The April 24, 2013 Changning M_s 4.8 earthquake: a felt earthquake that occurred in Paleozoic sediment

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Abstract The dense broadband seismic network provides more high-quality waveform that is helpful to improve constraint focal depth of shallow earthquake. Many shallow earthquakes occurring in sediment were regarded as induced events. In Sichuan basin, gas industry and salt mining are dependent on fluid injection technique that triggers microseismicity. We adopted waveform inversion method with regional records to obtain focal mechanism of an M_s 4.8 earthquake at Changning. The result suggested that the Changning earthquake occurred at a ESE thrust fault, and its focal depth was about 3 km. The depth phases including teleseismic pP phase and regional sPL phase shows that the focal depth is about 2 km. The strong, short-period surface wave suggests that this event is a very shallow earthquake. The amplitude ratio between Rayleigh wave and direct S wave was also used to estimate the source depth of the mainshock. The focal depth (2–4 km) is far less than the depth of the sedimentary layer thickness (6–8 km) in epicentral region. It is close to the depth of fluid injection of salt mining, which may imply that this event was triggered by the industrial activity.

Keywords Induced earthquake · Depth phase · Waveform inversion

1 Introduction

An earthquake sequence including the M_s 4.8 mainshock (Changning earthquake for short) shocked Changning, Sichuan, on April 25, 2013, which injured dozens and resulted in economic losses amounting to about 300 million RMB (Fig. 1). The Chinese Earthquake Network Center reported that both the M_s 4.8 mainshock and the strongest aftershock occurred at a depth of 4 km. (http://www.cenc.ac.cn/manage/html/402881891275f6df011275f971990001/_SUBAO/_content/13_04/25/13e3e2158b900.html), while the USGS National Earthquake Information Center determined the mainshock is a M 5.3 event occurring at 10-km depth (<http://comcat.cr.usgs.gov/earthquakes/eventpage/usb000gfau#summary>). Such divergence increases more interest in improving accuracy of focal parameters.

Most deconstructive and felt earthquakes in Sichuan occur at major fault systems such as the Longmenshan Fault system. However, the epicenter of Changning earthquake is about 40 km away from the Huayingshan Fault that is a major fault in eastern Sichuan basin. Since the thickness of sediment in southern Sichuan depression ranges from 6 to 8 km (Song and Luo 1995), the Changning earthquake was eventually an earthquake occurring in sediment. Because the strength of rock in shallow crust is too weak to accumulate enough strain, most earthquakes occur in the middle crust except in the area with anomaly geothermal flow (Shi and Zhu 2003; Klose and Seeber 2007). Therefore, there are only a few articles about deconstructive earthquakes occurring in shallow crust (<5 km) in India and Austria cratons (Dawson et al. 2008; Gupta et al. 1996). Luo et al. (2011) reported a deconstructive event occurring in Mesozoic sediment at the center of Sichuan basin. The 2010 Christchurch earthquake is also another recent example (Kaiser et al. 2012). Such

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Fig. 1 Historical seismicity ($M > 2.0$) between 2009 and 2013 at Changning. The *red star* denotes location of salt mine

cases provide an opportunity to study strain accumulation and failure in weak rock.

In recent years, production of shale gas experienced a great boom in the US, and many countries proposed ambitious plans for shale gas exploration and production. Because the permeability of shale or other tight rocks is very low, engineers pump huge volumes of pressurized mix of water, chemicals, and sand to create and hold open fractures. Seismicity events induced by fluid injection in geothermal sites (e.g., Eberhart-Phillips and Oppenheimer 1984) and wastewater disposal sites (e.g., Healy et al. 1968) have been reported in the recent decades. Several

moderate and felt earthquakes (up to $M_w 5.7$, Keranen et al. 2013) occurred in shale-gas fields in the US midcontinent, and such a situation was proposed to be posing a higher risk (Ellsworth 2013). There are several articles on induced seismicity in gas field (Zhu et al. 2007; Long et al. 2010) and salt mine (Lu et al. 2009). Changning–Weiyuan field is the first shale-gas production area of China. The historical seismicity concentrates in the range of 10–20-km depth. Therefore, the Changning earthquake is a rare case study to analyze seismic hazard caused by shallow event.

Due to sparsity of the sample, uncertainties of source parameters of shallow earthquake determined with

traditional methods are sizable. For travel-time location except nearby stations, sparse samples of takeoff vector in upper hemisphere increase uncertainty introduced by tradeoff between depth and origin time (Mori 1991). For first motion inversion, uncertainties of the depth and velocity model also introduce large errors. Methods based on waveform could use more information taken from later phases to constrain fault plane and centroid depth. In this article, we adopted waveform inversion method to obtain focal mechanism including centroid depth, and then used local and teleseismic depth phases and amplitude ratio of body wave and surface wave to determinate the focal depth.

2 Focal mechanism

The cut and paste (CAP for short) method is a popular waveform inversion method, which uses regional three-component records of body wave and surface wave to constrain fault plane and centroid depth (Zhao and Helmberger 1994; Zhu and Helmberger 1996). Recently, the teleseismic waveform was also introduced into CAP to provide more constraint for thrust event (Ni et al. 2010; Chen et al. 2012). We collected three-component records at stations within 200 km (Fig. 2a; Zheng et al. 2009) and

adopted Sichuan basin velocity model obtained from short-period surface-wave dispersion inversion (Fig. 2b; Xie et al. 2012). Velocity increases with the depth in sediment, and the total thickness of the crust reaches 40 km. Synthetic seismograms of arbitrary faults are built from those of the three basic faults that were computed with FK method (Zhu and Rivera 2002). Both synthetic and observed waveforms were bandpass filtered (0.02–0.15 Hz for body wave and 0.02–0.1 Hz for surface wave). Grid search scheme was employed to seek the best solutions at different depths, and the misfit function reaches the minimum at 3 km as the best centroid depth (3 km; Fig. 3a), while the magnitude of moment is 4.5. The fault planes of the best solution are $128^{\circ}/42^{\circ}/83^{\circ}$ (plane I) and $317^{\circ}/48^{\circ}/96^{\circ}$ (plane II) for strike, dip, and rake, respectively. Figure 3b shows comparison between the filtered synthetic and observed waveforms. Most cross-correlation coefficients of Pn1 Segment are larger than 0.8 except CQT and WAS stations that are further away from the epicenter. For surface-wave segment, the synthetic waveforms best fit observations at ROC and YAJ stations, and the cross-correlation coefficients are larger than 0.7. Strike of fault plane I is consistent with the Changning Anticline, and it is close to fault planes of historical events obtained from the amplitude ratio method (Ruan et al. 2008). Consequently, the fault plane I is possibly the rupture plane.

Fig. 2 **a** Epicentral and seismic stations used in this study. Star denotes epicenter, while triangles show stations. Faults are shown in solid lines, **b** basin velocity model. Dashed line denotes shear wave, while V_p is shown in solid line

Fig. 3 **a** Waveform misfit versus focal depth, **b** waveform comparison between synthetic (red) and observed waveforms (black line)

3 Depth phases

The depth phases are reflected at free surface upper hypocenter, and the paths of depth phase and reference phase are close to each other except the reflected segment. Hence, the differential time between two phases is dominated by depth, and it is slightly affected by heterogeneity along propagation path. Benefiting from radiation pattern of thrust event, the global seismic network provides high-quality records of the Changning earthquake. We selected broadband records at Global Seismographic Network. After removing instrument response and lowpass filtering (<1 Hz), we chose three high signal–noise–ratio records at different azimuths (Fig. 4a). When the focal depth is small, the pP and sP signals may be contaminated by direct P wave, and manual picking is difficult. The waveform modeling method, which best fits observation with synthetic waveforms of different focal depths, is a better choice. The synthetic waveform was computed with three steps involving effects of mantle, source, and receiver-side crust (Kikuchi and Kanamori 1982). The source-side crust model is the same as the previous one, and the velocity

model in the mantle is that of PREM model. The t^* (1.0 for P wave) was adopted to take into account the effect of inelastic attenuation. Figure 4b shows the comparison between the filtered observations and the synthetic waveforms of different focal depths. All traces were filtered and aligned with direct P arrival. The differential time between P and pP shows a clear growth trend in synthetic waveforms, and the preferred depth is around 1–2 km.

We also analyzed depth phases as recorded by the regional network. The sPL phase is an effective one for determining focal depth at near distance, and it has been widely used in several moderate earthquake studies (Luo et al. 2010; Chong et al. 2010). The dominant frequency of sPL is lower than direct P wave, and the radial component is much stronger than the vertical one. Three-component records of JLI pertain to the removed instrument response, and velocity records were integrated into displacement. Both the synthetic and observed waveforms are bandpass filtered between 0.05 and 1.0 Hz. As Fig. 5a shows, the sPL signal at the radial component is much stronger than the one at the vertical component. The synthetic waveforms of 2 and 3 km fit the observation better than other

Fig. 4 **a** Teleseismic stations map, **b** waveform comparison between the teleseismic synthetic (*red*) and the observed (*black*) ones

Fig. 5 **a** sPL waveform fitting at JLI station for M_s 4.8 mainshock, **b** sPL waveform fitting at JLI station for M_s 4.2 aftershock. Red the synthetic vertical component; gray the synthetic radial component; and blue the observed radial component

ones. The sPL is also clear for records of M_s 4.2 aftershock, and the differential time between sPL and P suggests that depth of this aftershock is close to that of the mainshock (Fig. 5b).

4 Short-period surface wave

At regional networks, we observed strong short-period surface wave that is an index of shallow earthquake. Tsai and Aki (1970) proposed that spectrum of surface wave could be used to constrain focal depth with the well-constrained fault plane. The short-period Rg wave also is considered as an important characteristic of shallow event (Kafka, 1990; Luo et al. 2011). Both the 90-degree phase differences between radial and vertical components and dispersion are helpful to us to identify Rg wave. Figure 6

shows clear Rg wave signals at HWS and LZH stations. In general, the Rg wave could be observed when epicentral distance exceeds by about five times of focal depth (Luo et al. 2011). Consequently, the Rg wave at HWS (distance = 31 km) suggests that the focal depth of the Changning earthquake may be not larger than 6 km. The amplitude ratio of the body wave and the surface wave is also sensitive to the focal depth (Luo et al. 2011). We compare the different ratios at the synthetic waveform and observation, as shown in Fig. 6. As Fig. 6 shows, deeper focal depth results in weaker Rg wave. At HWS, the best depth is about 2–4 km, while the other one is about 3–5 km at LZH. Most of the energy of the short-period Rg wave was trapped in sediment where inelastic attenuation is much stronger than that at middle crust. While path of the body wave bends toward the middle crust, inelastic attenuation of the body wave slightly increases with the

Fig. 6 **a** Observed (*black*) and synthetic (*red*) short-period surface waves at HWS, **b** observed (*black*) and synthetic (*red*) short-period surface waves at LZH

distance. Therefore, amplitude ratio between Rg and body wave at farther stations will be smaller than the one measured at closer station.

5 Discussion and conclusions

As mentioned above, the Changning earthquake is a thrust event on ESE fault plane, while the estimated focal depth is between 2 and 4 km. The preferred depth of 3 km was obtained from CAP inversion, and it is supported by both depth phases and short-period surface observations. In the southern Sichuan depression, thicknesses of Paleozoic and Mesozoic sediments are about 7 km (Song and Luo 1995), and so the hypocenter is positioned in the Paleozoic Dengying Formation. The most-destructive earthquake occurs in the crystalline basement, and Horton et al. (2005)

reported a rare case of a $M_w 4.2$ earthquake that occurred in Paleozoic sediment in Kentucky, U.S.A. The number of felt earthquakes at Changning has been significantly increasing since 2006 (Ruan et al. 2008). In October 2007, Earthquake Administration of Sichuan Province installed two temporal broadband seismometers to monitor micro-seismicity. The location result shows that most small earthquakes are shallower than 3 km, while stronger events occurred at greater depths, while the centroid of earthquakes between October 18, 2007 and November 12, 2007 lies at about 10 km east of the salt mine. The semi-major axis of the earthquake cluster is close to that of the fault plane I of this study's result. The focal mechanism solution indicates the axis of the compressive principal stress along NE. This result is similar to the previous result (Ruan et al. 2008), but it is different from the result of the regional tectonic stress field (Zhu et al. 2007). McKenzie (1969)

pointed out that the stress axes obtained from a few earthquakes might deviate from that of the regional tectonic stress. Another potential interpretation is that the present tectonic stress is different from the one in geological time. The rupture fault was formed in different tectonic stresses, and a strong horizontal stress induced the thrust sliding.

Changning–Weiyuan region is one among the first pilot shale-gas fields of China. Since hydraulic fracking increases concern on seismic hazard, the Changning earthquake provides a case to study the mechanism of earthquake in sediment that will be helpful to us to understand induced seismicity. The salt mining is a historical industry in Sichuan basin, and previous studies proposed that fluid injection during the salt mining induced microseismicity (e.g., Lu et al. 2009; Long et al. 2010). At Changning, the salt deposit is about 2,400–2,900 m deep, and the deepest injection well is about 3,000 m (Ruan et al. 2008). The number of felt earthquake shows similar variation with the net injected fluid volume (Ruan et al. 2008). Injected fluid not only induces seismicity around well but also possibly diffuses to nearby fault and results in the increase of pore pressure. The induced seismicity in Arkansas shows that the fluid injection increases the potential of deconstructive earthquake at blind faults (Horton 2012) even tens of kilometers away. Flows in the lower crust and the upper mantle may enhance stress in the upper crust, and it leads to the seismogenic fault reaching critical state (Zoback and Townend 2001). The lower mantle flow beneath Sichuan basin has been reported in recent decades, and high-frequency-induced seismicity in Rongchang region also supported the fact that faults are in critical state. Therefore, even a small stress perturbation caused by injected fluid could induce earthquake. Induced seismicity such as that occurred in the Changning earthquake raises public concern on seismic hazard.

Since the Changning earthquake occurred only 5 days after the April 20, Lushan $M_s 7.0$ earthquake and separation between two earthquakes is <300 km, the Changning earthquake raised concern on whether the Lushan earthquake would trigger strong earthquake in adjacent region. There are two main potential mechanisms about earthquake trigger: static and dynamic triggering mechanisms. Coseismic static displacement changes strain at nearby faults, and the resulting effect could be described as change of Coulomb failure stress (ΔCFS). Positive ΔCFS means that risk of earthquake increases, and the ΔCFS threshold of triggering is about 0.1 MPa (King et al. 1994). The coseismic static displacement decreases with distance as $1/r-1/r^2$. For example, in the $M_w 7.3$ Landers earthquake, the ΔCFS is only about 0.003 MPa at 200 km far away (Hill et al. 1993). Shan et al. (2013) show that ΔCFS caused by the Lushan earthquake at Huayingshan fault is less than

–0.01 MPa. Therefore, the possibility of static trigger is very low. The amplitude of surface wave excited by large earthquake decreases with distance, as such displacement could induce strong stress perturbation. Therefore, the dynamic triggering is still significant at far field. For example, the maximum dynamic stress perturbation caused by the $M_w 7.9$ Denali earthquake is up to 0.12 MPa at 3,000 km far away (Pankow et al. 2004). Most dynamic triggered events occurred in a few minutes after arrival of surface wave. However, Brodsky and Prejean (2005) proposed the fluid migration is a potential mechanism of dynamic trigger, and delay time would be affected by permeability and diffusion coefficient (Glowacka et al. 2002). The delay time ranges from seconds to days (Mohamad et al. 2000; Hough 2005). After fluid injection in past decades, rock in sediment may have been saturated and easier to be triggered. However, there is not clear creditable clue of triggering.

In summary, focal mechanism of the Changning earthquake was obtained from waveform inversion, and the fault plane I ($128^\circ/42^\circ/83^\circ$) is possibly the rupture plane. The focal depth (2–4 km) was determined with the depth phases and amplitude ratio of body wave and surface wave. Such shallow earthquake in Paleozoic sediment is possibly induced by fluid injection rather than triggered by the Lushan earthquake.

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References

- Brodsky EE, Prejean SG (2005) New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. *J Geophys Res* 110:B04302. doi:10.1029/2004JB003211
- Chen W, Ni S, Wang Z, Zeng X, Wei S (2012) Joint inversion with both local and teleseismic waveforms for source parameters of the 2010 Kaohsiung earthquake. *Chin J Geophys* 55(7): 2319–2328 (in Chinese with English abstract)
- Chong J, Ni S, Zeng X (2010) sPL, an effective seismic phase for determining focal depth at near distance. *Chin J Geophys* 54(11): 2620–2630 (in Chinese with English abstract)
- Dawson J, Cummins P, Tregoning P, Leonard M (2008) Shallow intraplate earthquakes in Western Australia observed by Interferometric Synthetic Aperture Radar. *J Geophys Res* 113: B11408. doi:10.1029/2008JB005807
- Eberhart-Phillips D, Oppenheimer DH (1984) Induced seismicity in The Geysers geothermal area, California. *J Geophys Res* 89(B2): 1191–1207
- Ellsworth WL (2013) Injection-induced earthquakes. *Science* 341(6142):1225942
- Glowacka E, Nava A, de Cossío D, Wong V, Farfan F (2002) Fault slip, seismicity, and deformation in Mexicali Valley, Baja

- California, Mexico, after the $M7.1$ 1999 Hector Mine earthquake. *Bull Seismol Soc Am* 92(4):1290–1299
- Gupta HK, Sarma SVS, Harinarayana T, Virupakshi G (1996) Fluids below the hypocentral region of Latur earthquake, India: geophysical indicators. *Geophys Res Lett* 23:1569–1572
- Healy J, Rubey W, Griggs D, Raleigh C (1968) The Denver earthquakes. *Science* 161(3848):1301–1310
- Hill DP, Reasenberg PA, Michael AJ, Arabaz WJ, Beroza G, Brumbaugh D, Brune JN, Castro R, Davis S, dePollo D, Ellsworth WL, Gomberg J, Harmsen S, House L, Jackson SM, Johnston MJS, Jones L, Keller R, Malone S, Munguia L, Nava S, Pechmann JC, Sanford A, Simpson RW, Smith RB, Stark M, Stickney M, Vidal A, Walter S, Wong V, Zollweg J (1993) Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. *Science* 260:1617–1623
- Horton S (2012) Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake. *Seismol Res Lett* 83(2):250–260
- Horton S, Kim WY, Withers M (2005) The 6 June 2003 Bardwell, Kentucky, earthquake sequence: evidence for a locally perturbed stress field in the Mississippi embayment. *Bull Seismol Soc Am* 95(2):431–445
- Hough SE (2005) Remotely triggered earthquakes following moderate mainshocks (or, why California is not falling into the ocean). *Seismol Res Lett* 76(1):58–66
- Kafka L (1990) Rg as a depth discriminant for earthquakes and explosions: a case study in New England. *Bull Seismol Soc Am* 80(2):373–394
- Kaiser A, Holden C, Beavan J, Beetham D, Benitesa R, Celentanob A, Collette D, Cousins J, Cubrinovskid M, Dellowa G, Denyse P, Fielding E, Frya B, Gerstenbergera M, Langridgea R, Massey C, Motagh M, Pondarda N, McVerrya G, Ristaua J, Stirlinga M, Thomash J, Umaa SR, Zhao J (2012) The $M_w6.2$ Christchurch earthquake of February 2011: preliminary report. *N Z J Geol Geophys* 55(1):67–90
- Keranen K, Savage H, Abers G, Cochran E (2013) Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 $M_w5.7$ earthquake sequence. *Geology*. doi:10.1130/G34045.1
- Kikuchi M, Kanamori H (1982) Inversion of complex body waves. *Bull Seismol Soc Am* 72(2):491–506
- King GC, Stein RS, Lin J (1994) Static stress changes and the triggering of earthquakes. *Bull Seismol Soc Am* 84(3):935–953
- Klose C, Seeber L (2007) Shallow seismicity in stable continental regions. *Seismol Res Lett* 78(5):554–562
- Long F, Du F, Ruan X, Deng Y, Zhang T (2010) Water injection triggered earthquakes in the Zigong mineral wells in ETAS model. *Earthq Res China* 26(2):164–171 (in Chinese with English abstract)
- Lu G, Peng Y, Gao F (2009) Progress of the study on induced earthquake and its countermeasure project in Leshan city. *Recent Dev World Seismol* 362(2):19–22 (in Chinese with English abstract)
- Luo Y, Ni S, Zeng X, Xie J, Chen Y, Long F (2010) The $M5.0$ Suining–Tongnan (China) earthquake of 31 January 2010: a destructive earthquake occurring in sedimentary cover. *Chin Sci Bull* 56(6):521–525
- Luo Y, Ni S, Zeng X, Zheng Y, Chen Q, Chen Y (2011) A shallow aftershock sequence in the north-eastern end of the Wenchuan earthquake aftershock zone. *Sci China D Earth Sci*. doi:10.1007/s11430-010-4026-8
- McKenzie D (1969) The relation between fault plane solutions for earthquakes and the directions of the principal stresses. *Bull Seismol Soc Am* 59(2):591–601
- Mohamad R, Darkal AN, Seber D, Sandvol E, Gomez F, Barazangi M (2000) Remote earthquake triggering along the Dead Sea Fault in Syria following the 1995 Gulf of Aqaba earthquake ($M_s = 7.3$). *Seismol Res Lett* 71(1):47–52
- Mori J (1991) Estimates of velocity structure and source depth using multiple P waves from aftershocks of 1987 Elmore Ranch and Superstition Hills, California, earthquakes. *Bull Seismol Soc Am* 81:508–523
- Ni S, Helmberger D, Pitarka A (2010) Rapid source estimation from global calibrated paths. *Seismol Res Lett* 81(3):498–504
- Pankow KL, Arabasz WJ, Pechmann JC, Nava SJ (2004) Triggered seismicity in Utah from the 3 November 2002 Denali fault earthquake. *Bull Seismol Soc Am* 94(6B):S332–S347
- Ruan X, Cheng W, Zhang Y, Li J, Chen Y (2008) Research of the earthquakes induced by water injections in salt mines in Changning, Sichuan. *Earthq Res China* 24(3):226–234 (in Chinese with English abstract)
- Shan B, Xiong X, Zheng Y, Jin B, Liu C, Xie Z, Hsu H (2013) Stress changes on major faults caused by 2013 Lushan earthquake, and its relationship with 2008 Wenchuan earthquake. *Sci China Earth Sci*. doi:10.1007/s11430-013-4641-1
- Shi Y, Zhu S (2003) Contrast of rheology in the crust and mantle near Moho revealed by depth variation of earthquake mechanism in continental China. *Chin J Geophys* 46(3):359–365 (in Chinese with English abstract)
- Song H, Luo Z (1995) The study of the basement and deep geological structures of Sichuan basin, China. *Earth Sci Front* 2(3–4):231–237
- Tsai Y, Aki K (1970) Precise focal depth determination from amplitude spectra of surface waves. *J Geophys Res* 75(29):5729–5744
- Xie J, Ni S, Zeng X (2012) 1D shear wave velocity structure of the shallow upper crust in central Sichuan Basin. *Earthq Res Sichuan* 143(2):20–24 (in Chinese with English abstract)
- Zhao L-S, Helmberger D (1994) Source estimation from broadband regional seismograms. *Bull Seismol Soc Am* 84(1):91–104
- Zheng XF, Ouyang B, Zhang D, Yao Z, Liang J, Zheng J (2009) Technical system construction of Data Backup Centre for China Seismograph Network and data support to researches on the Wenchuan earthquake. *Chin J Geophys* 52(5):1412–1417 (in Chinese with English abstract)
- Zhu L, Helmberger D (1996) Advancement in source estimation techniques using broadband regional seismograms. *Bull Seismol Soc Am* 86(5):1634–1641
- Zhu L, Rivera LA (2002) A note on the dynamic and static displacements from a point source in multilayered media. *Geophys J Int* 148(3):619–627
- Zhu L, Huang S, Wei H (2007) On fluid-injection induced earthquake in Rongchang area. *J Geod Geodyn* 27(6):86–90 (in Chinese with English abstract)
- Zoback M, Townend J (2001) Implications of hydrostatic pore pressures and high crustal strength for the deformation of intraplate lithosphere. *Tectonophysics* 336(1):19–30