions and complex subsurface wave propagation effects. The extensive desert sedimentary cover in the study area significantly attenuates seismic energy, particularly at larger offsets and for deeper arrivals. Additionally, strong lateral heterogeneities, ~~—ssuch as fault zones and intracrustal velocity variation,~~ ~~s—~~cause substantial wave scattering, dispersion, and multipathing. This, ~~resulting in phase superposition and waveform distortion that complicates accurate phase identification.~~ Following careful analysis and comparative evaluation, ~~s~~Six seismic phases, including Pg, P1, P2, P3, P4, Pm and Pn, are identified ~~based on the reduced seismic recordings (e.g. Fig. 2, Fig. 3).~~ Pg is a first-~~arriving~~ arrival phase ~~refracting through propagating over~~ the crystalline basement. Pm is the strongly wide-angle reflected phase from the Moho ~~discontinuity~~. Pn is the head wave refracted phase from the top of the mantle with a characteristic velocity of 7.7–8.0 ~~1 km/skm s⁻¹~~. P2–P4 are the reflected phases from the intracrustal second-order velocity interfaces. In Fig. 2 and Fig. 3, the dotted lines represent the identified phases, and the squares mark the position of the computed traveltimes.

The first-arrivals of Pg are picked up to offset of 100 km. ~~the-The~~ traveltimes ~~recorded at ofshotpoint~~ ZB1, located in the NQS, ~~areis early as are the , which reveals the shallow velocity of the NQS is high with 5.1–6.3 km/skm s⁻¹ and 4.0–6.1 km/skm s⁻¹ average velocity correspondingly. The traveltimes for the shot ZB8 located of the north branch of ZB8 is early too, demonstrating the shallow crustal velocity in the northern Beishan block~~BOC is with 3.3–6.3 ~~km/skm s⁻¹~~. Intracrustal reflection phases P2–P4 can be recognized at the offset ranges from 70–90 km, 100–150 km, and 120–150 km respectively. Pm can be correlated over an offset of 180 km for most shots (Fig. 4a). Pn was found with maximal amplitude in the offset range of 240–280 km (Fig. 3). ~~The Pn displayed in shot ZB1 seismic record is with 7.9–8.1 km/skm s⁻¹ velocity, while 7–8.1 km in shot ZB8 (Fig. 4).~~

The ~~V~~velocity structure ~~m~~Modelling

The 2-D crustal velocity structure is based on seismic phases identification, and the first initial 2-D crustal model ~~is was built constructed with using~~ the greatest-highest elevation of 4300 m as the datum. ~~The f~~The forward fitting calculation adopts the asymptotic ray tracing to fit the traveltimes of each shot (Fig. 4 (Cerveny et al. 1988; Vidale 1988; Zelt and Smith 1992; Cerveny 2001) and gradually improves the initial 2-D velocity structure by constantly modifying the interface depth and interval velocity (Fig. 4; Cerveny et al. 1988; Vidale 1988; Zelt and Smith 1992; Cerveny 2001). Model construction and editing are carried out with the RAYINVR software (Zelt and Smith, 1992). The traveltimes fitting of 5–6 phases for nine shots are conducted step by step, ~~top-down~~ to limit the multi-solution of the model. Fig. 4 illustrates the traveltimes fitting of the seismic recordings of the shot gather and the complete crustal ray coverage. The time error of the ray tracing forward fitting accuracy is typically less than 0.05 s, and the maximum is not more than 0.1 s. The root mean square error (RMS) of the traveltimes fitting for different earthquake phases is reported in Table 2. The velocity inaccuracy is controlled within 0.05 ~~km/skm s⁻¹~~, while the Moho depth error is less than 1 km. ~~Poorly-resolved areas based on ray coverage have been masked to prevent overinterpretation,~~ (The ultimate crustal-upper mantle velocity structure is found in Fig. 5. ~~Although the ray-tracing misfit is small (RMS < 0.05 s), two tests quantify potential biases. Ray-density gaps: Pn hits fall below 20 km⁻² beneath distance 250–350 km (Fig. 4a), increasing the Moho-depth uncertainty to ±1.2 km in that segment; velocity–interface trade-off: 200 bootstrap inversions give a velocity–depth correlation of r = -0.67; a 3% increase in lower-crustal velocity~~

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can be compensated by a ~1 km deeper Moho without raising misfit, so we adopt ± 1 km as the systematic Moho-depth bias bound.

The typical continental crust is stratified into three principal layers: the upper crust, comprising sedimentary cover overlying crystalline basement characterized by an average P-wave velocity of 6.0–6.3 km s⁻¹; the mid-dle crust, composed of interleaved silicic and basic lithologies, with velocities of 6.3–6.5 km s⁻¹; and the lower crust, dominated by more mafic assemblages, exhibiting velocities of 6.6–6.9 km s⁻¹ (Christensen, 1995; Jia et al., 2019). Based on our velocity structure result, The result shows the crust can be split/divided into upper crust (from the surface to P2C2), middle crust (from P2-C2 to P3C3), and lower crust (from P3-C3 to the Moho discontinuity). The upper crust can be separated into two layers by intracrustal interface C1 determined by seismic phase P2. The lower crust can also be subdivided/separated into two layers/strata as well as by intracrustal interface C4 indicated by seismic phase P4.

Velocity Sstructure of the Uupper Crust

The upper crust, frome/comprising delineated by the layer from- the surface to interface C2 at depth, has pronounced/exhibits pronounced lateral segmentation across the study region. Lower velocities extend to greater depth. Notably, A prominent a lower- velocity zone is prevalent beneath the NQSouth Qilian-Jiuquan basin, contrasting sharply laterally with the a significantly greater higher velocities characteristic of y zone in the Beishan-block/BOC. Along interface C1 amid-within the upper crust, discrete many- high-velocity entities/zones with an interval velocities of 6.3–6.4 km/skm s⁻¹ are seen/observed.

The base-of- iInterface C1 eorresponds to marks the basement surface, characterized by a velocities ranging frome of 3.4 to -6.5 km/skm s⁻¹. The basement profile-surface exhibits significant undulations extensively within the depths varying between of 6.1 and -12.5 km (Fig.-5b, 5). The interval velocity of the uppermost crust measures ranges from 5.2 to -6.05 km/skm s⁻¹, with an interface depth of 6.3–7.2 km in the middle-central QilianNQS. In the southern North QilianNQS, the interval velocity ranges fromis between 5.2 and -6.1 km/skm s⁻¹, having-and a high-velocity bodyzone is present in the bottom-lower section, with an interval velocities of 6.2–6.45 km/skm s⁻¹; here, the and-the interface deepenth-lowers to 10.8–11.4 km. In the northern section of the North-QilianNQS, the interval velocity falls-decreases to 4.0–6.0 km/skm s⁻¹, while the interface depth deepens-increases to 9.7–10.1 km.

WithinIn the Jiuquan basin, the interval velocity reducees ranges fromto 3.6 to -6.1 km/skm s⁻¹, with-anand the interface deepenspth-falling to 11.2–12.5 km. The Huahai basin has-showsan interval velocity-velocities of 3.8–6.2 km/skm s⁻¹, and-thewith interface depths between -ranges from-11.5 and -12.5 km. Additionally, a high-velocity body-zone with -an interval velocity-velocities of 6.3–6.5 km/skm s⁻¹ appears-is also observed beneath at the bottom-below the F5 fault/raeture. In the southern Beishan-block/BOC, layerinterval velocities on the south side measure-are 4.6–6.2 km/skm s⁻¹, with interface depths ranging-fromof 11.5–12.0 km, whereas on the northern side, layerinterval velocities reduce-decrease to 3.4–6.1 km/skm s⁻¹, and interface depths are-range from 9.4 to- 11.3 km.

In the Northern Beishan-block/BOC, layerinterval velocities are-vary from 4.2 to -6.2 km/skm s⁻¹, with thean interface at depths of 10.5–12.5 km. Further north within the Beishan block/BOC, the interval velocity is-remains between 4.2 and -6.2 km/skm s⁻¹, and the interface depth is-ranges from 10.0 to -11.3 km. At-the-bottom-of-the Beishan-block/BOC, multiple-several high-velocity bodies/zones are-observed-with layerinterval velocities of 6.3–6.4 km/skm s⁻¹ are identified at the base of the BOC, including one beneath the high-velocity body-under the Mazhoushan Mazongshan terrane/arc.

The deeper upper crustal/bottom layer exhibits velocities ranging-fromof 6.0–6.3 km/skm s⁻¹ and interface depths ranging-frombetween 13.2 and -27.6 km. Although this layer shows no While lacking-significantmajor lateral segmentation, its interface is highly undulatorythis-layer-exhibits considerable interface undulations (Fig.-5b, 5). South of fault F9, the interval velocity is 6.05–6.15 km/skm s⁻¹, with an-the interface depth-of-at 12.8–18.3 km depth. Between faults F9 and F5, the layer thickens substantiallyconsiderably, and the interface depth-climbsdeepens to 17.6–27.5 km. North of fault F5, the layer thickness reducees-decreases to values similar to those inmatch the southernmost part of the profile, but the velocity increases to 6.1–6.4 km/skm s⁻¹. This-These

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characteristics shows indicate that the North Qilian NQS and the Jiuquan basin have share a consistent basement structure, matching which aligns with the findings from residual gravity anomaly findings analyses (Yang et al. 2024).

Velocity Structure of the Middle Crust

The intermediate crust exhibits distinct zoning features of the intermediate crust are notably that differ from the top upper crust with interface depth of 23.4–38.7 km, and layer interval velocities of 6.2–6.5 km/skm s⁻¹. This layer is There're eC comparatively slowly low-velocity zones are observed occurring in beneath the northern North Qilian NQS and the Jiuquan basins (Fig. 5b, 5).

The interface C3 depth of the contact across the fault F8 between separating the NQS and the Jiuquan basin is varies from 23.4 to 38.7 kilometers km. The minimum lowest interval velocities is (6.2–6.35 km/skm s⁻¹) occur in the middle-central NQS Qilian, increasing northward to 6.25–6.45 km/skm s⁻¹ northward. In the Huahai basin, the interface depths lies at in the Huahai basin is 27.5–38.7 km depth, with interval velocities of y 6.25–6.5 km/skm s⁻¹; and the highest maximum interval velocity in this region reaches (6.32–6.45 km/skm s⁻¹) are found in its central part the middle region (Fig. 5b, 5).

Within the BOC, the interface C3 depth shallows in the Beishan block decreases to 24.4–31.2 km. Mid-crustal interval velocities in the Shibanshan arc arcs 6.3–6.5 km/skm s⁻¹, decrease to 6.25–6.4 km s⁻¹ whereas those in the southern Shuangyingshan terrane arc, and decrease to 6.25–6.4 km/s. The interval velocity increases to 6.3–6.42 km/skm s⁻¹ further north.

The Velocity contours display contrasting dip directions: in the NQS Qilian and the Jiuquan basin, they show a gently undulating northward inclination pattern, while those in the Huahai basin they dip steeply to the southward (Fig. 5b, 5).

Velocity Structure of the Lower Crust

The lower crust can be subdivided typically separated into three portions segments from south to north, bounded by faults F9 and F4 (Fig. 5b, 5). The consistent undulation of the interface C4 and Moho discontinuity is consistent, which signifies the thickness variations of the upper and lower layers portions of the lower crust is with the same follow a similar trend along the entire complete profile.

Upper layer: in this layer, with between C3 and C4 is characterized by a bottom depth of has 36.7–49.5 km and an interval velocity of 6.45–6.7 km/skm s⁻¹ (Fig. 5b, 5). distinguishing features emerge. South of fault F9, interface C4 lies is located at a depths of 36.7–42.4 km, indicating with an interval velocity of 6.45–6.7 km/skm s⁻¹. Between faults F9 and F4, interface C4 deepens to 38.6–49.2 km, and the interval velocity increases to 6.5–6.7 km/skm s⁻¹. Notably, a significant upward undulation of a high-velocity body zone is observed with found in this segment zone. North of the fault F4, interface C4 is positioned at a depth of shallow to 37.4–40.3 km, and the accompanied by a decrease in interval velocity decreases to 6.47–6.65 km/skm s⁻¹.

Lower layer: The Moho discontinuity is identified at a depths of 47.5–60.0 km and with and this lower layer between C4 and the Moho exhibit exhibiting an interval velocity of 6.65–6.85 km/skm s⁻¹ (Fig. 5b, 5). Beneath in the Qilian Shan and Jiuquan basin, the the Moho reaches is at a depth of 57.8–60.0 km, with an interval velocity of 6.7–6.85 km/skm s⁻¹. The central part of the Jiuquan basin displays exhibits the deepest Moho at (60 km), where accompanied by a decrease in the interval velocity decreases slightly to 6.7–6.78 km/skm s⁻¹. In the Huahai basin and Beishan block the BOC, the the Moho depths spans range from 47.5 to 57 km, and the velocity velocities of the layer reduces to 6.7–6.75 km/skm s⁻¹. The shallowest Moho, (at 47.5 km), is observed recorded beneath in the Que'er shan terrane arc, where the lowermost crust has with an interval velocity of 6.65–6.78 km/skm s⁻¹.

Upper mantle Pn velocity structure revealed from Pn

The upper mantle Pn velocity structure exhibits nuances distinct lateral variations across the study are throughout the analyzed locations (Fig. 5). The Qilian Shan is characterized by a relatively

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high uppermost mantle shows a top-of-the-upper-mantle velocity range of 7.9–8.4 km/skm s^{-1} , with sub-horizontal velocity approximately flat contours. A velocity reduction to 7.7–8.3 km s^{-1} is observed from the Jiuquan basin to the Shibanshan terrane arc, followed by a slight increase the velocity reduces to 7.7–8.3 km/s , then rises to 7.9–8.6 km/skm s^{-1} in beneath the Shuangyingshan terrane arc. Further north, the Mazongshan, Hanshan, and Que'ershan terrane arcs have show progressively lower decreasing Pn velocities, ranging from of 7.8 to 8.5 km/skm s^{-1} , indicating a progressive drop from south to north decreasing trend. The lowest Pn values eloeity (7.7–7.8 km/skm s^{-1}) is reported are localized beneath faults F5, F1, and F6.

Crustal Velocity Structure Implications

The crustal velocity structure proposes an unusual scenario where the deepest Moho is found in the central Jiuquan basin, rather than the North Qilian Shan with the highest elevation. Additionally, the Qilian Shan and southern Shibanshan terrane exhibit a thin upper-middle crust and a thick lower crust, while other parts have the reverse pattern (Fig. 5b, 5).

Crustal-Upper Mantle Velocity Anomaly Structure

To improve the visibility sensitivity of the velocity heterogeneity of the crustal-upper mantle structure the mean layer velocities are subtracted to produce a velocity anomaly structure of the crustal-upper mantle is determined (Fig. 6b, 6, the difference between the velocity contour values and their mean values). Figure 6b demonstrates that in the upper layer of the crust from depths of 0 to 12.5 km, the composition is significantly heterogeneous, and lateral segmentation is visible. The Qilian Shan is with a high positive velocity anomaly (0.3–1.0 km/skm s^{-1}). The Jiuquan basin and Huahai basin show are with negative velocity anomaly (-1.1– -0.15 km/skm s^{-1}), and extend northward to the southern Shuangyingshan terrane arc, which are prevented terminate at by the strong positive velocity anomaly in the central Shuangyingshan terrane arc. Three positive velocity anomaly bodies (0.12–0.45 km/skm s^{-1}) with closed contours exist beneath the faults F5, F4, and the core Shuangyingshan terrane arc. In the northern Shuangyingshan terrane arc, a negative velocity anomaly (-1.3–0.12 km/skm s^{-1}) develops, and thins out to the north extending to the southern Mazongshan terrane arc. The positive velocity anomaly (0.15–0.45 km/skm s^{-1}) starting from the Mazongshan terrane arc dives extends northward to the northern end of the Que'ershan terrane arc, and the central part is covered by the low-velocity negative anomalies (-0.4–0.08 km/skm s^{-1}) in the upper Hanshan terrane arc.

At a depth of 9.2–38.5 km between interface C1 and C3, the middle Qilian and the southern North Qilian NQS consisted of the northward-tilted, small-variation positive velocity anomalies (0.0 to 0.08 km/skm s^{-1}) and negative anomalies (-0.03–0.01 km/skm s^{-1}). The northern North Qilian NQS, the Jiuquan basin and the southern portion of the Huahai basin are northward-tilted, downward-curved layers of the low-velocity negative anomalies (-0.05–0.2 km/skm s^{-1}). The northern half of the Huahai basin and the Shibanshan terrane arc are positive anomaly (0.0–0.08 km/skm s^{-1}) layers with small velocity changes. The southern Shuangyingshan terrane arc is a mixed layer of the positive velocity anomaly (0.01–0.08 km/skm s^{-1}) and negative velocity anomaly (-0.01–0.04 km/skm s^{-1}). The velocity anomaly from the northern Shuangyingshan terrane arc to the Que'ershan terrane arc is positive (0.03–0.12 km/skm s^{-1}), and only locally negative (-0.01–0.03 km/skm s^{-1}).

In the upper layer of the lower crust, the Qilian Shan is characterized by a positive velocity anomaly (0.01–0.12 km/skm s^{-1}) in the upper section, and a negative velocity anomaly (-0.01–0.08 km/skm s^{-1}) in the lower part. The Jiuquan basin and Huahai basin are characterized by minor negative velocity anomalies (-0.02–0.08 km/skm s^{-1}). The Beishan-block BOC is characterized by a strong positive velocity anomaly (0.02–0.12 km/skm s^{-1}) and exhibits a northward-increasing trend (Fig. 6b, 6).

In the lowest layer of the lower crust, From the North Qilian NQS to the southern Huahai basin, the velocity anomaly reveals positive (0.01–0.07 km/skm s^{-1}) with a relatively minor variance. From the northern Huahai basin to the southern Shuangyingshan terrane arc, the velocity anomaly is with a positive to negative (0.01–0.07 km/skm s^{-1}) from top to bottom. From the northern Shuangyingshan to the Que'ershan terrane arc, lesser positive anomalies (0.01 to 0.03 km/skm s^{-1})

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are observed (Fig. 6b, 6).

At the top of the upper mantle, the North Qilian-Shan NQS and the southern Jiuquan basin show positive velocity anomaly with modest changes ($0.05\text{--}0.15\text{ km/s km s}^{-1}$), whereas negative anomaly with substantial velocity variations (-0.1 to $-0.25\text{ km/s km s}^{-1}$) from the northern Jiuquan basin to the Shibanshan terrane arc. The southern Shuangyingshan terrane arc is characterized with a gradient of the velocity anomaly ranging from negative to positive ($-0.1\text{--}0.12\text{ km/s km s}^{-1}$). The northern Shuangyingshan and Mazongshan display positive anomaly ($0.03\text{--}0.12\text{ km/s km s}^{-1}$) moving downwardly. The southern Hanshan terrane arc has a positive anomaly ($0.01\text{--}0.1\text{ km s}^{-1}$) characterized by a gradual reduction from south to north. The northern Hanshan terrane arc and the Que'ershan terrane arc show negative anomaly ($-0.01\text{--}0.12\text{ km s}^{-1}$) that diminish steadily from south to north (Fig. 6b, 6).

Discussion

The observed crustal-upper mantle structure (Fig. 5; Fig. 6) records a what is known to be a complicated outcome history shaped by both of vertical and lateral material mass transfer processes, reflecting Precambrian inheritance. These activities are related to Paleozoic subduction, collision, and accretion events, Mesozoic intracontinental deformations reworking, and the Cenozoic northward spread expansion of the NE Tibetan-Tibetan plateau (Cunningham et al., 2009; Zhang and Cunningham, 2012; Li et al., 2021 REFERENCES) since the Precambrian.

The Nature of the Beishan Orogenic Collage BOC crust

It has been previously interpreted that the middle-lower crust beneath the BOC behaves as a mechanically stable 'fossil archive' in the Cenozoic, preserving pre-Cenozoic architecture, whereas the uppermost mantle and upper crust show active deformation (Cui et al. 1995). Instrumentally recorded seismicity is confined to the Qilian Shan, the Hexi Corridor basins, the Huahai Basin, and local areas west of Xingxingxia, mostly at depths of 15–16 km (Fig. 7), which acted as the decollement as shown in the seismic profile (Fig. 5, Fig. 6; Fig. 8). The Beishan interior has spatially and temporally sparse low magnitude almost aseismic ($M < 4.7$) seismicity and exhibits low topographic relief (Xiong et al. 2003; Yang et al. 2019; Zhao et al. 2019), indicating limited present-day strain. Slight mid-lower-crustal flexure and reduced resistivity in southern Beishan (Xiao et al. 2015) nevertheless imply a rheologically (not seismically) slightly weaker zone relative to its surroundings. Active left-lateral and thrust faults in the southern BOC also indicate a weaker crust (Yang et al. 2019; Zhang et al. 2020; Yun et al. 2021; Zhang et al. 2023).

Paleozoic Subduction Subduction Polarity of the Qilian Ocean and the southern PAO and Accretionary Architecture

Strata of the North Qilian Ocean, a part-branch of the Proto-Tethys Ocean, deformed evolved predominantly along the Kunlun Mts., Qilian Shan and Altyn mountain belt Mts. in the northern Tibetan Plateau/Tibetan Plateau. The dynamics of the closure of the Qilian Ocean resulting from the collision via collision between the Kunlun-Qaidam continent and the southern boundary margin of the North China Craton remains a matter of considerable debate (Yin and Harrison 2000; Guterch et al. 2003; Xiao et al. 2009; Song et al. 2014; Wu et al. 2017; Zuza et al. 2017; 2019). The subduction polarity of this the ocean Qilian Ocean has been proposed as: 1) north-dipping (Zuo and Liu 1987; Song et al. 2013; Li et al. 2022); 2) south-dipping (Wang and Liu 1981; Li et al. 2016); 3) bidirectional (Zhao et al. 2024); or or divergent models (Wu et al. 2011; Chen et al. 2019). Although previous geophysical investigations have covered the Qilian Shan (Xiao et al. 2016; Guo et al. 2019; Shen et al. 2020; Li et al. 2021), focus on concentration has largely been on the neotectonics rather than the Paleozoic evolution. In this study, we observed north-dipping velocity contour from interface C2 to the uppermost mantle beneath the Qilian Shan, coupled with a lower-crust-upper-mantle low velocity anomaly beneath the Hexi Corridor (Fig. 6). These features most plausibly record early Paleozoic north-dipping subduction of the Qilian Ocean, which aligns with the surface geology; later collisional or bidirectional shortening may have locally overprinted the original polarity (Davis and Darby, 2010).

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Despite intensive geochemical and chronological research on Paleozoic rocks in the Dunhuang block and the BOC, the accretionary architecture of the PAO still remains enigmatic (Xiao et al. 2010; Shi et al. 2020, 2021; Li et al. 2023). Our deep seismic velocity model now provides the direct geophysical evidence for the subduction polarity within the northern BOC. Beneath the Que'ershan arc, the northernmost portion of the BOC, north-dipping velocity contours from interface C2 to the Moho imply south-dipping subduction of the Hongshishan Ocean, consistent with surface geology (Xiao et al. 2018; Duan et al. 2020; Niu et al. 2020; Xin et al. 2020). Velocity undulations between faults F9 and F1 probably reflect late-Paleozoic collision or Cenozoic bidirectional compression, obscuring primary dip direction.

Between faults F2 and F4, a positive upper-mantle velocity anomaly ($8.0\text{--}8.3\text{ km s}^{-1}$) between $\sim 45\text{ km}$ and $\sim 70\text{ km}$ depth likely represents a broken off fossil break-off subduction slab following north-dipping subduction of the Beishan Ocean, although residual oceanic crust or mafic underplating cannot be entirely excluded. This anomaly aligns with the Hongliuhe–Xichangjing ophiolite mélangé in surface (Yu et al. 2012; Hu et al. 2015; Song et al. 2015; Wang et al. 2015; Li et al. 2023).

Cenozoic Crustal Deformation and Strain Partitioning across Major Faults Mechanism

Northward-propagating crustal shortening since the Miocene is accommodated through a series of parallel NW-SE-trending thrust faults in the Qilian Shan and successively reaches the Hexi corridor and the BOC (Cunningham 2010, 2013; Wang et al., 2020; Yu et al., 2021; Zhang et al. 2023).

Symmetric downward undulation of the velocity contours ($6.2\text{--}6.8\text{ km s}^{-1}$) across the southern margin fault of the Beishan (F5) demonstrates that fault F5 acts as a lithospheric-scale partition zone rather than other faults (Fig. 5, Fig. 6). South of the fault F5, north-tilting high velocity anomaly bodies with $6.2\text{--}6.45\text{ km s}^{-1}$ at the base of the upper crust ($18\text{--}25\text{ km}$ depth) form the Qilian Shan to the Shibanshan arc, correlate to the north-vergent thrusting that decouples from a co-thickened middle-lower crust ($25\text{--}50\text{ km}$, $6.5\text{--}6.8\text{ km s}^{-1}$), which is consistent with the reflection structure (Xiong et al., 2025). North of the fault F5, complementary velocity gradients ($6.1\text{--}6.6\text{ km s}^{-1}$, $15\text{--}45\text{ km}$) indicate conjugate north-direction upper-crustal thrusting accompanied by whole-crust gentle folding in the BOC. The downward-undulation of the velocity contours imply co-thickening of the middle-lower crust of the NQS–Shuangyingshan area, with the uppermost crust experiencing thrusting and overthrusting. Our velocity structure indicated that low Pn velocity with $7.7\text{--}7.9\text{ km s}^{-1}$ and dome-shaped uplift of the crust directly beneath the fault F5 (Fig. 5). The electrical resistivity imaging (Yang et al. 2019) also highlighted the boundary fault, termed Baihewan fault (in Fig. 7) in the southernmost Shibanshan arc; this fault which penetrates the lower crust with low resistivity, to both sides of which the direction of the interpreted thrusting is opposing (Yang et al. 2019).

The seismic reflection profile revealed a south-dipping Cenozoic thrusting system that dislocated the Paleozoic–Mesozoic strata over the undeformed Meso-Cenozoic sediments in the Jiuquan basin (Zuza et al. 2016; Huang et al. 2021), consistent with our velocity model. The shallow velocity structure across the Huahai basin and the southern BOC likewise depicted the differences to both sides of F5 (Wu et al. 2022). Guo et al. (2019) likewise documented the northward expansion of the Qilian Shan across the Hexi corridor via uppermost-crustal overthrusting and lower-crustal thickening east of our seismic profile. High-resolution seismic reflection profile south of the fault F5 further reveals the middle-lower crustal thickening by duplexing (Huang et al. 2021).

Within the southern BOC north of the fault F5, north-direction thrusting dominates the uppermost crust, while the rest of crust undergoes gentle folding identical to the NQS–Hexi corridor style (Gaudemer et al. 1995; Meyer et al. 1998; Tapponnier et al. 2001; Yuan et al. 2013; Zuza et al. 2017; 2019). Crustal deformation across the fault F5 is therefore distinctly asymmetric: south of the fault, the uppermost crust is decoupled from the underlying crust (Fig. 5), whereas north of the fault the entire crust participates in coherent gentle folding (Fig. 8).

While past geophysical investigations have covered the Qilian Shan (Xiao et al. 2016; Guo et al. 2019; Shen et al. 2020; Li et al. 2021), concentration has largely been on neotectonics rather than

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|547 Paleozoic evolution.

Our data demonstrates a northward-tilted velocity contour from interface C2 to the topmost mantle beneath the Qilian Shan (Fig. 5b). This inclination suggests the northward descent of the middle crust to the uppermost mantle beneath the Hexi corridor. We speculate that this trait reflects a north-dipping subduction polarity of the Qilian Ocean in the early Paleozoic. Further corroborating our thought is the negative velocity anomaly body spanning from the lower crust to the topmost mantle beneath the Hexi corridor and southern Shibanshan (Fig. 6b).

The Central Asian Orogenic Belt (CAOB) is well acknowledged for its southward migration throughout development and composition from 1000 Ma to 250 Ma (Lehmann and al. 2010; Jian et al. 2014; Kröner et al. 2014; Xiao et al. 2018). Consequently, the Dunhuang block, positioned at the southernmost extent of the CAOB and associated with the Beishan block, assumes a vital role in unraveling the decisive closure of the southern Paleo-Asian Ocean (PAO). Despite detailed geochemical and chronological research on Paleozoic rocks in the Dunhuang block and the Beishan block, the amalgamation style of the PAO remains elusive (Xiao et al. 2010; Shi et al. 2020, 2021; Li et al. 2023).

The previous Golmud–Ejin seismic profile defined the crustal structure of the Beishan block into three strata with an active upper mantle and stable crust (Cui et al. 1995), consistent with our current profile. The stable crust, specifically the middle-lower crust, is crucial in conserving fossil architecture. The north-tilted velocity contour beneath the Que’ershan terrane from interface C2 to the Moho discontinuity implies the crust north of the Que’ershan subducted beneath the Hanshan terrane, a deduction supported by geological observations (Xiao et al. 2018; Duan et al. 2020; Niu et al. 2020; Xin et al. 2020). Consequently, we suggest the subduction polarity of the Hongshishan Ocean as south-direction. The zone between F9 and F1 faults reveals a peculiar undulation of velocity profiles, presumably caused by subsequent late Paleozoic collision or bidirectional compression in the Cenozoic, complicating the distinction of subduction direction. Combining geological findings (Yu et al. 2012; Hu et al. 2015; Song et al. 2015; Wang et al. 2015), we propose that the positive velocity anomaly body in the upper mantle between faults F2 and F4 could represent the fossil breakoff subduction slab following the north-dipping subduction of the Beishan Ocean, marked by the Hongliuhe–Xichangjing ophiolite mélange (Li et al. 2023).

Crustal deformation mechanism

Situated between the Tibetan Plateau and Mongolian plateau, the crust from the Qilian Shan to the Beishan block has undergone intracontinental deformation to varied degrees (Cunningham 2010, 2013; Zhang et al. 2023). The Qilian Shan, regarded as the youngest uplifted Mts. of the Tibetan plateau, absorbs significant shortening strain (Gaudemer et al. 1995; Meyer et al. 1998; Gao et al. 2013; Zuza et al. 2017), by a series of parallel NW-SE-trending thrust faults (Meyer et al. 1998; Tapponnier et al. 2001; Yuan et al. 2013; Zuza et al. 2017). Progressive deformation commenced in Miocene, extending northward to the Hexi corridor and Beishan-Alxa block (Wang et al. 2020; Yu et al. 2021; Zhang et al. 2023). The seismic profiles (Fig. 5b, Fig. 6b) reveal two distinct downward-undulation velocity contours on either side of the southern boundary fault of the Beishan (F5). This suggests F5 as the boundary fault restricting compressional stress from the north and south.

In the area south of F5, northward-tilted positive velocity anomaly bodies with 6.2–6.45 km/s velocity at the base of the upper crust from the Qilian Shan to the Shibanshan terrane, correlate to the north-direction thrust faults. In the area north of F5, the opposite velocity features imply north-direction thrusting in the upper crust of the Beishan block. The downward-undulation of the velocity contours imply co-thickening of the middle-lower crust of the NQS–Shuangyingshan area, with the upper crust experiencing thrusting and overthrusting. Our velocity structure indicated that low Pn velocity with 7.7–7.9 km/s and dome-shaped uplift of the crust directly beneath F5 (Fig. 5b). The electrical resistivity imaging also highlighted the boundary fault, termed Baihewan fault (BHWf in Fig. 7) in the southernmost Shibanshan terrane, which penetrates the lower crust with low resistivity, to both sides of which the direction of the thrusting is opposing (Yang et al. 2019). The shallow velocity structure across the Huahai basin and the southern Beishan block likewise depicted the differences to both sides of F5 (Wu et al. 2022), which is aligned with our result (Wu et al. 2022). Collectively, we suggest F5 is a large-scale strike-slip fault which restricts the stress transmission further to both sides.

Eastern Extension of the Altyn Tagh Fault (ATF)

The ~1600 km-long ATF is a major left-lateral strike-slip fault that defines the northern boundary of the Tibetan Plateau (Yin et al., 2002; Ritts et al., 2004; Dai et al., 2023; Xie et al., 2024). While its western and central segments are well-defined (Xie et al., 2023; Wu et al., 2024; Yao et al., 2025), its eastern termination and continuation remain highly controversial due to extensive sedimentary cover of the desert and discontinuous bedrock outcrops (Yue et al., 2001; Cunningham and Zhang, 2020; Yang et al., 2023). Definition of its eastern extent The resolution of this debate is critical for understanding deformation propagation into northeast Tibetan plateau and for regional seismic hazard assessment. Yue et al. (2001) proposed that the ATF likely extends east-northeast to northeast along the Alxa–East Mongolia fault (Donskaya et al., 2008), with Cenozoic motion displacing the Hexi Corridor and cutting through the BOC. An alternative view suggests that the ATF transfers its slip northward into the thrust systems along the northern margin of the Hexi Corridor, transitioning from predominantly strike-slip in the west to dip-slip in the east, where it eventually terminates against reverse faults within the Alxa Block (Xiao et al., 2015; Yang et al., 2023).

This study suggests that interprets F5 as the principal eastern splay of the ATF, the ATF does

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not terminate at the Qilian Shan frontland, but rather extendseontinues eastward to east-northeast into the BOC and the Alxa Block. The notable velocity contrast observed across the fault F5 may indicate the ATF extends at least across the southern margin of the BOC. The projected left slip rate with of 1.52–2.69 mm/a, is significantlysubstantially greater-higher than the thrust rate with of 0.35 mm/a in the southernmost Beishan area (Yang et al. 2019; Yun et al. 2021). Geodetic The-GPS motion-and-velocities (Yang et al. y-rate-result-fields revealed that the moving direction changed from northeast in the Qilian Shan to nearly-east in the Beishan-blockBOC with a significant lateral motion rates (Fig. 7; Yang et al., 2021). Darby et al. (2005) identified five major left-lateral strike-slip faults within the BOC and the Alxa block, which strike is consistent with the ATF, and accommodated >70 km post-Cretaceous offset based on Landsat/ASTER imagery and field mappingwork. Thus, we propose that the ATF continues straight-eastward along a consistent NEE strike at the southern margin of the BOC. Local faults identified within the southern margin of the BOC, such as the Beihewan fault, the Heishan fault, the Jiujing-Bantan fault, and the Ebomiao fault may be the secondary splays of the ATF and eventually terminate against it (Fig. 7; Yun et al., 2019; Zhang et al., 2020; Yang et al., 2019; 2024). These subsidiary structures collectively accommodate distributed crustal deformation. These results further lend support to our result. Thus, theregionally. This kinematic model also provides a coherent explanation for the distinct slip-rate decline from the western-central to eastern segment of the ATF (Yan et al., 2024). Furthermore, the distribution of seismicity supports this structural boundary: all recorded earthquakes of $M > 4.57$ occur south of the ATF and its eastern prolongation, with no events detected north of the fault within the interior of the BOC (Fig. 7). crustal deformation in this transition zone is different in the areas to both sides of F5. In the area south of F5, the upper and middle-lower-crust is decoupled, and the deformation mechanism in the upper-crust in north-direction-thrusting, and co-thickened in the middle-lower crust (Fig. 8).

The Seismic reflection profile revealed a south-dipping Cenozoic thrusting system that dislocated the Paleozoic–Mesozoic strata over the undeformed Meso-Cenozoic sediments in the Jiuquan basin (Zuza et al. 2016; Huang et al. 2021), which is compatible with our seismic imaging. Guo et al. (2019) also found the deformation and expansion of the Qilian Shan extended across the Hexi corridor by overthrusting in the top crust and thickening in the lower crust east to our study area. The seismic reflection profile over the southern segment of this section further supports the thickening mechanism of the middle-lower crust by duplexing (Huang et al. 2021). In the southern Beishan block north of F5, the north-direction thrust faults was playing the function in the top crust, and the middle-lower crust is folded alike the North Qilian–Hexi corridor area.

In NE Tibet and Beishan area, earthquakes predominantly occur in the Qilian Shan, Hexi Corridor basins, Huahai Basin, and local areas west of Liyuan, Hongliuhe, and Xingxingxia area, mostly at depths of 15–16 km (Fig. 7). The Beishan area is very stable, with few known earthquakes higher than magnitude 4.7 (Xiong et al. 2003; Yang et al. 2019; Zhao et al. 2019). The current low topographic relief also shows the Beishan block is relatively stable and tectonically inactive. However, our imaging suggests a slight bending of the middle-lower crust in the southern Beishan block, suggesting the middle-lower crust of the southern Beishan block is a little weaker than the bordering regions. Active left-lateral and thrust faults in the southern Beishan block support this assumption (Yang et al. 2019; Zhang et al. 2020; Yun et al. 2021; Zhang et al. 2023).

Conclusion

1). Crustal thickness decreases northward from 60 km beneath the central Jiuquan basin to 47.5 km beneath the Que'ershan arc; average crustal velocities (6.24–6.43 km s⁻¹) and uppermost mantle Pn velocities (7.7–8.1 km s⁻¹) reveal strong lateral heterogeneity.

2). North-dipping velocity contours and a lower-crust – upper-mantle low-velocity corridor beneath the Hexi Basin support early Paleozoic north-dipping subduction of the Qilian Ocean; a positive upper-mantle anomaly (8.0–8.3 km s⁻¹, 45–70 km) between faults F2 and F4 represents a fossil break-off slab after north-dipping subduction of the Beishan Ocean.

3). Fault F5 acts as a lithospheric-scale partition: north-vergent, decoupled thrusting south of F5 versus whole-crust gentle folding to the north; a dome-shaped Moho and slow mantle Pn phase (7.7–7.9 km s⁻¹) beneath F5 localise present-day strain.

4). The Altyn Tagh Fault continues east-northeast along F5 into the Beishan and Alxa Block

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at $1.52 \sim 2.69 \text{ mm a}^{-1}$ left slip, far exceeding the 0.35 mm a^{-1} thrust rate; secondary splays along the southern Beishan margin collectively accommodate deformation and explain the eastward slip-rate decrease. The crust thickness in the studied area spans from 47.5 to 60 km, separated into five strata. The thickest crust, measuring 58–60 km, spans from the Qilian Shan to the middle Jiuquan basin and gradually thins northward, with thicknesses of 55–58 km in the Dunhuang block, 51.5–55 km in the Shibanshan arc, and 47.5–51.5 km in the Shuangyingshan and Que'ershan terranes. Surprisingly, the deepest Moho (60 km deep) is found in the middle Jiuquan basin, not in the North Qilian Shan with the highest height. The average crustal velocity varies from 6.24 to 6.43 km/s, with crustal velocity fluctuations between 3.4 and 6.85 km/s. The velocity at the top of the upper mantle is observed at 7.7–8.1 km/s. The study region is grouped into three parts based on present-day activity: the Qilian-Hexi corridor, the southern Beishan block, and the northern Beishan. The middle unit has softer crust compared to the others, and the deformation of the middle-lower crust in the southern Beishan block is considerably stronger than in the other two units. (3) Subduction in the research area involves both north-direction and south-direction subduction of the Qilian Ocean and the Hongshishan Ocean. (4) Bounded by F5 operating as a regional large-scale strike-slip fault, the crustal deformation process on both sides is similarly disconnected. In the Qilian-Hexi corridor, north-direction thrusting and overthrusting dominate, while in the Beishan block, south-direction thrusting and overthrusting rule. The middle-lower crust co-thickens throughout the entire research area.

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Author contributions

XSX: Writing—original draft, Writing—review & editing, Visualization, Validation, Investigation, Data curation, Methodology, Formal analysis, Conceptualization, Project administration. **YKL**: Writing—draft writing, Investigation, Data curation, Methodology, Validation, Conceptualization. **XHC**: Funding acquisition, Conceptualization. **GWV**: Visualization, Methodology. **RG**: Supervision, Project administration. **JDE**: Writing—review & editing. All

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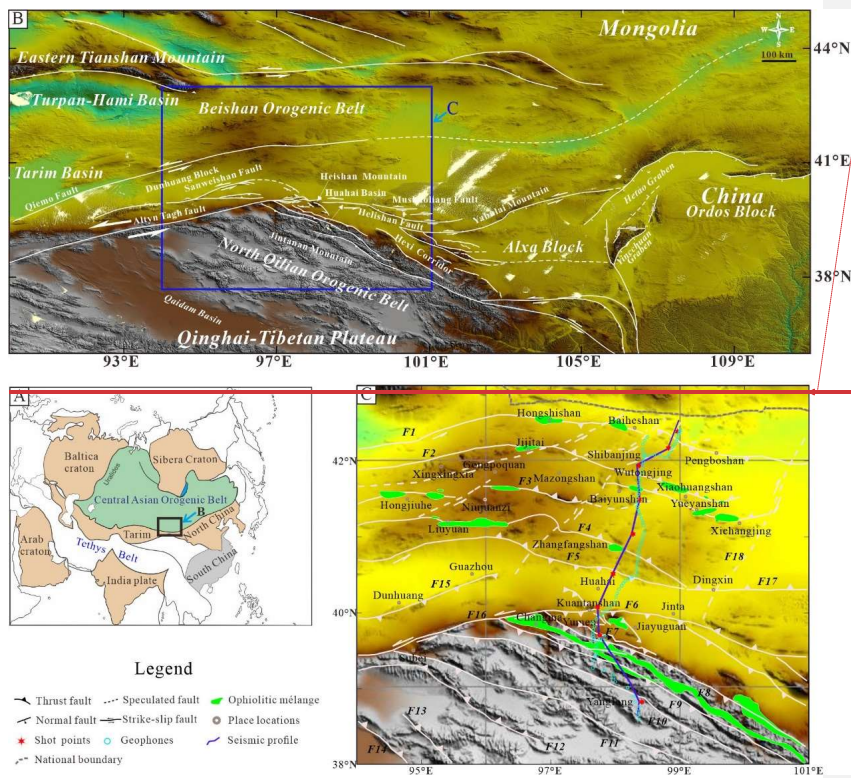
1061 authors contributed to the article and approved the submitted version.

1062
1063 **Code/Data availability**

1064
1065 Any additional requests for raw seismic traces, ray-coverage plots or modelling scripts should
1066 be directed to the corresponding author.

1067 **Declaration of competing interest**

1068 The authors declare that they have no known competing financial interests or personal
1069 relationships that could have appeared to influence the work reported in this paper.
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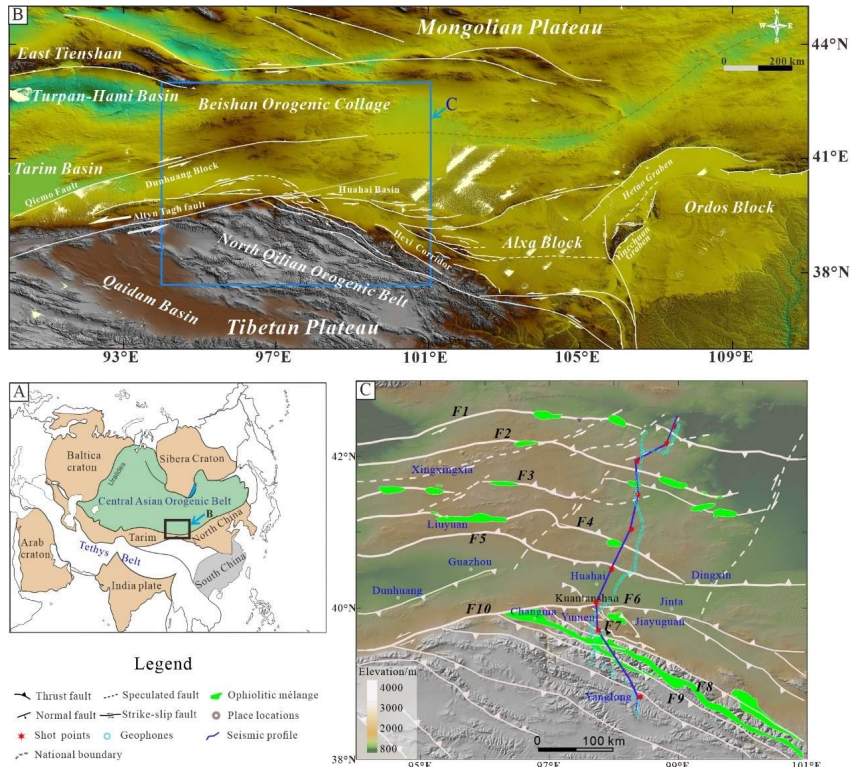


Fig. 1 (a) Simplified tectonic framework of East Asia, emphasizing the CAOB and the Tethys tectonic belt (modified after Xiao *et al.* 2017), and (b) Map of the distribution of main-fault systems in NE-Tibet (modified from Zhang *et al.* 2023). Base map: SRTM 30 m DEM, NASA/USGS (public domain). Processing: Global Mapper v24.0. (c) Map of the main faults in the NE Tibetan Plateau, the Beishan Orogenic Collage, showing the location of the seismic profile, faults and ophiolite mélangé zones. F0: North margin fault of the East Kunlun; F1: the Hongshishan-Baiyueshan-Pengboshan suture zone; F2: the Jijitai-Shibanjing-Xiaohuangshan fault; F3: the Hongliuhe-Baiyunshan-Yueyashan-Xichangjing suture zone; F4: the Liuyuan-Zhangfangshan suture zone; F5: the southern margin fault of the Beishan; F6: the Heishan-Jinta Nanshan; F7: the Yumen-Shuigoukou fault; F8: the northern margin fault of the North Qilian; F9: the North Qilian fault; F10: the northern margin fault of the Middle Qilian; F11: the southern margin fault of the Middle Qilian; F12: the Danghe Nanshan fault; F13: the southern margin fault of the South Qilian; F14: the northern margin fault of the Qaidam; F15: the Sanweishan fault; F16: the Altyn Tagh fault; F17: the northern margin fault of the Alxa; F18: the Ruoshui fault;

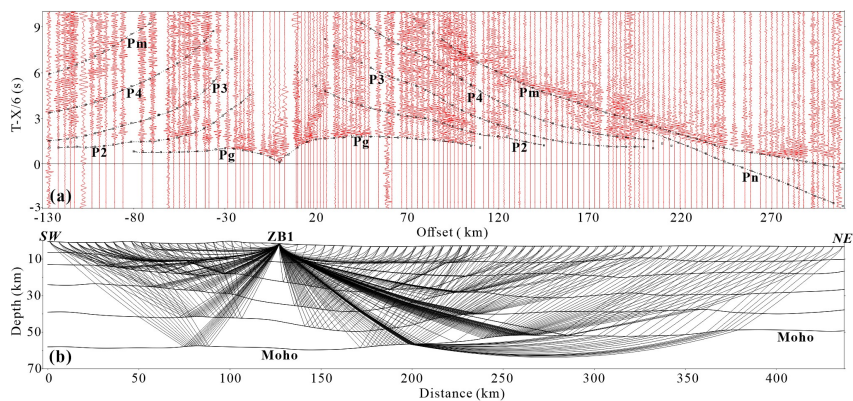


Fig. 2 P-wave record section (on a reduced time scale) corresponding to the shot point ZB1 and identified seismic phases. The seismic phases are marked by dotted lines, and the squares mark the location of calculated traveltimes.

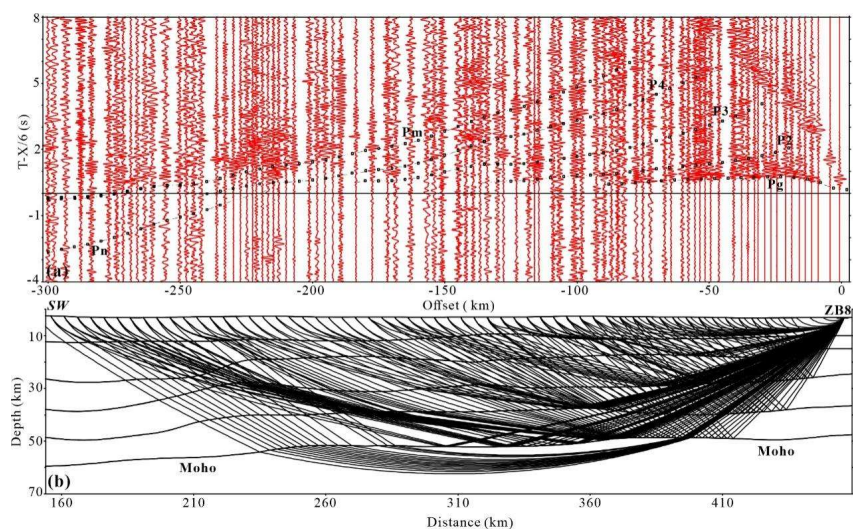


Fig. 3 P-wave record section (on a reduced time scale) corresponding to the shot point ZB8 and identified seismic phases. The seismic phases are marked by dotted lines, and the squares indicate the location of calculated traveltimes.

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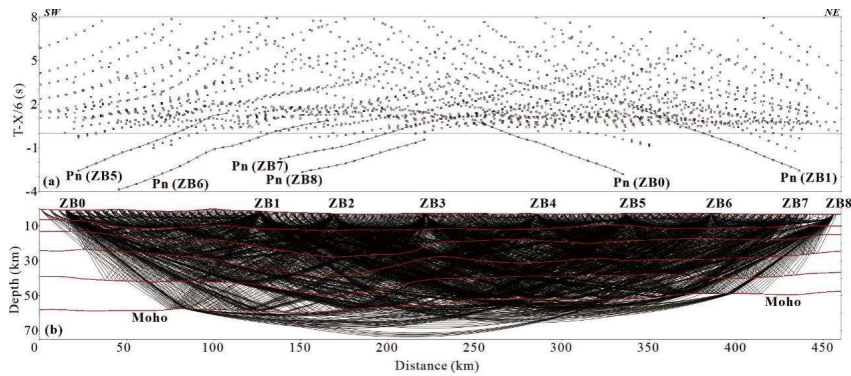


Fig. 4 Traveltime fitting and ray coverage of all shots. (a) ray tracing coverage of the model; (b) rays of all the phases for nine shots.

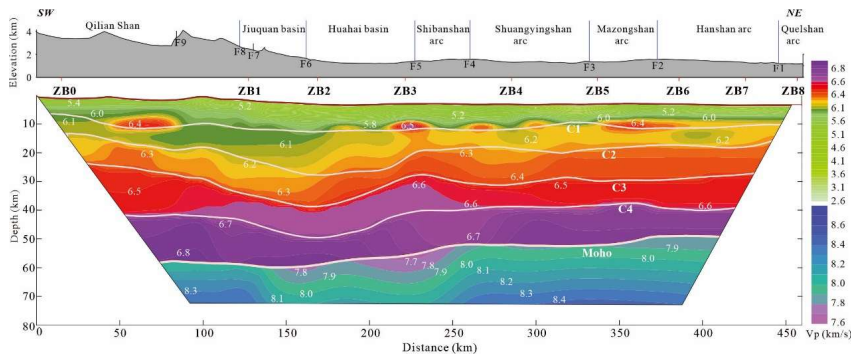


Fig. 5 2-D crustal-upper mantle velocity structure. (a) Upper section: topography showing main tectonic units; (b) lower section: crustal-upper mantle velocity structure. White solid lines denote the main interfaces resolved from wide-angle reflections.

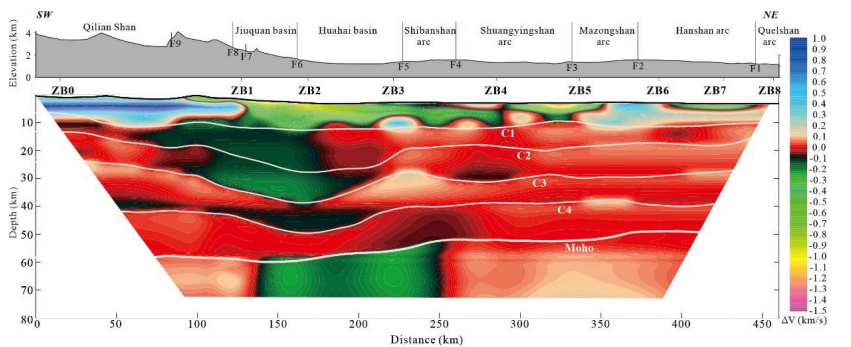


Fig. 6 2-D crustal- upper mantle velocity anomaly structure (layer means subtracted from velocities shown in Fig. 5). (a) Upper section: topography showing the main tectonic units; (b) lower section: crustal-upper mantle velocity anomaly structure. White solid lines denote the main interfaces resolved from wide-angle reflections.

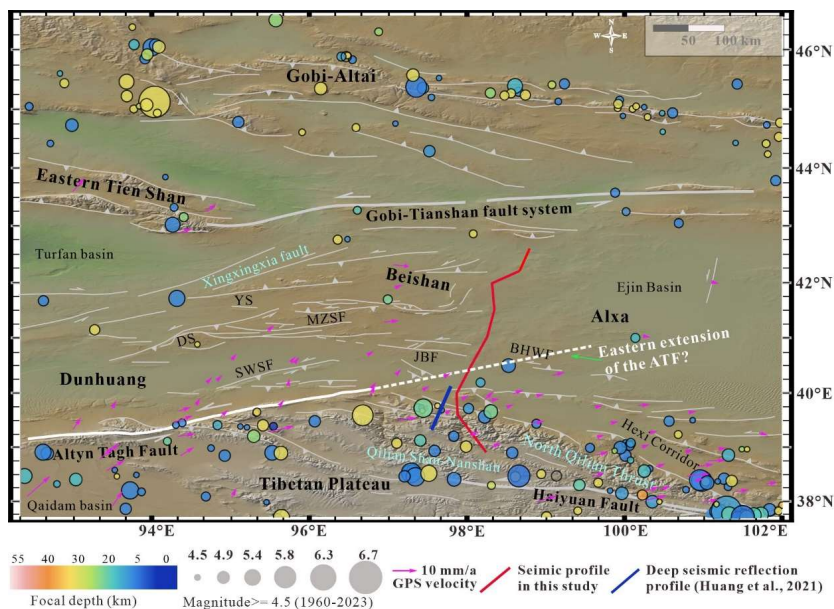


Fig. 7 Earthquake distribution, GPS motion direction, and velocity in NE-Tibet the NE Tibetan Plateau and the Beishan-Beishan Orogenic Collage (modified from Yang et al., 2021). Purple arrows indicate GPS vectors relative to stable Siberia. The dashed white line indicates the proposed eastern extension of the ATF. BHWF: Beihewan Fault; JBF: Jiujiang fault system; MZSF: Mazongshan fault system; SWSF: Sanweishan Fault; DS: Daquan Shan; YS: Yushi Shan.

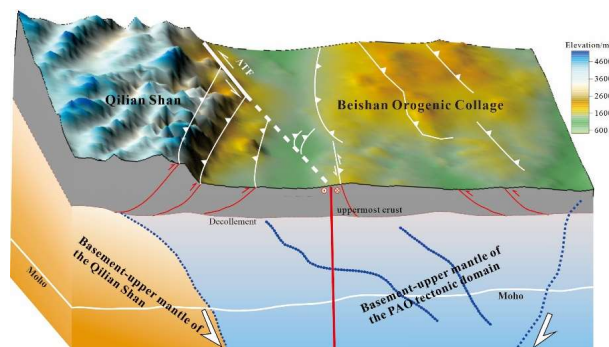


Fig. 8 Tectonic interpretations of observed features derived from the velocity model in across the North Qilian-Beishan Orogenic Collage area. Blue dotted lines represent indicate the inferred subduction directions of the fossil subduction slabs. Red solid lines denote the faults imaged at depth, whereas the white solid and dashed lines represent surface fault traces. Faults (F1-F8) align with Fig. 1.

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Table 1 Explosion position of the deep seismic sounding profile

Shot No.	Longitude (° E)	Latitude (° N)	Elevation (m)	TNT charge (kg)	Shot time (UTC+8)
ZB0	98.406	38.825	3387	2000	00:00:04.900
ZB1	97.761	39.702	2466	2000	23:59:46.890
ZB2	97.724	40.074	1447	2000	23:01:44.285
ZB3	97.965	40.512	1334	1500	22:04:11.157
ZB4	98.271	41.038	1302	1500	22:01:44.340
ZB5	98.367	41.495	1341	2000	22:00:13.350
ZB6	98.364	41.937	1520	3000	23:00:27.270
ZB7	98.818	42.172	1243	2000	20:05:02.438
ZB8	98.958	42.387	1154	3000	23:03:05.596

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Table 2 The RMS error of travelttime fitting for different seismic phases

Shot	Pg		P2		P3		P4		Pm		Pn		RMS time (s)
	No. of picks	RMS time (s)	No. of picks	RMS time (s)	No. of picks	RMS time (s)	No. of picks	RMS time (s)	No. of picks	RMS time (s)	No. of picks	RMS time (s)	
ZB0	16	0.0251	26	0.0137	33	0.0169	37	0.0144	47	0.0159	17	0.0127	
ZB1	58	0.021	58	0.02	57	0.0268	57	0.0207	75	0.0248	26	0.0265	
ZB2	52	0.0309	46	0.032	46	0.0238	55	0.0244	51	0.0266	17	0.0275	
ZB3	48	0.0157	60	0.0226	61	0.0144	59	0.0158	44	0.0123			
ZB4	35	0.0274	39	0.0216	36	0.0218	39	0.0351	35	0.0206			
ZB5	31	0.0118	29	0.0108	43	0.0191	34	0.0189	48	0.0225	13	0.0204	
ZB6	33	0.0228	36	0.0155	37	0.0254	41	0.0204	61	0.0218	19	0.0256	
ZB7	32	0.0246	29	0.019	31	0.0221	33	0.0197	48	0.018	21	0.0238	
ZB8	28	0.0309	25	0.033	33	0.0233	55	0.0228	53	0.0272	12	0.0228	
Mean RMS time (s)		0.0234		0.0209		0.0215		0.0214		0.0211		0.0227	
Total picks	333		348		377		410		462		125		

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