Evidence for Anthropogenic Surface Loading as Trigger Mechanism of the 2008 Wenchuan Earthquake

Christian D. Klose

Received: 22 August 2010 / Accepted: 9 September 2011

Abstract Two and a half years prior to China’s M7.9 Wenchuan earthquake of May 2008, at least 300 million metric tons of water accumulated with additional seasonal water level changes in the Minjiang River Valley at the eastern margin of the Longmen Shan. This article shows that static surface loading in the Zipingpu water reservoir induced Coulomb failure stresses on the nearby Beichuan thrust fault system at <17km depth. Triggering stresses exceeded levels of daily lunar and solar tides and perturbed a fault area measuring $416\pm96\text{km}^2$. These stress perturbations, in turn, likely advanced the clock of the mainshock and directed the initial rupture propagation upward towards the reservoir on the “Coulomb-like” Beichuan fault with rate-and-state dependent frictional behavior. Static triggering perturbations produced up to 60 years (0.6%) of equivalent tectonic loading, and show strong correlations to the coseismic slip. Moreover, correlations between clock advancement and coseismic slip, observed during the mainshock beneath the reservoir, are strongest for a longer seismic cycle (10kyr) of M>7 earthquakes. Finally, the daily event rate of the micro-seismicity (M≥0.5) correlates well with the static stress perturbations, indicating destabilization.

Keywords Earthquake · Geomechanics · Geoengineering · Triggered Earthquakes · Water Reservoir · Tides · Sun · Moon · Gravitation · Seismology

1 Introduction

The Wenchuan earthquake of May 12, 2008 occurred in the Sichuan province of the People’s Republic of China. This M7.9 event ruptured along the border of the Longmen Shan margin of the Tibetan plateau in the West and the Sichuan basin in the East. The earthquake’s nucleation point was at Long=103.364 and Lat=30.986 at about 16 km depth. The epicentral error is 5 km and the focal depth estimation error is 10 to 15 km [Huang et al. 2008].

The Beichuan fault system, consisting of listric and NNW dipping reverse faults, broke 250-300 km parallel along the Longmen Shan thrust belt (Fig. 1) [Burchfiel]
et al. 1995). This intra-continental region has been extensively studied both prior to and after the M7.9 earthquake in 2008, including a) paleo-seismicity studies (Burchfiel et al. 1995; Densmore et al. 2007; Zhang et al. 2009; Zhou et al. 2007; Burchfiel et al. 1995; Chen et al. 1994), b) instrumental recordings of the seismicity prior to and after the mainshock (1970-2009) (Hu 2007; Lei et al. 2008), c) inversion data analyses of teleseismic body waves of the mainshock (Wang et al. 2008a; Zhang et al. 2009), d) studies on coseismic ground deformations (Lin et al. 2008; Zhang et al. 2009). Finally, the trigger mechanism of the 2008 M7.9 Wenchuan earthquake has been debated since the earthquake’s occurrence (Klose 2008; Lei et al. 2008). Some studies suggest that the mainshock might have been triggered by pore pressure diffusion within the earth’s crust resulting from a nearby artificial lake, the Zipingpu water reservoir (Lei et al. 2008; Ge et al. 2009). Other studies reject the hypothesis of triggering due to pore pressure diffusion (Deng et al. 2010; Gahalaut and Gahalaut 2010). It can be anticipated that the earthquake cycle was already in its late stage in 2005 and close to failure conditions, because the Wenchuan earthquake ruptured in 2008. But, did the surface loading affect the earthquake cycle and the initial rupture? How many years of equivalent tectonic loading would the artificial loading advance the clock of the mainshock and how much of the coseismic slip would it produce?

This study shows that observations and data modeling support the initial argument that lithostatic stress changes and the poroelastic response of the earth’s crust due to the weight of the Zipingpu reservoir on the earth’s crust most likely triggered the 2008 M7.9 Wenchuan earthquake (Klose 2008). The article provides further evidence that a) surface loading due to water mass accumulations within the Zipingpu water reservoir in the Minjiang River Valley between 2005 and 2008 induced Coulomb failure stress changes in the earth’s crust and b) triggering stress perturbations beneath the artificial lake likely advanced the clock of the Wenchuan earthquake, while affecting the initial rupture propagation. Furthermore, the water reservoir impounding generated static triggering stress perturbations in the earth’s crust beginning in 2005 that biased daily stress alterations due to tidal elongations of the moon and the sun. Furthermore, it could have changed the natural earthquake cycle and advanced the clock of the 2008 Wenchuan earthquake by several decades.

2 Data

2.1 Seismicity prior to the mainshock

Instrumentally recorded seismicity with magnitudes up to 5.0 was observed in this region before 2004 (Yang et al. 2005; Liu 2007; Hu 2007; Yao et al. 2008; Huang et al. 2008). Paleoseismic studies also show evidence of Quaternary reverse faulting in the Longmen Shan region. Radiocarbon analyses (14C), for example, indicate that the last major earthquake (M<7.9) might have occurred between 4 and 10kyr ago (Densmore et al. 2007; Zhou et al. 2007). Moreover, deformation measurements suggest the Longmen Shan is a transition part between both a stable continental region (Sichuan Basin) with strain rates < 10^{−10} yr^{−1} and an active continental region (Tibet plateau) with strain rates > 10^{−8} yr^{−1}.
Fig. 1. Geology and tectonic situation in the Longmen Shan region (a) the Beichuan fault system that ruptured during the May 12 2008 M7.9 earthquake with a coseismic slip \( \sigma \) (Wang et al. 2008a) (b) and likely due to static Coulomb failure stress perturbations \( \Delta \text{CFS} \) (c) as a result of the surface loading in the Zipingpu water reservoir (see Fig. 2). The principal lithostatic stress elipsoids show the orientation of reverse fault conditions. The epicenter and the epicentral error of the mainshock are indicated by red circles. The geology is as follows: Qt-Quaternary, Cr-Cretaceous, Jr-Jurassic, Tr-Triassic, Pal-Paleozoic, Prot-Proterozoic, ProtG-Proterozoic granite, BM-Boashan Massif, PT-Pengguan Massif, WMT-Maowen thrust fault (WMT) and BT1/3-Beichuan thrust fault (Burchfiel et al. 1995; Jia et al. 2006).
The area where the mainshock nucleated tends to have low horizontal and vertical tectonic deformation rates of \( \leq 1.0 \pm 1.0 \text{ mm yr}^{-1} \), resulting in less seismic activities when compared to a) the seismic hazard regions in the Quiangtan block (Southwest) and the Kunlun Mountains (Northwest) and b) the Mesozoic deformation period \( \text{(Burchfiel et al. 1995; Densmore et al. 2007; Zhang et al. 2009; Zhou et al. 2007; Burchfiel et al. 1995; Chen et al. 1994)} \). High shear-wave velocity structures and Bouguer-gravity structures indicate a mechanically strong mid crust (10-20 km) and a cratonic-like lithosphere of the Sichuan Basin (Fig. 1a), in particular, in the Yangtze block along the SW Longmen Shan at the border to the Songpan-Garze block \( \text{(Yao et al. 2008; Burchfiel et al. 1995)} \). Yao et al. suggested a more unstable lower part of the crust (>20km) along the Longmen Shan which could be explained by low shear-wave velocity structures \( \text{(Yao et al. 2008)} \).

2.2 Seismicity associated with the Zipingpu reservoir impoundment

Between October 2005 and May 2008 shallow seismicity patterns (<10km) were observed on the Beichuan fault system along a \( \leq 20 \text{ km} \) long part of the lower Minjiang River Valley parallel to the extension of the Zipingpu water reservoir \( \text{(Lei et al. 2008; Klose 2009)} \). Such shallow seismicity could be indicative for earthquakes in a stable continental crust \( \text{(Klose and Seeber 2007)} \). However, Lei et al., reported that the seismicity change might be associated with a continuous water accumulation by the Zipingpu dam in the Minjiang River Valley almost three years prior to the rupture of the mainshock \( \text{(Lei et al. 2008; Klose 2008)} \). At the northern end of the valley, the Minjiang River flows into the Chengdu plain of the Sichuan basin. The artificial water reservoir extended sub-parallel to the Beichuan fault segment BT1 about 1.5 km westward and BT2 less than 1.0 km eastward (Figs. 2 and 1). After continuous impounding, the water level peaked twice in October 2006 and October 2007 at water reservoir capacity of \( 1.10 \times 10^9 \text{ m}^3 \) (upper water level) which is equivalent to a mass of 1.10 billion metric tonnes (Gt). Between October 2007 and May 12 2008 the reservoir was, again, seasonally drained to a remaining volume of \( 0.32 \times 10^9 \text{ m}^3 \) (lower water level). Lei et al. first mentioned that the seismic events of magnitudes ranging between 0.5 and 3.9 might have illuminated a destabilization process on BT during the loading period of the water reservoir. Prior to the surface loading, the correlation coefficient between the water level and the daily event rate (383 days) is -0.18 (Fig. 3). Since May 2005 - the start of the flooding season - a positive correlation exists between the water level (mass of water) and the micro-seismicity beneath the water reservoir. With a coefficient of 0.69, the correlation is strongest between 2005 and 2006 during the first 366 days of loading. Between 2006 and 2007 the correlation is weaker with a coefficient of 0.62. Thus, it could be anticipated that the earthquake nucleation processes started already in 2006.

2.3 Coseismic slip of the mainshock

Numerical inversion data of teleseismic body waves (P-waves) show that the mainshock described a complex rupture process on the Beichuan fault segment BT1 (Fig. 1b) \( \text{(Zhang et al. 2009; Wang et al. 2008a)} \). During the first 15-20 seconds, a reverse fault focal mechanism dominated at and above the nucleation point of the mainshock \( \text{(Zhang et al. 2009; Wang et al. 2008a)} \). The rupture propagated with a coseismic slip of up to
4 m on BT1 upwards toward the Minjiang River Valley. Thus, it propagated directly to the surface loading area of the Zipingpu water reservoir. After 20 seconds, the rupture propagation process changed to a right-lateral NNE strike-slip mechanism NE of the Minjiang River Valley [Zhang et al. 2009; Wang et al. 2008a].

3 Methods

3.1 Triggering stress perturbations caused by surface loading

An exact first order solution of stress states below the surface loading area (lower and upper water reservoir) in the Minjiang River Valley (Fig. 2) is according to Boussinesq’s classical solution (Boussinesq 1885; Love 1944). Boussinesq’s solution for point loads is based on the assumption that the modulus of elasticity is constant within a homogeneous 3-dimensional half-space (earth’s crust). Moreover, the principle of linear superposition is also assumed to be valid. For the given problem, surface areas of the lower and upper water level with arbitrary geometry were discretized in \( a_i \times b_i \) elements (e.g., 50\( \times \)50 m\(^2\)). With respect to the surface elements, A. Love developed a method to analytically determine stress states at a depth \( z \) beneath any uniform un/load \( L_i \) with the area \( A_i = a_i \times b_i \) (Love 1944). This analytical solution is free of any elastic constant and can be defined for each 2-D surface element \( i = 1, 2, 3, \ldots, N \):

\[
\sigma_{L,i}(\Delta m_i, z, a_i, b_i) = L_i(\Delta m_i, A_i) \frac{f(z, a_i, b_i)}{2\pi}, \quad \text{with (1)}
\]

\[
f(z, a_i, b_i) = \left[ \arctan \left( \frac{a_i b_i}{z R_i} \right) + \frac{a_i b_i}{R_i} z \left( \frac{1}{a_i^2 + z^2} + \frac{1}{b_i^2 + z^2} \right) \right], \quad \text{(2)}
\]

and where \( \Delta m_i \) is the mass change and \( R_i = \sqrt{(a_i^2 + b_i^2 + z^2)} \). \( f(z, a_i, b_i) \) describes the fraction of \( L_i \) in the vicinity beneath \( A_i \) and ranges between 0 and 1. The un/loads \( L_i \) induce a positive/negative vertical stress alteration \( \Delta \sigma_3 = \Delta \sigma_L \) superimposed over all \( \sigma_{L,i} \), whereas \( \sigma < 0 \) is compression. \( L \) also changes the horizontal stress components, due to the elastic response of the crust (Hook’s Law): \( \Delta \sigma_3 = \Delta \sigma_L \) and \( \nu/1-\nu \Delta \sigma_L \leq \Delta \sigma_{1,2} < \Delta \sigma_L \) (McGarr 1988), where \( \nu \) is the Poisson’s ratio. It is likely that \( \Delta \sigma_{1,2} \geq \nu/1-\nu \Delta \sigma_L \), because horizontal principal strains \( \epsilon_{1,2} \) are very small and can be assumed to be \( \epsilon_{1,2} = 0 \) in 11-19 km depth, where faults are generally locked in the Longmen Shan region (Wang et al. 2008b).

Table 1 shows the 3-dimensional model quantities that were taken into account to determine the lithostatic stress perturbations in the earth’s crust. Stress states were determined on 7\( \times \)4 km\(^2\) large fault elements of the double-listric Beichuan fault system (BT1, 2, and 3) near the artificial reservoir in the Minjiang River Valley. Thus, \( \sigma_{L,i} \) and the resulting static Coulomb failure stress \( \Delta CFS \):

\[
\Delta CFS = \Delta \tau_f + \tan \phi(\Delta \sigma'_n)
\]

were calculated on each fault element with respect to the lower and upper water level in the Minjiang River Valley (Fig. 2), whereby \( \sigma'_n \) is the effective normal stress. \( \Delta CFS \)-values were used for further estimations of the clock advancements \( \Delta t \) with respect to 4 kyr, 7 kyr, and 10 kyr earthquake cycles of the fault system (this methodology is described the next section).
Pore-pressure diffusion most likely played a major role for the micro-seismicity (M<4) that was observed beneath the water reservoir, according to the study of Lei et al. 2008. Thus, drained conditions might have existed in shallower depth (<10km) in the Paleozoic rocks and the permeable Mesozoic rocks. This suggests that the poroelastic response due to the lithostatic stress alterations of the surface loading played a minor role under these geological conditions. Thus, the Skempton coefficient $B$ was assumed to lie between 0.5 and 0.7 (Terzaghi 1938; Biot 1941; Rice and Cleary 1976).

$$\Delta p = -B\Delta \sigma,$$  

(4)

where $\Delta \sigma$ is the change of the mean stress.

In undrained conditions (>10km) the pore pressure $p$ increased due to the poroelastic effects and destabilized BT1 and BT2 within the low permeable Proterozoic granitic rocks. The poroelastic response tends to increase with both depth (confining pressure) and fracture density (Lockner and Beeler 2003b). The Skempton coefficient $B$, which describes the strength of the poroelastic response, was assumed to range between 0.7 and 0.8 in 10-23 km depth. It is also assumed that $B$ is additionally amplified up to 0.85, due to a higher fracture density (Lockner and Beeler 2003b) near the intersection regions of BT1 and BT2 in 15-17 km and at the South end of BT1 in direction to the intersection with the Wenchuan Maowen thrust fault WMT (Fig. 1). Furthermore, the Mohr-Coulomb failure criteria indicates that the poroelastic response dominated only on steep dipping fault segments (>60°). Geomechanical parameters, which were used to determine triggering stress perturbations, are summarized in Table 1.

### Table 1: Model quantities for determining the Coulomb failure stress on the Beichuan fault system due to the surface loading in the Minjiang River Valley (Fig. 2).

| Geomechanical quantity | Mean±SME | Characteristic element on the fault |
|------------------------|----------|-------------------------------------|
| Poisson’s ratio $\nu$  | 0.25±0.05 | Mesozoic rocks (<8.5km depths)      |
| Skempton’s coefficient $B$ (drained) | 0.60±0.10 | Mesozoic rocks (<8.5km depths)      |
| Skempton’s coefficient $B$ (undrained) | 0.75±0.05 | Proterozoic rocks (>8.5km depths)   |
| Skempton’s coefficient $B$ (undrained) | 0.85±0.25 | faults zones (>8.5km depths)        |
| Rock friction angle $\phi$: | 28±2° | Proterozoic rocks (>8.5km depths)   |
| Rock cohesion $c_0$: | 10±10 MPa |                                             |
| Rock density $\rho$: | 2700±50 kg m$^{-3}$ |                                      |
| Young modulus $E$: | 75±25 GPa |                                             |
| Shear modulus $G$: | 30±10 GPa |                                             |
| Lithostatic stress regime: | $\sigma_1 > \sigma_2 > \sigma_3$ | reverse fault regime |
| Horizontal lithostatic stresses: | $\sigma_1$ and $\sigma_2$ |     |
| Gravitational lithostatic stress $\sigma_3$: | $\rho g z$ | vertical stress |
| Fault dip angle $\theta$: | 20-60±1° | BT1, BT2, and BT3                     |

3.2 Clock advancement of the mainshock caused by surface loading

Paleoseismic analyses show evidence of Quaternary reverse faulting in the Longmen Shan region which indicate a M7 (or M8) earthquake recurrence interval of 7±3 kyr, (Denenmor et al. 2007; Zhou et al. 2007) given horizontal and vertical deformation rates
of $\dot{e} = 1.0 \pm 1.0 \text{ mm yr}^{-1} (5 \pm 5 \text{ 10}^{-9} \text{ yr}^{-1})$. The rate-and-state dependent friction law (Dieterich 1979; Ruina 1983), which was developed based on empirical observations and utilized in this study, describes the failure time of a preexisting fault (here: Beichuan fault system). Furthermore, such a rate-and-state model can estimate the seismic cycle by taking into account a) the Mohr-Coulomb failure law, b) the slip velocity of the fault, and c) the history of the slip velocity:

\[
\tau = \mu, \sigma_n, \text{ and } \mu = f(v, v(t)), \text{ where (5)}
\]

\[
\mu = \mu_0 + a \ln (v(t)/v_0) + b \ln (\xi(t) v_0 / d_c) \text{ (6)}
\]

$a$ and $b$ are dimensionless hyper-parameters and based on empirical observations (Blanpied et al. 1998). $\mu_0$ is the initial friction coefficient and $v_0$ is the initial slip velocity of the fault. $\xi(t)$ is a time dependent "state" quantity and $d_c$ is a critical slip distance (Dieterich 1979; Ruina 1983):

\[
\frac{d\xi}{dt} = 1 - \xi(t) v(t)/d_c \text{ (7)}
\]

This model can be used to determine the clock advancement of an earthquake, for example, due to static triggering stress perturbations applied during a seismic cycle. The static triggering stress perturbation can be approximated by a heavyside function (eq. 8), because the water reservoir impoundment process was abrupt in 2005 (Fig. 2). In detail, the clock advancement $\Delta t$ is the period between the time of failure without perturbation $t_f$ and the time of failure when the static triggering load perturbed the background (Gomberg et al. 1998).

\[
\Delta t = t_f - t_p = |\Delta CF S|/\dot{\mu} - a/\dot{\mu} \ln(1 - (L + 1) \exp(-\dot{\mu} t_f/a)), \text{ (8)}
\]

where $|\Delta CF S|$ is the Coulomb failure stress of the static perturbation, normalized by the associated normal stress $\sigma_n$, and $L$ describes the load function respectively:

\[
L = \begin{cases} 
\exp(\dot{\mu} t_p/a) (1 - \exp(|\Delta CF S|/a)) - 1 & \text{if tectonic and static surface load,} \\
-1 & \text{if tectonic load only.}
\end{cases} \text{ (9)}
\]

---

Table 2 Model quantities for three rate-and-state fault regimes describing the potential behavior of the Beichuan fault system.

| model parameters | rate-state model | regime 1 | regime 2 | regime 3 |
|------------------|-----------------|----------|----------|----------|
| $a$              | 0.15            | 0.005    | 0.0027   |
| $b$              | 0.15            | 0.15     | 0.15     |
| $\mu_0$          | 0.57            | 0.57     | 0.57     |
| $d_c$ m          | 0.001           | 0.001    | 0.001    |
Three rate-state models and three natural earthquake cycles (4kyr, 7kyr, and 10kyr) were chosen to estimating the clock advancement of the Wenchuan earthquake by static triggering stress perturbations of the artificial water reservoir behind the Zipingpu dam (Fig. 2). The different models and cycles will help to better understand the number of years by which the clock of the mainshock was advanced. Model parameters are summarized in the following Table 2.

Fig. 2. Map view of the Minjiang River Valley and the cross section of the double-listric fault model, including the extension of seasonal lower (L) and upper water level (U) in the valley (a). The construction of the Zipingpu dam (Z) was completed in 2004/5 (Lei et al. 2008), and followed by the impounding of an artificial water reservoir (b). The loading time is indicated by $t_0$ and the mainshock (black star) ruptured at $t_p = t_f - \Delta t$, while being clock advanced by $\Delta t$ year. The water level changed seasonally with a wavelength of $t_w = 1$ year.
4 Results and Discussion

The period of stress perturbation was about 2.5 years, which accounts for the time between the start of the loading $t_o$ in 2005 and the moment of failure $t_p$ in 2008. The 3-dimensional stress modeling results show that the static surface loading process during the Zipingpu water reservoir impounding altered the lithostatic stresses of the reverse fault conditions with a vertical minimum principal stress $\sigma_3$ and a horizontal maximum principal stress $\sigma_1$ (Fig. 1a). In fact, static stress perturbations brought BT1 closer to failure ($\Delta CFS > 0$) and shifted BT2 and the shallow dipping root of BT1 away from failure ($\Delta CFS < 0$) as shown in Figure 1c.

First, the water was at lower level (300 Mt) when the mainshock ruptured on May 12, 2008. This static load induced shear stresses of $>1$ kPa and normal stresses $>-2$ kPa (compression, if $\sigma < 0$) at $<17$ km depth on BT1 beneath the artificial water reservoir (see Section 3.1). Given the peak load at upper water level (1.10 Gt), shear stresses increased by $>3$ kPa and normal stresses increased by $>6$ kPa. Furthermore, the shear stress $\Delta \tau$ and the effective normal stress $\Delta \sigma_n'$, in turn, changed the Coulomb failure stress (see eq. 3) and brought BT1 closer to failure in $<17$ km depth. Again, it should be emphasized that $\Delta \sigma_n'$ also changed due to the poroelastic response (destabilization) of BT1 to the load of the Zipingpu water reservoir (eq. 4). BT1 responded, in particular, on steep dipping fault segments ($>60^\circ$) within the low permeable Proterozoic granitic rocks, as shown in Fig. 3. On the other hand, the influence of the pore pressure diffusion is infinitesimal small under undrained conditions in a compressive tectonic regime. This fact has been previously discussed (Klose 2008; Klose 2009; Deng et al. 2010; Gahalaut and Gahalaut 2010).

Second, from October 2005 until the mainshock nucleated in May 2008, $\Delta CFS$ exceeded triggering stresses of 4 kPa at $<12$ km depth. This stress level is critical,
since it is daily generated by tidal elongations of the earth due to both the moon and the sun (see Appendix). It has been empirically shown that tidal stress changes have weak or random effects on triggering medium- to large-size earthquakes (Mauk and Kienle 1973; Klein 1976; Beeler and Lockner 2003a; Cochran et al. 2004). Thus, it can be anticipated that any triggering stress perturbation in the earth’s crust must exceed at least stress levels of 1-10 KPa resulting from the tidal elongation of the earth.

![Figure 4](image-url)

**Fig. 4.** Relationship between the coseismic slip $s$ observed during the main-shock (Wang et al. 2008a) and the clock advancement $\Delta t$ of static triggering stress perturbations as result of the surface loading processes of the artificial water reservoir (see Fig. 2). $s$ and $\Delta t$ are sampled from non-interpolated finite elements of the double-listric Beichuan fault beneath the reservoir. $\Delta t$-values are based on a rate-and-state dependent friction law (see supplementary material). Positive/Negative $\Delta t$-values indicate a fault de/stabilization. Correlation coefficients between $s$ and $\Delta t$ are indicated by $\kappa$.

Third, the Zipingpu reservoir only provided the trigger for the limited, initial rupture on the thrust beneath the reservoir (Fig. 1c), which grew to engage the natural accumulated stress $\Delta \sigma$ along the full Beichuan system (BT1-3) of about 250 km length (Fig. 1b). $\Delta \sigma$ had been built up by natural tectonic loading during the seismic cycle along BT1-3 and the entire Longmen Shan. Moreover, the water reservoir also influenced the initial rupture propagation. In the first 20 seconds, the rupture propagation on a 32 km long and 13±3 km wide BT1-fault segment was directed upwards toward the Minjiang River Valley directly to the surface loading area of the Zipingpu water reservoir (Fig. 1b). Then, the rupture propagation process changed to a right-lateral NNE strike-slip rupture mechanism (Zhang et al. 2009; Wang et al. 2008a). Thus, although expected and observed fault geometries differ, the expected seismic magnitude still falls, with an underestimation, into the statistical uncertainty of the observed magnitude. Last, modeling results based on a rate-and-state dependent friction law (see Section 3.2) suggest that the clock advancement $\Delta t$ of the mainshock varies for different earthquake cycles and model regimes (Tab. 3). As discussed by Gomberg et al. 2000, the smaller $a$ is relatively to $b$, the more the fault becomes Coulomb-like. This
might be true at 11-19 km depth, where faults are generally locked in the Longmen Shan region (Wang et al. 2008b). Thus, regime 3 in Table 3 might be more suitable to model the seismic cycle of the Beichuan faults, due to low deformation rates and the stiff behaving Pengguan Massif (Fig. 1). Static perturbations of the water reservoir more likely produced ≤41 years of equivalent tectonic loading in a 4 kyr earthquake cycle or ≤57 years in a 10 kyr cycle. The more (less) the surface loading of the water reservoir perturbed BT1 and BT2 in its near vicinity (15 km radius) the more (less) it contributed to the coseismic slip observed on both faults during the main rupture (Fig. 4). This contribution, however, was <1%. Although the static triggering seems to contribute only up to 6 decades of equivalent tectonic loading, it strongly correlates with the coseismic slip observed on BT1 and BT2 beneath the reservoir (Fig. 4). It should be noted that seasonal water level changes might advance the clock even further. According to the rate-and-state dependent friction law by Gomberg et al. (1998), dynamic stress perturbations applied late in the earthquake cycle, would advance the clock by several hundred years. Problematic, however, is that the friction law approximates the dynamic load as a box function instead of a wave function, which results in a non-optimal solution. Thus, dynamic loads are not considered in this study.

Table 3 Expected clock advancement times ∆t (in years) for the 2008 Wenchuan due to static triggering stress perturbations ∆CFS of about 2 kPa at hypocentral depth and 9 kPa at 4 km beneath the Zipingpu water reservoir. Results are based on the rate-and-state model suggested by Gomberg et al. (1998) with respect to a) three earthquake cycles and b) three model regimes describing the potential behavior of the Beichuan fault.

| tf  | ∆CFS | ∆t (years) | regime 1 | regime 2 | regime 3 |
|-----|------|------------|----------|----------|----------|
| 4000| 9    | 3          | 13       | 41       |
| 4000| 2    | 1          | 2        | 4        |
| 7000| 9    | 3          | 14       | 51       |
| 7000| 2    | 1          | 3        | 5        |
| 10000| 9     | 3          | 15       | 57       |
| 10000| 2    | 1          | 3        | 6        |

5 Conclusion

This study suggests that surface loading of at least 320 million metric tons of water, which accumulated in the Zipingpu water reservoir in the Minjiang River Valley between 2005 and 2008, most likely triggered advanced China’s Wenchuan M7.9 earthquake of May 12, 2008, while enhancing a reverse-fault rupture propagation within the first 20 seconds. Specifically, 3-dimensional geomechanical modeling results based on a rate-and-state dependent friction law show that static triggering stresses brought parts of the Benchuan thrust fault system nearby the water reservoir closer to failure and advanced the clock of the mainshock by up to six decades. Conversely, other fault segments, directly beneath the reservoir, were brought away from failure due to the weight of the reservoir.

The estimated slip of equivalent tectonic loading that was produced by the water reservoir on the Beichuan fault system indicates a strong correlation with the observed coseismic slip during the mainshock of May 12, 2008. The highest correlation coefficient
of 0.93 was found for an earthquake cycle of 10 kyr. Moreover, correlations become weaker with decreasing recurrence time of the earthquake cycle. This confirms results of previous paleoseismicity studies, which show evidence that the Longmen Shan and, in particular, the Pengguan Massif is characterized by a >7 kyr seismic cycle for major M>7 earthquakes.

6 Acknowledgments

The author is grateful to Think Geohazards for its generous financial support. He also thanks the five anonymous reviewers for their constructive critiques and C.H. Scholz and L. Seeber from Lamont-Doherty Earth Observatory for their suggestions and comments to improve this manuscript.

7 Appendix

Everyday, the moon and sun cause tidal elongations on earth (Bartels 1985). These daily pull/push effects, in turn, induce stabilizing and destabilizing stresses on preexisting fault zones in the earth’s crust and are independent from any geological forces on earth, including endogenous forces (e.g., volcanism, tectonics) and exogenous forces (e.g., erosion, sedimentation). Moreover, it has been shown that tidal stress changes have weak effects on triggering medium- to large-size earthquakes (Beeler and Lockner 2003a). Thus, it can be anticipated that any triggering stress perturbation on the earth’s crust must exceed at least stress levels resulting from the tidal elongation of the earth. Analytically, it can be shown how high these tidal stress changes are.

Let’s assume, $F_0$ is the earth’s gravitational potential, which results from both attraction force and centrifugal force of the earth and moon/sun. Tidal forces $V$, however, deform $F_0$:

$$F = F_0 - V$$

(10)

This results in a vertical surface displacement $\xi$ with respect to the average value of the gravitation acceleration on earth $g = 9.798 \text{ ms}^{-1}$.

$$\xi = \frac{F_0 - F}{g} = \frac{V}{g}. \quad (11)$$

Tidal forces change with geocentric zenith distance $\theta$ from the moon/sun (Bartels 1985), whereas the main term of the tidal potential is

$$V \approx \left( \frac{G_l}{r_E^2} \right) r_E^2 \left( \cos 2\theta + \frac{1}{3} \right)$$

(12)

with the lunar tidal constant $G_l = 2.6206 \text{ m}^2\text{s}^{-2}$ and the solar tidal constant $G_s = 1.2068 \text{ m}^2\text{s}^{-2}$, the radius of the earth $r_E$ and the mean radius of the earth $r_E = 6371.221 \text{ km}$. Assuming the earth is a sphere ($r_E = r_E$), the general form of vertical surface displacement is

$$\xi = \frac{G_s}{g} \left( \cos 2\theta + \frac{1}{3} \right). \quad (13)$$
The displacement due to the moon and sun is

\[ \xi_l = 0.267 m \left( \cos 2\theta + \frac{1}{3} \right), \quad \xi_s = 0.123 m \left( \cos 2\theta + \frac{1}{3} \right), \]  

(14)

Thus, the \( \xi_l \) and \( \xi_s \) are amplified at the zenith \( (\theta = 0^\circ) \) by 0.356 m and 0.164 m. On the other hand, they are depressed at the nadir \( (\theta = 90^\circ) \) by 0.178 m and 0.082 m. The peak-trough difference for the moon is 0.534 m and 0.246 m for the sun.

Both vertical displacements induce maximal shear stresses \( \tau \) and normal stresses \( \sigma_n \) on preexisting faults (e.g., dipping 45°) in the earth’s crust with an average shear modulus of about \( G = 30 \) GPa and friction angle of, let’s assume, \( \phi \) of 29°:

\[ \tau = \frac{\xi}{\tau_E} \frac{2G}{\tau}, \]

(15)

\[ \sigma_n = \frac{\tau}{\tan \phi}. \]

(16)

Thus, maximum induced stresses that need to be exceeded by any additional triggering stress (e.g., due to surface loading) are:

by the moon \( \tau_l = 5.03 \text{ kPa} \) and \( \sigma_n,l = 9.07 \text{ kPa} \),

by the sun \( \tau_s = 2.32 \text{ kPa} \) and \( \sigma_n,s = 4.18 \text{ kPa} \).
References

Bartels, J. (1985) Tidal Forces. In: Harrison, J.C. Earth Tides. Van Nostrand Reinhold Company New York.

Beeler, N.M. and Lockner, D.A. (2003) Why earthquakes correlate weakly with the solid Earth tides: Effects of periodic stress on the rate and probability of earthquake occurrence. JGR 108 B8 2391.

Biot, M. (1941) General theory of three-dimensional consolidation. Journal of Applied Physics 12 155.

Blanpied, M.L., Marone, C.J., Lockner, D.A., Byerlee, J.D., King, D.P. (1998) Quantitative measure of the variation in fault rheology due to fluid-rock interactions. JGR 103 9691.

Boussinesq, J. (1885) Application des Potentials a l ‘Etude de l ‘Equilibre et du Mouvement des Solides Elastiques Gauthier Villars, Paris.

Burchfiel, B.C., Chen, Z., Liu, Y., Royden, L.H. (1995) Tectonics of the Longmen Shan and adjacent regions. Int. Geol. Rev. 37 661.

Burchfiel, B.C., L.H. Royden, R.D. van der Hilst, B.H. Hager, Z. Chen, R.W. King, C. Li, J. Lu, H. Yao, E. Kirby (2008) A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, Peoples’s Republic of China. GSA Today 18, 4.

Chen, S., Wilson, C.J.L., Deng, Q., Zhao, X., Luo, Z. (1994) Active faulting and block movement associated with large earthquakes in the Min Shan and Longmen Mountains, northeastern Tibet Plateau. J. Geophys. Research 99 24025.

Cochran, E., Vidale, J. and Tanaka, S. (2004) Earth tides can trigger shallow thrust fault earthquakes, Science, 306:1164–1166.

Deng, K., Zhou, S., Wang, R., Robinson, R., Zhao, C., Cheng, W. (2010) Evidence that the 2008 Mw 7.9 Wenchuan Earthquake Could Not Have Been Induced by the Zipingpu Reservoir, Bulletin of the Seismological Society of America 100(5B) 2805-2814.

Densmore, A., Ellis, L.M.A., Li, Y., Zhou, R., Hancock, G.S. Richardson, N. (2007) Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau. Tectonics 26 1.

Dieterich, J.H. (1979) Modeling of friction, 1, Experimental results and constitutive equations. JGR 84 2169.

Gahalaut, K. and Gahalaut, V.K. (2010) Effect of the Zipingpu reservoir impoundment on the occurrence of the 2008 Wenchuan earthquake and local seismicity, Geophys. J. Int. 183, 277285.

Ge, S., Liu, M., Lu, N., Godt, J.W. and Gang L. (2009) Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake? Geophysical Research Letters, 36, L20315, doi:10.1029/2009GL040349

Gomberg, J., Beeler, N.M., Blanpied, M.L., Bodin, P. (1998) Earthquake triggering by transient and static deformations. JGR 103 24,411.

Gomberg, J., Beeler, N., Blanpied, M. (2000) On rate-state and Coulomb failure models. JGR 105 7857.

Hu, X-M. (2007) Natural earthquake activities before the Zipingpu dam began to store water. Earthquake Research in China 2.

Huang, Y., Wu, J., Zhang, T., Zhang, D-N. (2008) Relocation of the M8.0 Wenchuan earthquake and its aftershock sequence. Sci. China Ser. D-Earth Sci. 51(12) 1703.
Jia, D. et al. (2006) Longmen Shan fold-thrust belt and its relation to the western Sichuan Basin in central China: New insights from hydrocarbon exploration. *AAPG Bulletin* 90(9), 1425.

Klein, F.W. (1976) Tidal triggering of reservoir-associated earthquakes. *Engineering Geology* 10(2-4) 197-210.

Klose, C.D. (2008) The 2008 M7.9 Wenchuan earthquake - Result of Local and Abnormal Mass Imbalances?, EOS Trans. AGU, 89(53), Fall Meet. Suppl., Abstract U21C-08. [http://adsabs.harvard.edu/abs/2008AGUFM.U21C..08K](http://adsabs.harvard.edu/abs/2008AGUFM.U21C..08K)

Klose, C.D. (2009) On to what extent stresses resulting from the earth's surface trigger earthquakes, AGU Fall Meet. S54A-08S54A-08. [http://adsabs.harvard.edu/abs/2009AGUFM.S54A..08K](http://adsabs.harvard.edu/abs/2009AGUFM.S54A..08K)

Klose, C.D. and Seeber, L. (2007) Shallow seismicity in stable continental regions. *SRL* 78 554.

Lei, X-L., Ma, S-L., Wen, X-Z., Su, J.R., Du, F. (2008) Integrated analysis of stress and regional seismicity by surface loading - a case study of Zipingpu reservoir. *Seismology and Geology* 30(4) 1046.

Lin, A., Ren, Z., Don, J., Wu, X. (2009) Co-seismic thrusting rupture and slip distribution produced by the 2008 Mw 7.9 Wenchuan earthquake, China. *Tectonophysics* 471 203.

Liu, P-J., Diao, G-I., Ning, J-Y. (2007) Fault plane solutions in Sichuan-Yunnan rhombic block and their dynamic implications. *Acta Seismologica Sinica* 20(5) 479.

Lockner, D.A. and Beeler, N.M. (2003) Stress-induced anisotropic poroelasticity response in sandstone. *16th ASCE Engineering Mechanics Conference, University of Washington, Seattle*.

Love, A.E.H. (1944) A treatise on the mathematical theory of elasticity. *First American*.

Mauk, F. J. and Kienle, J. (1973) Microearthquakes at St. Augustine Volcano, Alaska, Triggered by Earth Tides. *Science* 182 (4110) 386-389.

McGarr, A. (1988) On the state of lithospheric stress in the absence of applied tectonic forces. *Journal of Geophysical Research* 93, 13,609.

Rice, J. and Cleary, M. (1976) Some basic stress diffusion solutions for fluid-saturated porous elastic media with compressible constituents. *Review of Geophysics* 14 227.

Ruina, A. (1983) Slip instability and state variable friction laws. *JGR* 88 10,359.

Terzaghi, K. (1938) *Einfluß des Porenwasserdrucks auf den Scherwiderstand der Tone.* 33 Berlin.

Wang, W-M., Zhao, L-F., Li, J., Yao, Z-X. (2008) Rupture process of the Ms8.0 Wenchuan earthquake of Sichuan, China. *Chinese J. Geophys.* 51(5) 1403.

Wang, Y.Z., EN. Wang, ZK. Shen, M. Wang, W.J. Gan, XJ. Qiao, GJ. Meng, TM. Li, W. Tao, YL. Yang, J. Cheng, P. Li (2008) GPS-constrained inversion of present-day slip rates along major faults of the Sichuan-Yunnan region, China. *Science in China Series D: Earth Sciences* 51(9) 1267.

Yang, Z.X., Waldhauser, F., Chen, Y.T., Richards, P.G. (2005) Double-difference relocation of earthquakes in central-western China, 1992-1999. *Journal of Seismology* 9 241.

Yao, H., Beghein, C., van der Hilst, R.D. (2008) Surface-wave array tomography in SE Tibet from ambient seismic noise and two-station analysis: II - crustal and upper mantle structure. *Geophys. J. Int.* 173 205.
Zhang, Y., Feng, WP., Xu, LS., Zhou, CH., Chen, YT. (2009) Spatio-temporal rupture process of the 2008 great Wenchuan earthquake. *Science in China Series D-Earth Sciences* **52**(2) 145.

Zhou, R. et al. (2007) Active tectonics of the Longmen Shan region of the eastern margin of the Tibet Platau. *Acta Geologica Sinica* **81** 593.