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Regional crustal deformation characteristic before 2016 Yuncheng M4.4 earthquake swarm based on CMONOC continuous GPS data

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ABSTRACT

To further study regional deformation characteristic in the southeast margin of Ordos Block during the period between the Alanshan M5.8 and Yuncheng M4.4 earthquake swarm, we analyze continuous GPS sites around the study area. The time-varying strain parameters removed a linear trend deviated from the background state in varying degrees since April, 2015, and began to turn back at the end of the year 2015, meanwhile, the maximum extension strain and shear strain have the bigger variation relative to others. The GPS measurement also shows that the eastward displacement rate of the stations decreases during 2015–2016 in varying degrees compared to 2011–2015, and the variation is closely related to its geologic structural location. The differential movement between the stations is converted into regional strain accumulation due to the fault locking. Furthermore, during 2015–2016, the maximum extension rate oriented at near NS direction obviously increased, and the maximum contraction strain direction is changed from NW to EW direction, which contributes to strengthen extension and shear strain of the NE-striking faults, it's consistent with the regional background strain state of Shanxi seismic zone, this may be an important contributor to occurrence of M4.4 earthquake swarm in Yuncheng basin.

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1. Introduction

On March 12th, 2016, a M4.4 earthquake swarm occurred at Yanhu district, Yuncheng City, Shanxi Province (35.00°N, 110.88°E), which is located in southeast margin of Ordos Block. The event broke the M4.0 seismic activity quietude in past six years in Shanxi, suggesting that this area may enter into M4.0 earthquake active period once again.

On April 15th, 2015, the Alashan M5.8 earthquake occurred in northwest margin of Ordos Block. The event is the most significant earthquake in Ordos massif in recent years. What is the relationship between the two earthquakes, and what had changed the characteristic of the regional crustal deformation of Ordos southeast margin?

2. GPS data

We select six CMONOC GPS continuous stations around Linfen–Yuncheng Basin, they're SXLF, SXGX, SXXX, HAJY, XIAA and SNYA. The sites are all built on the bed rock, and have high quality of the observation data.

The time series results were provided by the First Crust Monitoring and Application Center, China Earthquake Administration. The processing strategy is as follows: using GAMIT software to get the single-day solution, and some crustal movement observation network reference and IGS stations are added in processing. Using QOCA software to perform the overall adjustment, and select eighty IGS stations distributed uniformly in the world as the framework points, finally getting the time sequence of each station in ITRF 2008, repairing the step caused by instrument renewal, strong earthquake effect, and some unknown reasons [1,2].

3. Geodetic estimates of time-varying strain

3.1. Strain calculation methodology

During the inter-seismic period, active faults are expected to produce strain localizations above their creeping upper tip lines [3], therefore, calculation of strain in a region can be useful for identifying active faults and characterizing deformation patterns throughout a region.

If we suppose the velocity of any point in the crust is contributed by regional overall movement and uniform deformation, we can use the entire GPS velocity data in the area and perform each station's velocity using the following model [4,5].

$$\begin{bmatrix} V_e \\ V_n \end{bmatrix} = \begin{bmatrix} -R\sin\varphi\cos\lambda & -R\sin\varphi\sin\lambda & R\cos\varphi \\ R\sin\lambda & -R\cos\lambda & 0 \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} \varepsilon_e & \varepsilon_{en} \\ \varepsilon_{ne} & \varepsilon_n \end{bmatrix} \begin{bmatrix} (\lambda-\lambda_0)R\cos\varphi \\ [\varphi-\varphi_0]R \end{bmatrix}$$

where λ and ϕ are longitude and latitude of the observation points, V_e and V_n are eastward and northward velocity, ω_x, ω_y

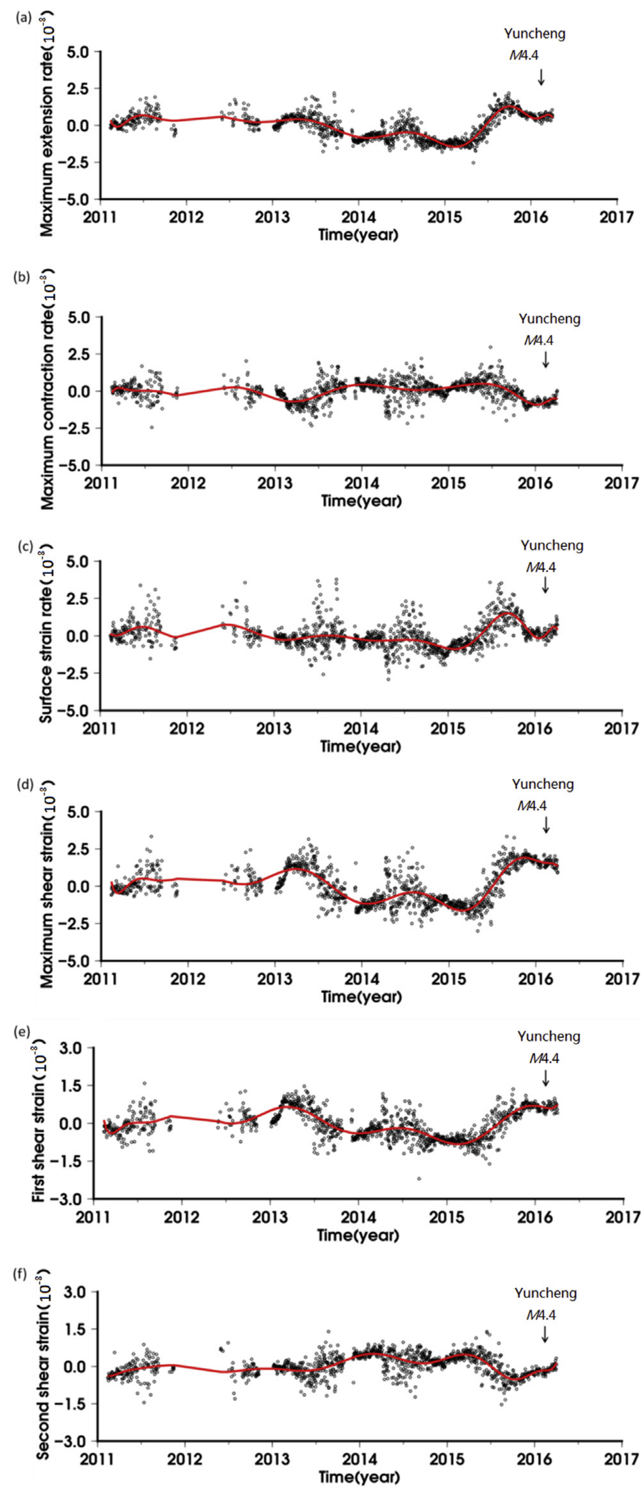


Fig. 1 – Time-varying strain parameters of the south–west margin of Ordos block deduced from six continuous GPS stations (a) SXLF, (b) SXGX, (c) SXXX, (d) HAJY, (e) XIAA and (f) SNYA, each strain parameter removes linear trend by a robust least squares fit, and then fits residual data by the polynomial function, the red lines indicate the fitting results.

and ω_z are block Euler's vector, R, λ_0 and ϕ_0 are respectively the mean curvature radius, longitude and latitude of geometric center of the block, ε_e, ε_{en}, ε_{ne} and ε_n are infinitesimal strain tensors.

Using the corrected horizontal GPS velocities, we can estimate the horizontal strain tensors, useful aspects of strain tensors can be directly calculated including the maximum extension strain, maximum contraction strain, surface strain, maximum shear strain, first shear strain and second shear strain.

Calculating the strain tensors from velocity and spatial information associated with GPS sites can be formulated as a linear inverse problem. In general, there are six unknown parameters in two dimensions, the simplest inversion requires three GPS sites, in this paper, in order to provide a more robust estimate of regional strains, we use more than three GPS sites and utilize least squares inversion methods to solve the over-constrained problem [6].

3.2. *Characteristic of time-varying strain*

We choose six continuous GPS sites around the area, they're SXLF, SXGX, SXXX, HAJY, XIAA and SNYA, by which we perform inversions to get six kinds of strain parameters mentioned above, our focus here is studying the trends and not matching the specific strain magnitudes or even anomalies in the inversion results before the earthquake. In order to highlight the short-term variation characteristics of each parameters, we remove a linear trend from the raw data by a robust least squares fit with respect to outliers, and weighted by the error of each value during the fitting, then fit the above residual data by the polynomial function, and the fitting is made robust by iterative reweighting of the data.

Fig. 1 suggests that the result can reflect the micro strain variation characteristic since 2013, although the data lost much from 2011 to 2012 because the observation continuity rate of station SNYA, SXLF and SXXX is poor. It can be seen that all calculated strain parameters deviated from the background state in varying degrees since April, 2015, and turned back at the end of the year 2015. The maximum variation range of all strain parameters is shown in Table 1.

From the perspective of regional stress and strain, the southwest margin of Ordos is in an expansion state after Alashan *M*5.8 earthquake, the maximum extension strain changed from -1.7×10^{-8} to 1.2×10^{-8} in less than half a year, which indicates that the regional extensional stress is constantly strengthened. The maximum shear strain changed from -1.5×10^{-8} to 2.0×10^{-8}, which indicates that the shear stress changed to the opposite direction. The regional fracture is generally NE trend, more detailed analyses indicate that the left lateral shear stress of faults are persistently strengthened because the first shear strain changes from negative to positive.

4. Continous GPS velocity and regional strain rate

4.1. *Continuous GPS velocity variation*

In order to study the GPS velocity variation before Yuncheng *M*4.4 earthquake swarm, we get East and North velocities of the above six GPS stations during 2011–2015 and 2015–2016 by piecewise linear fitting, and the segmentation is based on the following two reasons: (1) the regional time-varying GPS strain parameters deviated from the background status between 2015 and 2016 before Yuncheng *M*4.4 earthquake swarm. (2) the regional seismic activity was relatively calm in 2011–2015, there is no *M*4 earthquake occurred. So we use the data during 2011–2015 as background state, and data during 2015–2016 as anomaly state. The results are listed in Table 2 and Fig. 2.

It can be seen that the displacement rate errors are less than 0.12 mm in the East, and 0.7 mm in the North except SXGX station. Compared to 2011–2015, the rate of eastward movement of stations decreases during 2015–2016 in varying

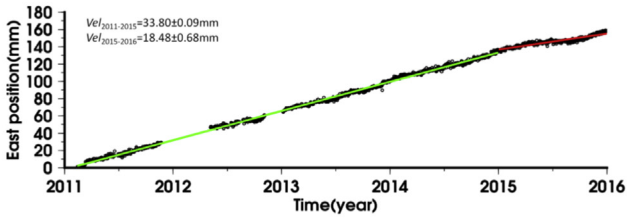
Table 1 – Maximum variation range of the strain parameters.

Strain Parameter	Maximum extension strain	Maximum contraction strain	Surface strain	Maximum shear strain	First shear strain	Second shear strain
Maximum variation range	2.9×10^{-8}	-0.9×10^{-8}	2.0×10^{-8}	3.5×10^{-8}	1.5×10^{-8}	-1.0×10^{-8}

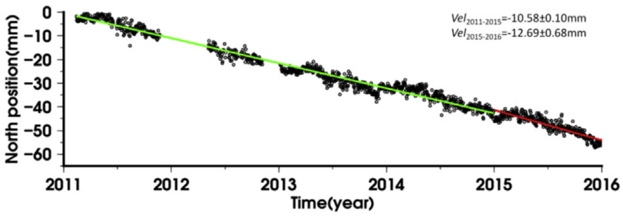
Table 2 – GPS velocity during 2011–2015 and 2015–2016 (with 95% confidence).

Station Name	East velocity (mm/a)			North velocity (mm/a)		
	2011–2015	2015–2016	Variation	2011–2015	2015–2016	Variation
SNYA[a]	33.80 ± 0.09	18.48 ± 0.68	−15.32	−10.58 ± 0.1	−12.69 ± 0.68	−2.11
XIAA[b]	35.40 ± 0.09	29.86 ± 0.52	−5.56	−7.53 ± 0.11	−7.60 ± 0.63	−0.07
SXXX[c]	33.42 ± 0.10	28.19 ± 0.54	−5.23	−9.69 ± 0.12	−8.52 ± 0.70	1.17
SXLF	33.76 ± 0.09	30.25 ± 0.51	−3.51	−10.94 ± 0.10	−11.1 ± 0.67	−0.16
SXGX	33.02 ± 0.08	30.63 ± 0.67	−2.39	−10.29 ± 0.10	−10.5 ± 1.11	−0.21
HAJY	33.24 ± 0.10	31.61 ± 0.52	−1.61	−11.2 ± 0.11	−10.24 ± 0.70	0.96

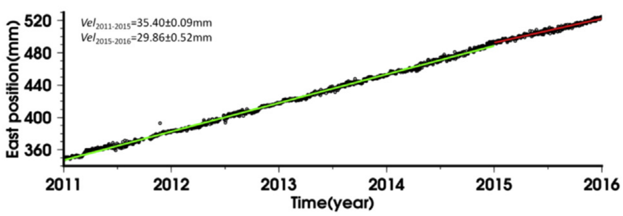
[a] The velocity fitting result is shown in Fig. 2(a) and (b).
[b] The velocity fitting result is shown in Fig. 2(c) and (d).
[c] The velocity fitting result is shown in Fig. 2(e) and (f).



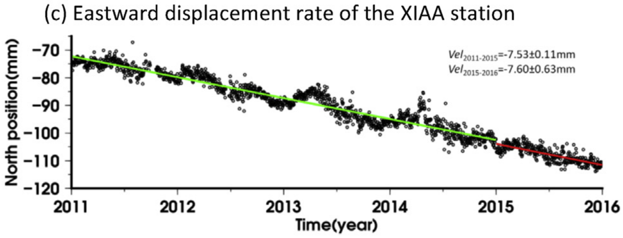
(a) Eastward displacement rate of the SNYA station



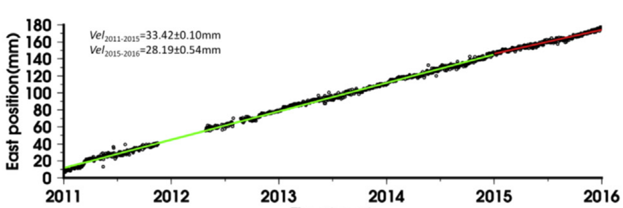
(b) Northward displacement rate of the **SNYA station**



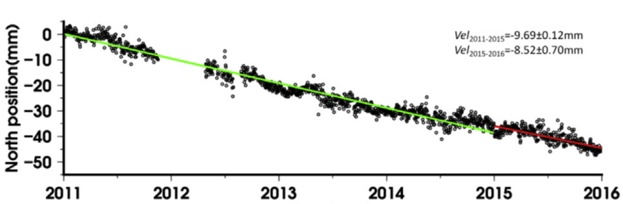
(c) Eastward displacement rate of the XIAA station



(d) Northward displacement rate of the **XIAA station**



(e) Eastward displacement rate of the SXXX station



(f) Northward displacement rate of the **SXXX station**

Fig. 2 – Eastward and northward displacement rate of the station SNYA, XIAA and SXXX during 2011–2015 and 2015–2016, the green lines indicate the velocity fitting results during 2011–2015, the red lines indicate the velocity fitting results during 2015–2016.

Table 3 – Regional strain rate during 2011–2015 and 2015–2016.

Time interval	Number of sites	ε_1,[a] (nstrain/yr)	ε_2,[a] (nstrain/yr)	Azimuth,[b] (deg.)
2011–2015	6	0.01371	−8.448	−35.07
2015–2016	6	6.271	−12.06	−87.08

[a] The parameters ε_1 and ε_2 are maximum extension rate and contraction rate, respectively.
[b] Azimuth is measured anticlockwise from north to the contraction rate axis.

degrees, the SNYA station in Ordos Block decreases 15.32 mm/a, almost fifty percent of the original rate; the XIAA and SXXX stations in Weihe basin decrease 5.56 mm/a and 5.23 mm/a respectively, about eighteen percent; the SXLF and SXGX stations in Linfen Basin, and HAJY station in south area of Taihang mountains decrease 3.51 mm/a, 2.39 mm/a and 1.61 mm/a separately, all less than ten percent. The northward velocities change a little, and the variation closed to data error level except SNYA station increasing 2.11 mm/a and SXXX station decreasing 1.17 mm/a in southward movement rate.

4.2. *Regional strain rate variation*

An additional calculation that can be made from the GPS velocities is an estimate of the average regional strain rate. Such estimations have been used to study the regional deformation mechanism [7–9]. To calculate a best-fitting regional strain rate, a least squares inversion can be made based on the entire horizontal GPS velocity data set using equation in 3.1, if the sites are supposed to be reliable [10]. Using the velocities in 2011–2015, the inversion results in a best-fitting maximum contraction rate of −8.448 nstrain/yr oriented at −35.07 to the North, with a maximum extension rate of 0.01371 nstrain/yr oriented perpendicular to the contraction direction. But in 2015–2016, we estimated a regional maximum contraction rate of −12.06 nstrain/yr oriented at −87.08 to the North, and a maximum extension rate of 6.271 nstrain/yr (see Table 3).

It can be seen that the maximum extension rate obviously increased in southeast margin of Ordos Block in 2015–2016, and oriented nearly along NS direction, the maximum contraction strain direction changed from NW to EW direction, which contribute to strengthen extension and shear strain of the NE-striking faults (see Fig. 3).

5. Discussion

Previous research suggests that there are characteristics of spatial and temporal migration of earthquakes around Ordos block margin [11], Yuncheng M4.4 earthquake swarm occurred after Alashan M5.8 earthquake in less than a year, this point is proved once again. The time-varying strain parameters in southeastern margin of Ordos block deviated from the background state after Alashan M5.8 earthquake that occurred in northwestern margin, and turned back several months before Yuncheng M4.4

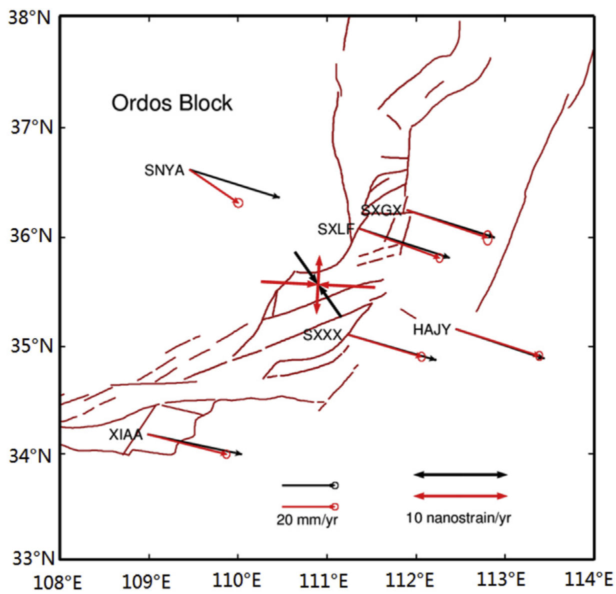


Fig. 3 – GPS velocities and regional uniform strain rate during 2011–2014 and 2015–2016, the black arrows indicate velocities or regional uniform strain rate in 2011–2014, the red arrows indicate velocities or regional uniform strain rate in 2015–2016, the ellipse at the tip of each velocity vector is 95% confidence. The deep red lines indicate active faults.

earthquake swarm, which shows that the nature of spatiotemporal migration is the change of regional stress and strain field caused by earthquakes, and this kind of micro dynamic change of the crust can be observed by CMONOC continuous GPS stations.

The variation of the GPS station displacement velocities is closely related to its geologic structural location. The station SNYA in Ordos Block has the maximum changes, and its movement direction changes from SEE to SE, the variation of XIAA and SXXX stations located in the NEE-striking faults zone was significantly decreased, and that of SXLF and SXGX stations located in the NNE-striking faults zone was further reduced, the HAJY station outside the Ordos periphery fault system has the minimum change. This kind of velocity variation may be related to the focal mechanism characteristic with strike-slip and thrust of Alashan M5.8 earthquake, however, due to the fault locking, the differential movement of different parts of earth's crust results in significant stress and strain accumulation in some special parts of regional faults zone, Yuncheng *M*4.4 earthquake swarm occurred in the intersection of NEE and NNE trending faults zones, in which the stress and strain is easier to be accumulated. This may be why the *M*4.4 earthquake swarm occurred in Yuncheng basin.

6. Summary

Inversion of continuous GPS data for time-varying strain show obvious anomaly relative to the background variation after Alashan *M*5.8 earthquake occurring in northwest margin of Ordos block, the anomaly began to turn back several months before Yuncheng *M*4.4 earthquake swarm, suggesting that Alashan *M*5.8 earthquake changed the state of regional stress field in southeast margin of Ordos block, which contributes to occurrence of Yuncheng *M*4.4 earthquake swarm. It also shows that the nature of spatiotemporal migration is the change of regional stress and strain field caused by earthquakes, and this kind of micro dynamic change of the crust can be observed by CMONOC continuous GPS stations.

Compared to 2011–2015, the rate of eastward movement of stations decreases during 2015–2016 in varying degrees, the variation is closely related to its geologic structural location, and the velocity gradient of the crustal surface between the stations may be a performance of the regional strain accumulation and faults activity.

The uniform strain model predicts fast contraction and extension oriented at near EW and NS direction in 2015–2016, which contribute to the tensile and shear strain accumulation for NE trending faults, it's consistent with the regional background strain state of Shanxi seismic zone, and this state contributes to the activity of earthquakes.

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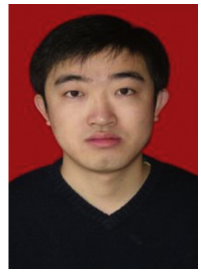

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