1 Contemporary kinematics of the Ordos block, North
2 China and its adjacent rift systems constrained by dense
3 GPS observations

4 Bin Zhao^{a,b}, Caihong Zhang^b, Dongzhen Wang^b, Yong Huang^b, Kai Tan^b, Ruilin
5 Du^b, Jingnan Liu^a

6 ^a GNSS Researcher Center, Wuhan University

7 ^b Institute of Seismology, China Earthquake Administration

8 Corresponding author: cugzhaobin@163.com

9 **Abstract**

The detailed kinematic pattern of the Ordos block, North China and its surrounding rift systems remains uncertain, mainly due to the low signal-to-noise ratio of the Global Positioning System (GPS) velocity data and the lack of GPS stations in this region. In this study, we have obtained a new and dense velocity field by processing GPS data primarily collected from the Crustal Motion Observation Network of China and from other GPS networks between 1998 and 2014. The GPS velocities within the Ordos block can be interpreted as counterclockwise rotation of the block about the Euler pole with respect to the Eurasia plate. Velocity profiles across the graben-bounding faults show relatively rapid right-lateral strike-slip motion along the Yinchuan graben, with a rate of 0.8~2.6 mm/a

from north to south. In addition, a right-lateral slip rate of 1.1~1.6 mm/a is estimated along the central segment of the Shanxi rift. However, strike-slip motion is not detected along the northern and southern margins of the Ordos block. Conversely, significant extension motion is detected across the northwestern corner of the block, with a value of 1.6 mm/a, and along the northern segment of the Shanxi rift, where an extensional rate of 1.3~1.7 mm/a is measured. Both the Daihai and Datong basins are experiencing crustal extension. On the southwestern margin of the block, deformation across the compressional zone of the Liupanshan range is subtle; however, the far-field shorting rate is as high as 3.0 mm/a, implying that this region is experiencing ongoing compression. The results reveal that present-day fault slip occurs mainly along the block bounding faults, with the exception of faults along the northern and southern margins of the block. These results provide new insights into the nature of tectonic deformation around the Ordos block, and are useful for assessing the seismic activity in this region.

10 *Keywords:* crustal deformation; Ordos block; fault slip rate; rift systems; block
11 rotation

12 **1. Introduction**

13 The Ordos block, which is the western part of the north China block (NCB),
14 is characterized by low strain rate and seismicity. In contrast, the margins of this

15 stable block have been active since Cenozoic. The block is surrounded by four
16 rift systems: the Yinchuan rift along its western margin, the Hetao rift along its
17 northern margin, the Shanxi rift along its eastern margin, and the Weihe rift along
18 its southern margin (Yin, 2010) (Figure 1). The block is surrounded by transten-
19 sional right-lateral shear faults to the east and west, and is bounded by left-lateral
20 shear extensional faults to the north and south. The southwestern marginal belt
21 of the block contains a thrust-fold zone in the Liupanshan area, which links with
22 the northeast Tibetan Plateau. Over the past three decades, different models have
23 been developed to describe the tectonic evolution of the graben systems around the
24 Ordos block (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Tian
25 et al., 1992; Northrup et al., 1995; Yin, 2010; Liu et al., 2007). Some researchers
26 considered that the tectonic deformation and evolution of the Ordos area are the
27 result of the far-field Indo-Asian collision (Molnar and Tapponnier, 1975; Tap-
28 ponnier and Molnar, 1977). Alternatively, Some interpreted the idea that North
29 China crustal thinning and volcanic activity may be closely related to the westward
30 subduction of the Pacific plate beneath the Eurasian continent and the roll-back
31 mechanism (Tian et al., 1992; Northrup et al., 1995). Recently, effects from both
32 Indo-Asian collision and Pacific-Asia subduction models have been combined to
33 understand the extensional structures in north China (Yin, 2010; Liu et al., 2007).

34 Thus precise measurement of crustal deformation patterns in this region will be
35 helpful to further improve these models.

36 In the last two decades, space geodetic techniques, especially the Global Po-
37 sitioning System (GPS) have been widely used for quantitative measurements of
38 crustal deformation across tectonic deformation zones in mainland China (Chen
39 et al., 2000; Shen et al., 2000, 2001; Wang et al., 2001; Zhang et al., 2004; Shen
40 et al., 2005; Calais et al., 2006; Gan et al., 2007; Thatcher, 2007; Meade, 2007;
41 Wang et al., 2011a). Kinematic studies in north China and the surrounding area
42 show a first-order crustal deformation pattern in this region as follows. The north
43 China region is moving at $\sim 5\text{--}11$ mm/a eastward relative to the stable Eurasia
44 plate (Shen et al., 2000; Wang et al., 2001). The GPS-based study of Shen et al.
45 (2000) showed that the northern segment of the Shanxi rift around 40°N is under
46 ESE-WNW extension at a rate of 4 ± 2 mm/a. He et al. (2003) compiled more
47 GPS data sets but did not detect clear signs of extension across the same segment
48 of the Shanxi rift. In the study of He et al. (2003), the discrepancy was ascribed
49 to time-dependent crustal deformation. Recently, Wang et al. (2011a) reported
50 the fault slip rates of major faults around the Ordos block using an elastic block
51 model based on GPS data from 1999 to 2007, which depicted the first-order kine-
52 matic features. However, more detailed knowledge of graben-bounding fault slip

53 rates for determining the relative activity along the different segments of the same
54 fault or different faults qualitatively are yet to be archived. These parameters are
55 important not only for understanding the deformation mechanism of North China
56 but also for assessing the earthquake hazards in the rift systems surrounding the
57 block (Meade and Hager, 2005).

58 In this study, following a brief introduction of the GPS data processing, we
59 present the latest horizontal velocity field around the Ordos region based on more
60 recent GPS data. We then present the method of estimating the slip rates of
61 graben-bounding faults around the stable block in the framework of the rigidly
62 rotating Ordos block itself and document the detailed kinematic characteristics of
63 these faults. Finally, we compare the results with previous geodetic and geologic
64 results and discuss the implications of the findings for the crustal deformation.

65 **2. GPS data and processing**

66 GPS data used in this study are mainly obtained from the Crustal Movement
67 Observation Network of China(CMONOC) project from 1999 to 2014 (Ma et al.,
68 2001; Wang et al., 2003; Niu et al., 2005; Li et al., 2012). There are 61 continuous
69 GPS stations and 615 survey mode stations in the study area. All the survey mode
70 stations were observed continuously for at least 4 days during each session. In

71 addition, we also collected GPS data from 2000 to 2014 at 224 campaign stations.
72 Some of them have been established to monitor regional crustal deformation and
73 others are used as survey control markers.

74 All the GPS Receiver-Independent Exchange(RINEX) data were processed
75 using GAMIT/GLOBK software (Herring et al., 2010) in three steps (Zhao et al.,
76 2015). First, the GPS carrier phase data were processed to obtain loosely con-
77 strained daily solutions for satellite orbits, station positions, satellite antenna off-
78 sets, and atmospheric zenith delay parameters. Second, the regional daily solu-
79 tions were combined with the global solutions produced by the Scripps Orbital
80 and Position Analysis Center (SOPAC, <http://sopac.ucsd.edu/>) using the GLOBK
81 software (Herring et al., 2010), and then aligned into to ITRF2008 (Altamimi
82 et al., 2011) through approximately 50 globally distributed reference stations us-
83 ing seven parameters transformation: translation, rotation, and scale. Third, ve-
84 locities were estimated along with offsets induced by earthquakes or equipment
85 changes from position time series using the least squares method. In the solution
86 (for which spans were longer than 2.5 years), we determined the random walk to
87 be applied using the “realistic sigma” method of Herring (2003) and described by
88 Reilinger et al. (2006). The velocity field was finally transformed into the Eurasia-
89 fixed reference frame using plate rotation poles from Altamimi et al. (2011).

90 The GPS horizontal velocity data contain some outliers from various non-
91 tectonic sources. These outliers are usually of large formal errors and are not
92 coherent with other nearby observations, and mainly due to poor observational
93 conditions (sky visibility and multipath issues), or instability of the monuments
94 from sources such as ground water withdrawal, and too short observation spans.
95 Thus, velocity values are rejected if they satisfy any of the following criteria: (1)
96 GPS stations with too short observational time span, typically shorter than 2.5
97 years, which is the minimum time span for estimating reliable velocity accord-
98 ing to Blewitt and Lavalle (2002). (2) Velocity values that are visually different
99 from nearby velocities. These outliers are recognized by detecting large residuals
100 between the interpolated values using the Kriging method and observations. (3)
101 Vectors with uncertainties larger than three times the average uncertainty. After
102 excluding outliers, we finally obtain regional horizontal velocity values at 724
103 stations (Figure 2, see the supplementary for GPS velocity). The average velocity
104 uncertainties are 0.26 and 0.28 mm/a for the east and north components respec-
105 tively. The vertical motion in this region are poorly determined, and stations lo-
106 cated in the graben systems are contaminated heavily by rapid subsidence caused
107 by groundwater withdrawal. We therefore do not examine the vertical motion in
108 this study.

109 **3. Estimation of the fault slip rates**

110 *3.1. Ordos reference frame*

111 A major issue in interpreting GPS-derived surface velocities is to choose the
112 appropriate reference frame. For the kinematic analysis, the velocity field is trans-
113 formed from the Eurasian reference frame into the Ordos reference frame. In this
114 section, we compute the position and angular velocity of the Euler pole of the Or-
115 dos block for the Eurasian reference frame. As the Ordos is one of the most stable
116 blocks in mainland China from geological view (Replumaz, 2003) and there is a
117 very low strain rate within the block from the geodetic perspective, GPS vectors
118 within the block are used as much as possible to estimate the Euler vector via an
119 iterative procedure. During each iteration, the site with the largest postfit resid-
120 ual is rejected and the estimation is redone, until the postfit residual velocities fit
121 a normal distribution with a mean value close to zero. We finally use 62 GPS
122 stations to define the Euler vector. The residual velocities are between -1.5 and
123 1.5 mm/a, with a mean value of 0.18 mm/a and a variance of 0.68 mm/a. The
124 final best fit model is illustrated in Figure 3. The angular velocity pole of rotation
125 from Eurasia to Ordos is located at 116.48°E , 51.81°N with a counterclockwise
126 rotation rate of 0.168 rad/Ma. These results show good agreement with previously
127 published GPS-based models of the Ordos block motion (Wang et al., 2011a). In

128 contrast, it differs from the geological results (Replumaz, 2003), which were de-
129 fined graphically from the trends of Quaternary active normal faults bounding the
130 grabens and from the mean tensional stress axes computed from focal solutions
131 of earthquakes and kinematics of late Cenozoic faults in this region (Zhang et al.,
132 1998). This discrepancy is probably result from the difference in timescales of the
133 geological and geodetic models.

134 The GPS horizontal velocity field with respect to the stable Ordos block in
135 Figure 4 further confirms that deformation is very subtle in the interior of the
136 block and only occurs along the rift systems around the Ordos block, particularly
137 concentrates on the southwestern margin.

138 *3.2. Velocity profiles and average velocity method*

139 In order to investigate the kinematic characteristics of the rift systems around
140 the block in detail, twelve velocity profiles are studied across chosen rifts or faults.
141 These profiles are based on the Ordos fixed local reference frame, such that there
142 are no rotational effect left on the Ordos block side of the velocity field. The
143 profiles illustrated in Figure 4 are mainly across the faults close to the block, and
144 the length and width of each profile are determined depending on the fault we
145 investigated. For example, profile length and width are shorter for the Luoshan
146 fault (profile L in Figure 4) than others, avoiding slip rate basis from the Haiyuan

147 fault.

148 Because of the low fault slip rates, we do not employ dislocation for strike-slip
149 fault or reverse-slip faults to constrain the slip rate and lock depth simultaneously.
150 We only estimate the slip rates of individual faults by calculating the differences in
151 the average site velocities on both sides of the fault trace. In general, the velocity
152 profiles run across the basins around the Ordos block, basin-bounding faults, and
153 other faults. To delineate the detailed kinematic features, the slip rates are esti-
154 mated if it appeared obvious difference motion across the fault. The uncertainties
155 of those slip rates are the sum of the dispersions between the site velocities, with
156 the dispersion being calculated as the root-mean-square of the differences of indi-
157 vidual site velocities with respect to the mean velocity (Walpersdorf et al., 2014).

158 **4. Results**

159 The slip rates for major faults around the Ordos block are summarized in Table
160 1, and illustrated in Figures 5 and 6. In the following subsections, detailed fault
161 slip results are documented.

162 *4.1. Yinchuan graben*

163 The Yinchuan graben is controlled by the range-front fault of the Helan Moun-
164 tains to the west and the Huanghe Fault to the east (Deng and Liao, 1996). The

165 thickness of Quaternary sediments within the basin is as much as 2000m. Dur-
166 ing historic times, one earthquake with magnitude of 8 occurred in the Yinchuan
167 Basin. The magnitude 8 Yinchuan Pingluo earthquake on January 3, 1739 had a
168 maximum intensity of more than 10 (Deng and Liao, 1996). The focal mechanism
169 of this event indicates right-lateral strike slip motion. In this study, we determine
170 the right-lateral slip across the Yinchuan rift at a rate of 2.1 ± 1.0 mm/a. This
171 value is slightly less than the 2.6 mm/a right slip across the Yinchuan rift reported
172 by Wang et al. (2011a). An extensional slip at a rate of 1.2 ± 0.7 mm/a is esti-
173 mated, which agrees well with the results of Wang et al. (2011a). It is still hard
174 to determine the partitioning of slip between the Helan Fault and the Huanghe
175 Fault, although there are several GPS stations in the Yinchuan Basin. From vi-
176 sual inspection, however, an extension rate of roughly 2.0 mm/a is inferred across
177 the Bayanwulashan, which is located approximately 100 km west of the Helan
178 Mountains (Figure 4).

179 4.2. *Jilantai graben*

180 To the north of the Yinchuan graben, the nearly NS trending Jilantai graben
181 is bounded by the Dengkou-Benjing buried fault to the east and by the Bayanwu-
182 lashan to the west. The thickness of Quaternary sediments within this graben is
183 as much as 400 m. The result for the fault-parallel velocity component indicates

184 that the right-lateral slip is only 0.8 ± 0.7 mm/a across the Bayanwulashan fault
185 (Figure 5B). The extensional slip rate across the Jilantai Basin, however, is rela-
186 tively larger, 1.6 ± 0.4 mm/a. A Ms 5.8 earthquake occurred in this basin on April
187 15, 2015, with a strike-slip focal mechanism solution, which is consistent with the
188 tectonic background stress.

189 4.3. *Hetao graben*

190 The EW trending Hetao graben is located on the northwestern segment of the
191 Ordos block. From a geographical perspective, this graben is the northern ex-
192 tension of the Yinchuan-Jilantai graben. It is controlled by the frontal Langshan-
193 Seertengshan fault to the north and by the north frontal Ordos fault to the south.
194 The slip rates of both fault-parallel and fault-normal components are very low:
195 left-lateral slip rate of 0.3 ± 0.9 mm/a and extension of 0.5 ± 1.0 mm/a (Figure 5C).
196 Our results are consistent with the left-lateral slip rate of 0.6 mm/a and the exten-
197 sional rate of 0.5 mm/a inferred from a block model derived using GPS data by
198 Wang et al. (2011a). Although there are eight stations in the Hetao Basin, it is
199 difficult to distinguish the partitioning of slip between the south and north edges
200 of the basin due to their low signal-to-noise ratios.

201 4.4. *Baotou-Hohhot graben*

202 The EW trending Baotou-Hohhot graben is the eastern extension of the Hetao
203 graben: the entire system has been called the Hetao rift system in previous studies.
204 The east end of the Baotou-Hohhot graben is the Shanxi rift; however, how the
205 Hetao and Shanxi rifts terminate in the north is not clear (Yin, 2010). Figure 5D
206 shows the deformation across the Baotou-Hohhot graben. Left-lateral slip of only
207 about 0.6 ± 0.8 mm/a is measured across the north frontal Ordos fault. In contrast,
208 a slip rate of approximately 0.4~0.6 mm/a is estimated across the Daqingshan
209 fault, which is the northern edge of the basin and is a fold-and-thrust belt (Davis
210 and Darby, 2010). However, this result may be arguable because the uncertainty
211 in the estimated slip is large.

212 4.5. *Datong graben*

213 The Datong graben is located in the northern segment of the Shanxi rift. This
214 segment contains a series of en echelon depressions bounded by normal faults, in
215 which Quaternary basaltic volcanoes are present (Xu et al., 1993). A velocity pro-
216 file is projected across the Liulengshan fault, which is the southeastern boundary
217 of the Datong graben. The profile also runs across the Daihai normal fault and
218 the Kouquan fault, which is the northwestern boundary of the basin. No obvious
219 left-lateral slip across the graben is observed, but extensional deformation is de-

220 terminated to be dominant (Figure 5E and F). The total extensional slip is 1.3 ± 0.5
221 mm/a across the Daihai and Datong from northwest to southeast, in which the
222 Kouquan fault accommodates 0.8 mm/a extensional slip, absorbing more than
223 60% of the total extensional deformation.

224 On the southwestern segment of the Datong graben, the horizontal velocity is
225 projected parallel to the strike of the north frontal Hengshan fault and along fault-
226 normal components. The velocity profile illustrates subtle right-lateral slip but
227 significant fault-parallel motion with an extensional slip rate up to 1.7 ± 0.7 mm/a
228 across the whole profile. Extensional slip rates of approximately 1.1 mm/a and 0.6
229 mm/a are measured across the Daihai fault and the north frontal Hengshan fault
230 respectively. Thus, GPS velocity profiles across the Datong Basin demonstrate
231 that the extensional deformation is still occurring in this region. The value for
232 extensional slip herein is less than that of the model documented by Shen et al.
233 (2000) whose GPS campaign solutions were derived from 1996 to 2001.

234 4.6. *Xinding graben*

235 The Xinding graben is located in the north-central segment of the Shanxi rift,
236 and contains the Daixian, Yuanping , and Dingxiang depressions. The graben is
237 bounded by the Yunzhongshan frontal fault to the west, by the Wutaishan frontal
238 fault to the northeast, and by the Xizhoushan frontal fault to the east. There are

239 historical records of three magnitude 7 earthquakes in this basin. The Yunzhong-
240 shan frontal fault shows undetectable fault normal motion but a right-lateral slip
241 of 1.7 ± 0.5 mm/a (Figure 5G). Other mapped faults located in the east of the Yun-
242 zhongshan frontal fault, which are called the Wutaishan and Xizhoushan frontal
243 faults, show no detectable strike-slip motion; therefore, the right-lateral strike-slip
244 is confined to the Yunzhongshan frontal fault. The dextral component is much
245 larger than the average slip rate for the entire Shanxi rift system given by Wang
246 et al. (2011a).

247 4.7. *Taiyuan graben*

248 The Taiyuan graben is situated in the middle of the Shanxi rift, and is a major
249 NE trending basin. The graben is enclosed by the Jiaocheng fault to the northwest
250 and by the Taigu fault to the southeast, and extends for about 90 km along the
251 Fen River from the Taiyuan city in the north to the Lingshi city in the south.
252 We observe a right-lateral strike-slip of 1.1 ± 0.9 mm/a across the whole basin;
253 however the slip partitioning across the Jiaocheng and Taigu faults is not clear due
254 to the lack of enough GPS sites within the basin. The GPS-derived extension rate
255 across the Taiyuan Basin is less than 0.3 mm/a. These results are close to those of
256 Wang et al. (2009), who predicted right-lateral slip rate along whole Shanxi rift
257 on the basis of an earlier GPS solution.

258 4.8. *Linfen graben*

259 The Linfen graben is the southernmost segment of the Shanxi rift. It is bounded
260 by the Luoyunshan frontal fault to the west (Zhang et al., 2003) and by the Huoshan-
261 Fushan frontal fault to the east (Xu et al., 1993). Two magnitude 8 destructive
262 events, the Hongdong earthquake of 1303 and the Linfen earthquake of 1605, oc-
263 curred in the basin(Xu et al., 1993; Liu et al., 2007). The Hongdong earthquake
264 took place on the Huoshan fault in the south and ruptured the Taigu fault in the
265 north with a total rupture length of approximately 163 km(Jiang et al., 2004),
266 while the Linfen earthquake was related to the abrupt sinistral offsetting of the
267 WNW-trending fault in the Linfen graben (Xu et al., 1993). The presence of
268 abundant ground fissures and Quaternary faulting indicate that this region is still
269 tectonically active. The GPS velocity profile across the Linfen Basin shows a dex-
270 tral slip at a rate of 0.8 ± 0.7 mm/a and subtle extensional slip at a rate of 0.2 ± 0.6
271 mm/a. The fault-parallel velocity profile (Figure 6I) shows that the deformation
272 difference across the Luoyunshan frontal fault is negligible, while the velocity
273 difference across the Huoshan-Fushan frontal fault is significant.

274 4.9. *Weihe graben*

275 The nearly east trending Weihe graben is the southern margin of the rigid Or-
276 dos block. It is bounded to the south by the Qingling Mountains, which were

277 formed by the collision of the North China and South China blocks during the
278 Triassic Period, and to the north by the Beishan Mountains. At least three large
279 historic earthquakes with magnitude greater than 7 have occurred in the Weihe
280 graben, including the 1556 M8.5 Huaxian great earthquake that caused more than
281 830,000 deaths (?). The high level of historical seismicity indicates that the nor-
282 mal faults in the Weihe Basin are still currently active. Previous work showed that
283 the Weihe rift has a sinistral slip at a rate of 1.4 ± 0.4 mm/a (Wang et al., 2011a);
284 however, the GPS results of this study indicate no obvious deformation in both the
285 fault-parallel and fault-normal components (Figure 6J).

286 *4.10. Liupanshan thrust system*

287 The Liupanshan thrust belt on the southwestern edge of the stable Ordos
288 Plateau is the transitional zone between the Tibetan Plateau and the Ordos block.
289 This thrust fault started its formation during the Pliocene. Zhang et al. (2004)
290 pointed out that shortening occurs in this area at a rate of 6.0 ± 2.0 mm/a along
291 over zones of hundreds of kilometers in the direction N75°E. The fault-normal
292 component of the GPS velocity profile across the Liupanshan thrust shows ap-
293 proximately continuous deformation across the southwestern side of the fault over
294 a distance of 150 km, but the estimated shortening rate is 3.0 ± 1.1 mm/a, only half
295 of that reported by Zhang et al. (2004). Lateral strike-slip was not determined for

296 the Liupanshan fault in previous works. In this study right-lateral slip at a rate of
297 1.6 ± 0.8 mm/a over a distance of more than 200 km is calculated, and the deforma-
298 tion pattern suggests that the lateral strike-slip is not localized at the Liupanshan.
299 This result is not consistent with the small left-lateral slip determined by Wang
300 et al. (2011a) from an elastic block model. Furthermore, the difference in deforma-
301 tion within 50 km on both sides of the Liupanshan thrust fault appears to be
302 negligible, which is similar to the subtle shortening across the Longmenshan fault
303 before the Wenchuan earthquake (Shen et al., 2005).

304 *4.11. Luoshan fault*

305 The NS trending Luoshan fault connects the southern tip of the Yinchuan
306 graben (Qingtongxia) and the northern end of the Liupanshan fault, and is the cen-
307 tral segment of the western boundary of the Ordos block. Approximately 2.6 ± 0.9
308 mm/a of right-lateral slip and an undetectable extensional rate are constrained for
309 this fault from the GPS velocity data. The lateral slip rate in this segment is the
310 largest one around the Ordos block, and is consistent with the result of Wang et al.
311 (2011a).

312 **5. Discussion**

313 *5.1. Comparison between geodetic and geologic slip rates*

314 The neotectonic deformation of the graben-bounding faults around the Ordos
315 block has been studied previously using available geological data, field investi-
316 gations(Xu et al., 1993; Deng and Liao, 1996; Zhang et al., 2003; Min et al.,
317 2003). Most previous studies have focused on the Yinchuan and Shanxi rifts, es-
318 pecially on the faults where historical earthquakes ruptured. For the Shanxi rift,
319 the kinematic deformation is characterized by its S-shaped geometry with broad
320 extensional domains in the north and south and a narrow transtensional zone in the
321 middle (Zhang et al., 2003). Our new results are more close to the average fault
322 slip rate of 1~4 mm/a on the western border faults of the NNE-trending basins
323 (Ma, 1987). However, right-lateral slip rates from Xu et al. (1993) are generally
324 a factor of 3~8 times greater than geodetic ones for the Shanxi rift. Previous
325 geological work demonstrated that right-lateral slip of 4.9~6.4 mm/a occurs at
326 the Huoshan fault in the central-southern part of the Shanxi rift, decreasing to
327 5.68 mm/a at the Xizhoushan fault, and finally reducing to less than 4 mm/a in
328 the north end of the rift during the Holocene according to the previous geologi-
329 cal work (Xu et al., 1993). The geodetic fault slip data in this study, in contrast,
330 indicate much smaller values of the right-lateral strike. The right-lateral slip rate

331 of the entire Shanxi rift is no more than 2.0 mm/a, with maximum slip occur-
332 ring across the Xinding graben, and 0.8 mm/a right-lateral slip across the Linfen
333 graben that is bounded by the Huoshan fault to the east. The slip rate discrepancy,
334 especially at the Huoshan fault, may be attributable to their critical position in the
335 rift system and also the magnitude 7~8 earthquakes that they have ruptured, and
336 the maximum amount of surface displacement caused by those earthquakes (Xu
337 et al., 1993).

338 For the western margin of the Ordos block, Min et al. (2003) reported a min-
339 imum slip rate of 2.15 ± 0.2 mm/a on the Luoshan fault, which is located at the
340 northeastern margin of the Tibetan Plateau. This fault strikes roughly N-S, based
341 on the right-lateral strike-slip offsets of the oldest alluvial fan, and of a gully, and
342 on the average displacement of the same order of gullies. Right-lateral strike-slip
343 at a rate of 2.6 mm/a is measured on the basis of the GPS data in this study, which
344 agrees well with the geological result but is less than the crude value for the whole
345 rift system. Different GPS-derived slip rates in the western segment of the block
346 show good coincidence, however, different geological results may be biased by
347 the differences in geological dating. For example, Min et al. (2003) estimated that
348 the right-lateral slip at the Luoshan fault has been about 2.15 mm/a since the Late
349 Pleistocene, whereas Deng and Liao (1996) reported a rate of 4~5 mm/a since

350 the Holocene for the same fault. The discrepancy between the short-term geodetic
351 and secular geological slip rates can probably be attributed to secular variation in
352 slip history or systematic errors caused by different methodological approaches to
353 reconstruction of offsets (Cowgill, 2007).

354 For the extensional component, the geodetic and geologic fault slip values
355 show good agreement. Zhang et al. (1998) documented an extensional slip rate
356 of 0.5 mm/a across the central Shanxi graben, and an opening rate of 3.1 mm/a
357 on the northwestern margin of the Ordos block. GPS-based results also reveal
358 that the extensional rate is insignificant in the central Shanxi rift and has a much
359 more significant value of 1.6 mm/a across the Jilantai graben. Both geodetic and
360 geologic fault slip values demonstrate that extensional deformation is confined
361 only to individual locations in the rift systems around the Ordos block rather than
362 occurring in the all graben systems.

363 *5.2. Kinematic pattern of the southwestern Ordos block and its counterclockwise* 364 *rotation*

365 The southwestern margin of the Ordos block connects with the northeast cor-
366 ner of the Tibetan Plateau, where thrust structure faults and folds are well devel-
367 oped. The GPS velocity profile across the Liupanshan thrust fault indeed shows
368 a significant shortening over a distance of approximately 300 km; however, no

369 obvious velocity differences are observed close to the Liupanshan fault (Figure
370 6K), implying that the fault maybe locked and is building up elastic strain. Spirit
371 leveling data across the northern segment of the Liupanshan demonstrates that a
372 maximum uplift rate of more than 6 mm/a is measured near the fault trace on
373 the hanging wall, similar to the vertical deformation pattern prior to the Mw 7.9
374 Wenchuan earthquake of 2008 (Hao et al., 2014). Thus, this area has been the
375 focus of a great deal of attention. More detailed fault coupling ratio based on
376 geodetic observation and historic earthquakes should be investigated in future.

377 Counterclockwise rotation of the Ordos block have been observed by geolog-
378 ical field works and GPS measurements. So what is the possible mechanism of
379 the block rotation? Zhang et al. (1998) proposed that the Ordos block rotates
380 counterclockwise as a result of the push of Tibet through the left-lateral strike-
381 slip Haiyuan fault and the Liupanshan thrust and fold belt. They also inferred
382 that the left-lateral strike-slip Kunlun-Taibai faults have also rotated the continen-
383 tal fragments, such as the Ordos block (Zhang et al., 1998). This study provides
384 further evidences from a geodetic perspective. Crustal shortening rate across the
385 Liupanshan thrust fault results from stress transferred from northeastern Tibet,
386 which is the most important mechanism for the block rotation. Additionally, rapid
387 deformation occurs along the east left-lateral strike-slip Haiyuan fault, which ter-

minates against the compressional zone of the Liupanshan range. Therefore, it is likely that the left-lateral slip on the Haiyuan fault may have been transferred to push the southwestern margin of the block, and may consequently have caused the block to rotate counterclockwise. However, it is uncertain whether the left-lateral Taibai-Qinling faults have played an important role, as there is no detectable fault slip along the Taibai-Qinling faults based on GPS measurements.

5.3. *Implications for opening of the northern Shanxi rift*

Interestingly, a striking deformational feature is detected in the northern segment of the Shanxi rift. The deformation is not the same as the significant opening across the Daihai basin of as much as 4 ± 2 mm/a reported by Shen et al. (2000), nor is it the smooth variation across the active faults presented by He et al. (2003). On the basis of improved GPS station coverage and a longer time span, the results of this study reveal that the northern segment of the Shanxi rift is indeed undergoing ENE opening across the whole velocity profile at a slip rate of $1.3\sim 1.7$ mm/a, which is less than half of the extension rate reported by Shen et al. (2000). We find the Daihai fault is not the only active tectonic structure that is experiencing opening; we also find detectable extension rate across the Kouquan fault, Liulengshan fault, and the north frontal Henshan fault, all of which bound the Datong basin. Although the Daihai basin, which has been recognized as a young rift in geolog-

407 ical studies, is more seismically active than the Datong basin, previous studies
408 indeed underestimated the extensional rate across the Datong basin. Thus, the
409 diffuse extensional deformation on the northern Shanxi rift is accommodated by
410 several basin-bounding faults and the Daihai basin together. The moderate earth-
411 quakes that have occurred within the Datong basin further support this geodetic
412 finding.

413 Two end member models have been developed to interpret the diffuse exten-
414 sive deformation of the northern Shanxi rift. One model proposed a far-field ef-
415 fect of the India-Eurasia convergence; the other involves the westward subduc-
416 tion of the Pacific plate beneath the Asia continent. It is now generally accepted
417 that the above end member plate kinematic models interact spatially and tempo-
418 rally in north China and caused episodic evolution of Cenozoic basins (Zhang
419 et al., 2003). Further geophysical evidences from seismic tomography (Huang
420 and Zhao, 2006; Lei, 2012), geothermal heat flow (He, 2015), and the thickness of
421 lithosphere (Tang et al., 2013) appear to provide the necessary information to ad-
422 dress this question. From geodetic view, GPS inferred right-lateral slip rate along
423 the different segments of Shanxi rift and earthquake induced right-lateral offsets
424 verify the counterclockwise rotation of the Ordos block, which is a result of push-
425 ing stress from northeastern Tibetan Plateau. On the other hand, GPS observation

426 have provided evidence of extensive deformation due to the westward subduction
427 of the Pacific plate. For instance, continuous GPS station in North China recorded
428 far field coseismic deformation of the 2011 Mw 9.0 Tohoku-Oki earthquake (Zhao
429 et al., 2012). Static offsets caused by coseismic rupture along subduction area lead
430 to static extensional strain in North China (Wang et al., 2011b). Although the in-
431 duced strain rate is only approximately $1 \times 10^{-8}/a$ in Shanxi rift system, it sheds
432 light on understanding crustal deformation of North China.

433 5.4. *Earthquake cycle in the central segment of Shanxi rift*

434 GPS observed short term slip rates along active faults can deviate from long
435 term geological values due to unmodeled transient process associated with the
436 earthquake cycle (Hilley et al., 2009). Rheology of lithosphere plays an important
437 role for the earthquake cycle modelling (Devries and Meade, 2013). A complete
438 historic earthquakes occurred along the Shanxi rift have been recorded. One of the
439 strongest events occurred at Hongdong in 1303, which ruptured Huoshan fault in
440 the south and Taigu fault in the north, with a total rupture length of approximately
441 160 km and coseismic slip of 6~10 m (Jiang et al., 2004). Another magnitude of
442 7.75 earthquake attacked the Lenfen Basin 392 year later. Geodetic data follow-
443 ing large earthquakes suggest the viscoelastic relaxation driven by viscous flow in
444 lower crust and upper mantle is almost totally relaxed after more than 100 years.

445 The latest study suggest GPS data can detect transient late postseismic deforma-
446 tion following the 1700 M9 Cascadia subduction earthquake(Pollitz et al., 2008).
447 We believe our GPS inferred right-lateral slip rates along the Shanxi rift are not
448 biased by transient deformation. Integrating our new results and those from Wang
449 et al. (2011a), the right-lateral slip rate along the central segment is around 1.0
450 mm/a. On the basis of this geodetic observed slip rate and average coseismic
451 slip of 1303 Hongdong earthquake, the recurrence interval of this typical event is
452 about 6000 years, which is 3~4 times larger than the estimate by Xu et al. (1993).
453 Given the low slip rate in North China and long recurring interval of large earth-
454 quakes, it is a big challenge to evaluate the seismic hazards along the faults in this
455 region.

456 **6. Conclusions**

457 The density and quality of the GPS velocity data, combined with a detailed
458 analysis of the graben-bounding faults that accommodate the current strain ac-
459 cumulation, allow estimation of the contemporary kinematics and slip rates on
460 major faults surrounding the Ordos block. Our results show a weak counterclock-
461 wise rotation of the block with respect to the Eurasia plate, confirming that it is
462 stable and rigid like the Sichuan and Tarim basins. Compared to previous results

we not only confirm the first-order kinematic pattern but also detect detailed kinematic processes along the graben-bounding faults. For instance, an extensional rate of approximately 1.3~1.7 mm/a along northwest-southeast profiles across both the Daihai and Datong basins is measured, indicating both the Daihai and Datong Basin are accommodating the opening displacement of northern segment of the Shanxi rift. By integrating GPS inferred interseismic kinematic deformation and static strain changes induced by 2011 Mw 9.0 Tohoku-Oki earthquake, it is prone to conclude that both the Indo-Asian collision and Pacific-Asia subduction models contribute to the extensional structures in North China. In addition, modern GPS derived low slip rates along graben-bounding faults and several M8 historic earthquakes occurred in the graben systems indicate the recurrence interval of typical large earthquake is a long time span, increasing the challenge of earthquake hazard assessment in this region. For the case of the Liupanshan thrust fault, there is not significant velocity difference across the fault in the near field, however the far-field shortening rate reaches 3.0 mm/a. It seems the shallow portion of the fault is locked in interseismic stage. Therefore a detailed fault coupling ratio distribution should be inverted using dense geodetic data especially the vertical motion in future.

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666 Fig. 1: Topographic relief and tectonic map of the Ordos block and its sur-
667 rounding area. Pink solid circles are earthquakes from 780 B.C. to 2015. The
668 earthquake focal mechanisms were obtained the Harvard CMT catalog, 1976-
669 2015. Active faults were adapted from Zhang et al. (2003). Red solid circles
670 denote cities in the rift systems. Abbreviations are HLF, Helanshan fault; HHF,
671 Huanghe fault; BYF, Bayanwula shan fault; LSF, Langshan fault; SETF, Seerteng
672 shan fault; NFOF, north frontal Ordos fault; DQF, Daqingshan fault; DHF, Daihai
673 fault; KQF, Kouquan fault; LLF, Liulengshan fault; NHSF, north frontal Heng-
674 shan fault; WTSF, Wutaishan fault; XZSF, Xizhoushan fault; JCF, Jiaocheng fault;
675 TGF, Taigu fault; HSF, Huoshan fault.

676 Fig. 2: The GPS horizontal velocity field around the Ordos block with re-
677 spect to the stable Eurasian reference frame. The error ellipses represent 95%
678 confidence.

679 Fig. 3: Horizontal GPS velocity data used for Euler vector estimation. (a) Ob-
680 served and modelled GPS velocities in Eurasia reference frame, (b) residual ve-
681 locities between observed and predicted using block rotation model. Inset shows
682 histogram of residuals, which are fit well by a Gaussian distribution with mean of
683 0.18 and standard deviation of 0.68 mm/a.

684 Fig. 4: GPS horizontal velocity field with respective to the stable Ordos block.

685 The black rectangular frames surrounding fault segments mark the regions within
686 which GPS stations are depicted for slip rate estimation; velocity profiles for these
687 stations are illustrated in Figure 5. Blue and red labels in the gray boxes are exten-
688 sional(positive in sinistral) and strike slip(positive in extension) rates respectively.

689 Fig. 5: GPS velocity profiles across major active faults (rifts) around the Ordos
690 block. (left) Fault-parallel (sinistral positive) and (right) fault-normal (extensional
691 positive) components, with respect to the distance along the profile. Data entries
692 are indexed by regions outlined in Figure 4. Vertical bars denote the locations
693 of main faults. Gray bars depict the scattering range of data on both sides of the
694 fault.

695 Fig. 6: (continuation of Figure 5) GPS velocity profiles across major active
696 faults (rifts) around the Ordos block. (left) Fault-parallel (sinistral positive) and
697 (right) fault-normal (extensional positive) components, with respect to the dis-
698 tance along the profile. Data entries are indexed by regions outlined in Figure 4.
699 Vertical bars denote the locations of main faults. Fault abbreviations as for Figure
700 1. Gray bars depict the scattering range of data on both sides of the fault.

701 Table 1: Slip rates of graben-bounding faults around the Ordos block

Figure 1:

Figure 2:

Figure 3:

Figure 5:

Figure 6:

Table 1:

Profile index	Rift system	Basin/Fault	strike-slip(mm/a) ¹	extensional-slip(mm/a) ²
A	Yinchuan	Yinchuan	-2.1±1.0	1.2±0.7
B		Jilantai	-0.8±0.7	1.6±0.4
C	Hetao	Hetao	0.3±0.9	0.5±1.0
D		Baotou-Hohhot	0.6±0.8	-0.4±1.0
E F	Shanxi	Datong	-0.4±0.7	0.6±0.6 ~ 0.9±0.5
E F		Daihai	—	0.3±0.2~1.1±0.9
G		Xinding	-1.7±0.5	-0.1±0.5
H	Weihe	Taiyuan	-1.1±0.9	0.0±0.7
I		Linfen	-0.8±0.7	0.2±0.6
J		Weihe	-0.3±0.6	0.2±0.8
K		Liupanshan	-1.6±0.8	-3.0±1.1
L		Luoshan	-2.6±0.9	0.1±0.7

¹ Positive denotes sinistral motion; negative dextral motion.

² Positive denotes extension (normal fault); negative contraction (reverse fault).