Lithospheric structure across the northeastern margin of the Tibetan Plateau: Implications for the plateau’s lateral growth

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A B S T R A C T

Variations of lithospheric structure across the northeastern Tibetan Plateau and its bounding Asian blocks, the Alxa block to the north and the Ordos block to the east, are crucial for understanding the rise and lateral growth of the Tibetan Plateau. Using waveforms from high-density seismic arrays in northeastern Tibetan Plateau and the surrounding regions, we investigated the lithospheric structure with S- and P-wave receiver functions. The results show strong and relatively simple negative velocity gradients in the depth range of mantle lithosphere (~70–150 km) under the Ordos and Alxa blocks, similar to those under typical stable continental lithosphere. In contrast, under northeastern Tibetan Plateau including its marginal regions, the velocity gradients are weak and diffusive for the mantle lithosphere, which may be explained by elevated temperature and presence of partial melts. The changes of lithospheric structures are sharp between the Tibetan Plateau and the bounding Ordos and Alxa blocks, suggesting that these two blocks have restricted the lateral growth of the Tibetan Plateau as rigid boundaries. However, across the northeastern corner of the Tibetan Plateau to the Yinchuan rift, the lithospheric mantle structures are similar, suggesting a lateral mantle flow from the Tibetan Plateau to the gap between the Ordos and the Alxa blocks. The crustal structures along this transition show evidence of lateral growth of the Tibetan Plateau. In particular, the edge of thickened crust and evidence of Moho superposition are found between the Haiyuan Fault and the Tianjin-shan Fault, which may have replaced the Haiyuan Fault as the front boundary of the laterally growing Tibetan Plateau in its northeastern corner.

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1. Introduction

The rise and growth of the Tibetan Plateau are driven by the Indian–Eurasian continental collision 50–70 million years ago and the continued plate convergence ever since (Dewey et al., 1988; Yin and Harrison, 2000). How the Tibetan Plateau has grown in time and space, however, is unclear and controversial. Models that approximate the Asian lithosphere as a thin viscous sheet show that the indentation of a rigid Indian plate would cause gradual northward rise and growth of the Tibetan Plateau (England and Houseman, 1986). Other models emphasize lateral extrusion of Asian lithospheric blocks in accommodating the plate convergence (Tapponnier et al., 1982). Recent three-dimensional geodynamic models have shown that both lateral variations of lithospheric properties within the plateau and the boundary conditions could play a major role in the rise and growth of the Tibetan Plateau (Yang and Liu, 2013).

Geological evidence for the spatiotemporal growth of the Tibetan Plateau has been inconclusive (Yin and Harrison, 2000; Wang et al., 2014a, 2014b), but it is clear that northeastern Tibetan Plateau is one of the areas of concentrated crustal deformation through the late Cenozoic (Duvall and Clark, 2010; Wang et al., 2014a, 2014b). Yuan et al. (2013) have suggested that the rigid Indian indenter to the south and the Asian lithosphere to the north have largely confined the growth of the Tibetan Plateau in between, with only limited lateral expansion.

The different evolution models of the Tibetan Plateau predict distinct lithospheric deformation in the plateau’s boundary zones. So the lithospheric structure across the northeastern margin of the Tibet Plateau, bounded by the Alxa and the Ordos blocks (Fig. 1),
are crucial for understanding how the plateau has grown. Some studies using receiver functions have suggested that the Asian lithosphere (i.e., North China craton) has subducted as a coherent slab underneath northern and central Tibet (Kumar et al., 2006; Ye et al., 2015). But the tomographic results using data from a more densely distributed network of seismic stations by Liang et al. (2012) suggested that the high-velocity bodies below central Tibet represent fragments of the Indian slab, rather than a coherent Asian mantle lithosphere from the north. Using seismic data from the permanent stations in northeastern Tibetan Plateau, Shen et al. (2015) imaged the lithosphere–asthenosphere boundary (LAB) in this region and found no significant underthrusting of the Asian lithosphere beneath northern Tibetan Plateau. However, the coverage of permanent stations in this region was not dense enough to image detailed variations of crustal and mantle lithospheric structures across the northeastern margin of the Tibetan Plateau, which are needed to determine whether and how the Tibetan Plateau has grown laterally.

In this study we used waveform data from two high-density temporary seismic arrays in northeastern Tibetan Plateau, in addition to the permanent seismic stations (Fig. 1a), to image the lithospheric structure using both S and P receiver functions. Our results show no clear evidence of significant lateral expansion of the Tibetan Plateau except across its northeastern corner into the Yinchuan rift, under which the mantle lithospheric structures are similar to those under the Tibetan Plateau, and the crustal structures across this boundary zone show clear signs of shortening and thickening.

2. Tectonic setting

Our study region is the northeastern corner of the Tibetan Plateau where it meets the Ordos and Alxa blocks (Fig. 1a). The Ordos block is a relic of the North China craton, whose eastern part was thermally reactivated in the Mesozoic (Zhu et al., 2012). The Ordos block has been tectonically stable throughout the Cenozoic (Zhang et al., 1998). The Alxa block is part of the old Asian lithosphere consisting mainly of early Precambrian basement overlain by Cambrian to middle Ordovician strata (Song et al., 2006). The Haiyuan Fault, which connects with the Qilian-shan orogen and joins the Altyn Tagh strike-slip faults further to the west, bounds the Tibetan Plateau from the Alxa block. Near its eastern terminal, the Haiyuan Fault branches into the Tianjin-shan Fault (Fig. 1a), whose age of activation is unclear. The west part of the Tianjin-shan Fault is left-lateral slip; it changes to thrust along the SEE direction around 105.2°E. The Tianjin-shan fault is thought to merge at depth with the Haiyuan Fault (Cavalié et al., 2008).

The Haiyuan and Tianjin-shan faults merge at their eastern ends with the Liupan-shan thrust fault, which separates the Tibetan Plateau from the Ordos block. The initial thrusting on the Liupan-shan Fault started before 7.3–8.2 Ma (Zhang et al., 2006), generally interpreted as indicating the age that the laterally expanding Tibetan Plateau reached the Ordos block (Wang et al., 2014a, 2014b).

The Alxa and the Ordos blocks are separated by the Yinchuan rift basin, part of the circum-Ordos rift system that initiated in the past few million years (Zhang et al., 1998). From the Yinchuan rift to the eastern margin of the Tibetan Plateau is the so-called South–North Seismic Belt in China marked by intense seismicity.

3. Data and method

In this study, we used the seismic waveforms from two high-density portable arrays across the northeastern margin of the Tibetan Plateau: 1) the Haiyuan seismic array of 24 stations deployed by the Institute of Earthquakes, China Earthquake Administration, during December 2012–October 2014, and 2) the Qingling seismic array of 15 stations, deployed by the Institute of Geomechanics of the Chinese Academy of Geological Sciences during February 2011–February 2013. To further improved the coverage we also used data recorded during January 2008–December 2011 from 13 permanent stations of the Gansu and Ningxia seismic networks of China Earthquake Administration (CEA). Fig. 1a shows the map of the station locations. All the 52 stations used in this work are equipped with broadband seismometers.
We use receiver functions to study the variations of crustal and lithospheric mantle structures in this region. Receiver function is a commonly used seismic method to detect discontinuities in the crust and upper mantle with tele-seismic earthquake events. This method isolates the P-to-S or S-to-P wave conversions and reverberations related to the discontinuities by deconvolving the incident P or S waves (Yuan et al., 2006; Kumar et al., 2006; Shen et al., 2015). The waveform of receiver functions provides information of the depth and sharpness or other characteristics of the discontinuities. P receiver function, which uses the P-to-S wave conversions, is well fitted for studying the Moho and upper mantle discontinuities, but not ideal for the LAB because of the interference with multiples from the Moho or shallower structures. For detecting the LAB, the S receiver function has the advantage because the reverberations from shallow structures in the P receiver functions are earlier than the S phase, whereas multiples arrive after the main phase. Nonetheless, the P receiver function is usually stable and easy to be calculated because of no signals before P arrival. The signals before the S arrival are more complicated than P wave, so separating the stable S-to-P phase from S phase is more challenging. In this study, we use both the P and S receiver functions to explore the Moho and LAB in the study area. In order to ensure the objectivity and repeatability, we constructed the P and S receiver functions automatically and simultaneously, and use the P-to-S phase from the Moho on P receiver functions as a criterion to evaluate the validity of S receiver functions.

First, we selected the teleseismic events for P- and S-wave receiver function calculation. The records of teleseismic events with Ms > 5.4 with epicentral distances in the range of 30–90 degrees are collected for P-wave receiver functions. For the S-wave receiver functions, we chose teleseismic events with Ms > 5.6 with epicentral distances in the range of 60–85 degrees to avoid interfere from the SKS phase (Yuan et al., 2006). Fig. 1b shows the location of these seismic events.

For the P-wave receiver function calculation, we cut the three-component records in the time window of 20 seconds prior to and 150 seconds after the P-arrival, and then rotate the waveforms from the north-east-vertical (N–E–Z) to the radial-transverse-vertical (R–T–Z) coordinates according to the events’ back-azimuth. All the selected waveforms are filtered with Butterworth band filter of 1–10 s. The waveforms of three components (R–T–Z) are deconvolved by the Z component in the time window of 10 s prior to and 90 s after the P-arrival, which represents the source information of teleseismic waveforms. The deconvolution is performed in time domain as described by Kumar et al. (2006). The deconvolved results of the R and Z component are used to determine the incident angle (actual incident angle) by maximizing the P-wave energy on the L-component within a time window spanning ±2 s on either side of the theoretical P-onset. If the difference between the actual incident angle and the synthetic incident an-
Fig. 3. E–W stacking profiles of S receiver functions at various latitudes. (a) The locations of the profiles. (b)–(d) Stacking sections of moveout corrected S receiver functions along profiles #1–5 in (a). Topography along the profile is indicated in the top panel. The numbers on the right are corresponding to the depth estimated by S-to-P arrival time. The dashed line marks the Moho, and the gray areas highlight the mantle lithosphere marked by the trains of negative velocity gradients.

gle calculated from IASP91 model (Kennett and Engdahl, 1991) is larger than 10 degrees, the waveforms were rejected. According to the synthetic back-azimuth and the actual incident angle, the three-component Z–N–E records of the P waveforms were rotated into a ray-based L–Q–T coordinate system, oriented in the P–SV–SH directions, and then the Q component was deconvolved by the P signal on the L component in the time window of 10 s prior to and 90 s after the P-arrival. Normally, the L component receiver function is simply a delta function for the normal receiver functions. However, some abnormal receiver functions show strange signals with big amplitude in the L component. For these abnormal receiver functions, we rejected the ones whose root square of the L component between 5–60 s is three times larger than the root square between −2–2 s.
Similar procedure was used to calculate the S-wave receiver functions, for which we used the waveform data with the time window of 200 s prior to and 100 s after the S-arrivals. The waveforms were rotated from the north-east-vertical (N–E–Z) to the R–T–Z coordinate system using the events’ back-azimuth as for P receiver function, then the deconvolved results of the Z and R components are used to determine the actual incident angle by maximizing the SV-wave energy on the Q component within a time window spanning ±2 s on either side of the theoretical S-onset. The waveforms with incident angle difference large than 25 degree are rejected. This criterion is weaker than that for the P-wave receiver functions, because the S phase is more complicated than the P phase. Consequently, only a few extreme abnormal observations are rejected. Then the S receiver function of L component is calculated by deconvolving the S signal on the Q component based on the synthetic back-azimuth and the actual incident angle. The time axis and the amplitude are reversed to keep consistency with the P receiver function. The ratio of root square of Q component receiver function between 5–60 s and between −2–2 s is also used as a criterion to select the S receiver functions.

Compared with our previous work (Shen et al., 2015) that used manual selection, the automated procedure of the data processing used in this study is more objective and repeatable.

4. Results

Using these procedures, and applying the Butterworth band filter to the raw P and S receiver functions, we obtained 5069 P-wave
receiver functions and 3545 S-wave receiver functions. The pierce points of P50s of P-wave receiver functions and S90p of S-wave receiver functions are also plotted in Fig. 1b.

Fig. 2 shows all the P- and S-wave receiver functions, filtered by the Butterworth band filter with 5–50 s, aligned by epicentral distance. The positive signals on the P and S receiver functions around 7 s represent the P-to-S and S-to-P converted phase from the Moho; the consistency of these signals demonstrates the stability and reliability of the calculated P and S receiver functions.

4.1. The lithospheric structures

In addition to the positive signals around 7 s caused by the Moho (Fig. 2b), negative velocity gradients between 10 s and 20 s
provide information of the lithospheric mantle structures. These variations are better seen in the S receiver functions, which is free of the problem of multiple interferences from shallow structures suffered by P receiver functions. These negative signals within this time window (or depth range) have been reported for other continental lithosphere as indicating the LAB (Karato et al., 2015), although it could also be caused by other mid-lithosphere discontinuities (see below). In the following, we call these signals SLp, with the understanding that they could be the signals from the LAB or other discontinuities within the lithosphere.

We stacked the S receiver functions along several profiles across the northeastern margin of the Tibetan Plateau (Fig. 3a). All traces are corrected for distance moveout using a reference slowness of 6.4 s/deg based on the IASP91 global reference model. For each profile, the S receiver functions with the S90p pierce point within 1 degree from the profile are selected, and then the S receiver functions are stacked by bins of piercing point within 0.2 degrees of the longitude. The S receiver functions within the neighboring bins, weighted by the inverse square of the distance, are used to smooth the stacking results.

Figs. 3b–f show the stacked S receiver functions along the profiles at various latitudes. These five profiles cut across part of the Tibetan Plateau, the Ordos block, and the transition zone in-between. The SMp phase from the Moho between 5–7.5 s and the SLp between 10–20 s from the mantle are clear in all profiles. Note that the SLp is stronger and simpler under the Ordos
functions in each region are stacked and the bootstrap resampling method (Efron and Tibshirani, 1998) is used to estimate the error of the stacks. Only the signals with amplitudes exceeding two times of the standard deviation are shown, which gives a 95% confidence detection level. Fig. 5b shows the stacked S receiver functions for each region. The SMp phase around 6 s converted from the Moho is clear in all regions. The SLP phase around 9 s is strong and tight in the Ordos and Alxa blocks, but is weaker and split in the transition zone, indicating a more complicated lithospheric mantle structure in the margins of the Tibetan Plateau.

The contrasting lithospheric structures between these regions show that the Ordos and Alxa blocks have kept their original mantle structure, but along the northeastern corner of the Tibetan Plateau into the Yinchuan rift, the mantle lithospheric structure are reworked by the Tibetan tectonics.

4.2. The crustal structures

The P receiver function, with its shorter period hence better resolution, is better suited for studying crustal structures. The pierce points of P receiver functions (Fig. 1) are close to the stations and do not well cover the whole area as S receiver functions do. But the pierce points of PMs have fine coverage along the three profiles in Fig. 6a, which cross the Haiyuan, Tianjin-shan and Liupan-shan faults with reasonable coverage. Figs. 6b–6d show the stacking of P receiver functions after moveout correction, similar to those for S receiver functions, along these profiles; the bin length of the stacking P-wave receiver functions is 0.1 degree. We used the Butterworth band filter of 2–50 s to the raw P receiver functions to investigate the detailed crustal structures along these profiles.

Along the AA′ profile (Fig. 6a), the Moho is deeper south of the Haiyuan Fault, the tectonic northern boundary of the Tibetan Plateau. However, between the Haiyuan and the Tianjin-shan faults, the crustal structures are complicated by an apparent double discontinuities around the Moho depth, which may indicate the superposition of the Asian and Tibetan crust. Similar features are found in the BB′ profile (Fig. 6b). These P receiver functions suggest that the Tibetan crustal thickening and lateral growth have gone beyond the Haiyuan Fault and reached the Tianjin-shan Fault. The CC′ profile across the Liupan-shan mountains that separate the margin of the Tibetan Plateau from the Ordos block (Fig. 6d). Under the Liupan-shan thrust fault the Moho is the deepest and with the apparent double-discontinuities, consistent with the Liupan-shan mountains being the product and frontier of the lateral growth of the Tibetan Plateau.

5. Discussions

The negative signals from LAB on S receiver functions (SLp) are very close to SMp signals. Furthermore, the side lobe from the filter might also cause the negative signals after SMp. In order to test the stability of the SLp signals, we compared the S receiver functions with different filters. Fig. 7a and 7b show the stacking results of S receiver functions with 5–50 s and 3–50 s band-pass filters along profile#1 in Fig. 3a. The arrival of SMp phase for 5–8 s and SLp signals for 6–12 s are picked up according to the peak value of the positive and negative pulse. Fig. 7c shows the arrivals of SMp and SLp with two filters. The arrival and time difference of SMp and SLp phases are stable for different filters. So the negative signals are from structures rather than from side lobe.

The trains of negative velocity gradients in the depth range of typical mantle lithosphere in our S receiver functions (Figs. 3–4) are also found in many other regions and are often attributed to the LAB (Kind et al., 2012; Sodoudi et al., 2013). The velocity
reduction of these discontinuities is about 2–6%, which in many areas is larger than that at the LAB determined by surface wave dispersion, often much deeper (200–300 km) (Gung et al., 2003). One explanation for these shallower negative velocity gradients is the elastically accommodated grain-boundary sliding model (EAGBS) (Karato et al., 2015), which predicts a substantial velocity drop at the mid-lithosphere discontinuity 60 to 150 km deep beneath stable continents. The negative signals about 10 s in our S receiver functions represent velocity drop at ~90 km depth, which is consistent with the mid-lithosphere discontinuity predicted by the EAGBS model.

The mid-lithosphere discontinuity by elastically accommodated grain-boundary sliding is sensitive to temperature and the water (or melt) content (Karato et al., 2015). Such mid-lithosphere discontinuity beneath stable continent is relatively simple with large velocity drop (Karato et al., 2015), as those beneath the Or-
This notion of a relatively hot mantle lithosphere, with elevated contents of water and perhaps some melts, under the northeastern margins of the Tibetan Plateau is consistent with seismic results from tomography with body waves (Liang et al., 2012), surface waves (Fu et al., 2010) and Pn waves (Liang and Song, 2006), all indicating that the mantle lithosphere and asthenosphere beneath northeastern Tibetan Plateau are hotter than the reference values of Asian continent. The simple and sharp receiver functions beneath the Ordos and the Alxa blocks indicate that the hot mantle material beneath the Tibetan Plateau has not encroached into these bounding Asian blocks. The exception is the Yinchuan rift between the Ordos and the Alxa blocks, where the mantle lithospheric structures are similar to those under the margin zones of the Tibetan Plateau. This may suggest that the eastward mantle flow under the Tibetan Plateau (Owens and Zandt, 1997) is resisted by the rigid Ordos block and redirected to the NNE direction under the Yinchuan rift, and this flow may have facilitated the lateral growth of the Tibetan Plateau in its northeastern corner, as indicated the crustal structures.

In Fig. 8 we sketched the boundaries of the Tibetan Plateau and the bounding Asian blocks in the crust and in the mantle lithosphere, based on our P and S receiver functions, respectively. The crustal structure suggests that, in the northeastern corner of the Tibetan Plateau, lateral growth of the plateau has gone beyond the Haiyuan Fault and reached the Tianjin-shan Fault. This lateral expansion of the Tibetan Plateau in the crust is perhaps associated with a mantle flow that has reached at least to the Yinchuan rift.

This narrow zone of inferred lateral crustal growth and mantle flow may also played a role in the intense seismicity in this region (Fig. 8), which forms the northern part of the so called “South-North Seismic Belt” in China (the southern part of this belt is along the eastern margin of the Tibetan Plateau). One of the large earthquakes in this seismic belt is the Haiyuan earthquake (Mw ~ 8) in 1920, which killed over 200,000 people (Deng et al., 1986; Zhang et al., 1987). Becker et al. (2015) suggested that active mantle flow can contribute to intraplate seismicity by changing the deviatoric stress field in a laterally heterogeneous lithosphere. Beneath the transition zone in front of the expanding Tibetan Plateau, the receiver functions indicate a complicated heterogeneous uppermost mantle. Its interaction with a hot mantle flowing from the Tibetan Plateau would increase the deviatoric stress in the crust and contribute to the intense seismicity.

Fig. 9 is a cartoon summarizing our data and interpretation of the lithospheric structures and their implications for the lateral growth of the Tibetan Plateau. The lateral growth of the Tibetan Plateau has been constrained by the strong Ordos and Alxa blocks. The eastward mantle flow under northern Tibetan Plateau is resisted by the Ordos block and redirected to the gap between the Ordos and Alxa blocks, under the Yinchuan rift. This encroachment by the Tibetan mantle material facilitated the lateral growth of the Tibetan crust in this corridor, with the Tianjin-shan Fault replacing the Haiyuan Fault as the new front boundary fault of the Tibetan Plateau in this region. The different reaches of the Tibetan Plateau crust and mantle also suggest that the crustal and mantle deformation is decoupled in the lateral growth of the Tibetan Plateau.

6. Conclusions

We have used S and P receiver functions from local high-density seismic arrays and permanent stations to investigate the change of mantle lithospheric and crustal structures across the northeastern margin of the Tibetan Plateau. Major conclusions we may draw from this study including the following.

1. The negative velocity gradients within the depth ranges of the mantle lithosphere, which may reflect the LAB or mid-lithospheric discontinuities, are simple and strong beneath the Ordos and the Alxa blocks, similar to those reported for other stable continents and in contrast to those under the Tibetan Plateau. These results indicate that these Asian lithospheric blocks have resisted the lateral growth of the Tibetan Plateau. Under the transition regions between the elevated Tibetan Plateau and the Ordos and Alxa blocks, although the crust has not been significantly thickened, the mantle lithosphere shows weak and diffusive negative velocity gradients similar to those observed under the elevated northern Tibetan Plateau. These negative velocity gradients in mantle lithosphere, according to recent laboratory studies, may be caused by increased temperature and presence of partial melts or water, which would be consistent with previous studies showing high seismic attenuation and low velocity under northern Tibetan Plateau. Our results suggest that alteration of the mantle lithosphere, perhaps by interaction of the lateral mantle flow from under the Tibetan Plateau with the bounding Asian lithosphere, is the prior condition for the lateral growth of the Tibetan Plateau.

2. The change of the lithospheric mantle structures is sharp between the Tibetan Plateau and the Ordos–Alxa blocks and spa-
Fig. 7. Stacking profile of S receiver functions with different filters and arrivals of SMp and SLp phases. (a) S receiver functions with 5–50 s band-pass filter along #1 profile in Fig. 3a. Triangle and diamond represent the arrival of SMp and SLp. (b) S receiver functions with 3–50 s band-pass filter along #1 profile in Fig. 3a. Square and circle represent the arrival of SMp and SLp. (c) The picked arrivals of SMp and SLp phase with different filters.

...atially correlates well with the surface boundaries between these tectonic units. However, the weak and diffusive mantle receiver functions typical of the Tibetan lithospheric mantle extend beyond the Haiyuan Fault, the surface boundary between the Alxa block and the Tibetan Plateau, into the Yinchuan rift, between the Ordos and the Alxa blocks. This may indicate that the lateral mantle flow under the Tibetan Plateau, driven by the Indo-Asian collision, is diverted by the rigid Ordos block and into the gap between the Ordos and the Alxa blocks. Such active mantle may have contributed to the intense intraplate seismicity in the Yinchuan rift by increasing the deviatoric stress in a laterally heterogeneous lithosphere.

3.Localized crustal thickening, with receiver functions suggestive of a double Moho, occurs under the Liupan-shan mountain belt, indicating strong resistance of the Ordos block to the laterally expanding Tibetan Plateau. However, across the Tibetan Plateau’s northeastern corner, the thickened crust has extended beyond the Haiyuan Fault, the main northern boundary of the Tibetan Plateau, and ended at the Tianjin-shan Fault. The receiver functions show double-Moho signals, similar to those under the Liupan-shan mountains, between the Tianjin-shan and the Haiyuan faults. These results suggest that, between the Ordos and the Alxa blocks, the Tibetan Plateau has grown later-
Fig. 8. Boundaries of the different crust and the mantle lithosphere. The blue dashed line marks the boundary of the thinned crust. The orange dashed line marks the boundary of contrasting mantle lithosphere. The white dots are epicenters of earthquakes ($M \geq 5.0$) (http://data.earthquake.cn/data/index.jsp). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Fig. 9. A cartoon interpretation of the lithosphere structures across the northeastern margins of the Tibetan Plateau. The lateral growth of the Tibetan Plateau is restricted by the rigid Ordos block to the east and the Alxa block to the north. Along the northeastern corner, however, a lateral mantle flow (indicated by the arrow) from the Tibetan Plateau has reached the Yinchuan Rift, and crustal thickening has passed the Haiyuan Fault and reached the Tianjin-shan Fault. YR: Yinchuan Rift; TF: Tianjin-shan Fault; HF: Haiyuan Fault; LF: Liupan-shan Fault.

ally from the Haiyuan Fault northeastwards to the Tianjin-shan Fault.

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