GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L20315, doi:10.1029/2009GL040349, 2009

Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake?

Shemin Ge,[1] Mian Liu,[2] Ning Lu,[3] Jonathan W. Godt,[4] and Gang Luo[2]

Received 1 August 2009; revised 15 September 2009; accepted 28 September 2009; published 28 October 2009.

[1] The devastating May 2008 Wenchuan earthquake (M_w 7.9) resulted from thrust of the Tibet Plateau on the Longmen Shan fault zone, a consequence of the Indo-Asian continental collision. Many have speculated on the role played by the Zipingpu Reservoir, impounded in 2005 near the epicenter, in triggering the earthquake. This study evaluates the stress changes in response to the impoundment of the Zipingpu Reservoir and assesses their impact on the Wenchuan earthquake. We show that the impoundment could have changed the Coulomb stress by −0.01 to 0.05 MPa at locations and depth consistent with reported hypocenter positions. This level of stress change has been shown to be significant in triggering earthquakes on critically stressed faults. Because the loading rate on the Longmen Shan fault is <0.005 MPa/yr, we thus suggest that the Zipingpu Reservoir potentially hastened the occurrence of the Wenchuan earthquake by tens to hundreds of years.

Citation: Ge, S., M. Liu, N. Lu, J. W. Godt, and G. Luo (2009), Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake?, *Geophys. Res. Lett.*, *36*, L20315, doi:10.1029/2009GL040349.

1. Introduction

[2] Some large reservoirs are known to induce earthquakes [*Gupta and Chadha*, 1995; *Talwani*, 1997]. Speculation on the role of reservoirs in triggering earthquakes has pervaded discussions following the devastating 12 May 2008 Wenchuan earthquake (M_w = 7.9) in China that killed nearly 90,000 people [*Kerr and Stone*, 2009; *Klose*, 2008]. At the center of the controversy is the Zipingpu Reservoir, impounded in 2005 and located approximately 20 km from the epicenter (Figure 1). A key unsolved issue is how the reservoir water changed the stress state in the vicinity of the reservoir. This study aims to evaluate the stress changes in the hypocentral region in response to the impoundment of the Zipingpu Reservoir and assess their impact on the Wenchuan earthquake.

2. Effective Coulomb Stress

[3] The Wenchuan earthquake, which resulted from thrusting of the Tibet Plateau on the Longmen Shan fault zone, is a consequence of the Indo-Asian continental collision. When a reservoir is built on or near a fault, the rise or fall of the water level may affect the stability of the fault plane by two physical processes: 1) the static load due to the weight of water changes the shear ($\Delta\tau$) and normal stresses ($\Delta\sigma_n$) on the fault plane, and 2) water impoundment changes the pore pressure (ΔP) in the rocks below the reservoir due to fluid diffusion. These effects can be expressed by the change in effective Coulomb stress (auxiliary material), ΔS_e:

$$\Delta S_e = \Delta\tau - \mu\Delta\sigma_n + \mu\Delta P \tag{1}$$

where μ is the friction coefficient.[5] Positive $\Delta\tau$ indicates an increase in shear stress in the fault slip direction, positive $\Delta\sigma_n$ an increase in compressive stress that clamps the fault, and positive ΔP an increase in pore pressure that unclamps the fault. Hence positive change in ΔS_e promotes failure, and negative change inhibits failure. Coulomb stress increases of $\geq$0.01 MPa have been shown to be associated with seismicity rate increase and in many cases triggering earthquakes [*Reasenberg and Simpson*, 1992; *Stein*, 1999].

[4] The fluid diffusion term, $\mu\Delta P$, in equation (1) includes two parts: 1) the instantaneous pore pressure response to the volumetric stress resulting from the static load of the reservoir pool, known as the "undrained" response, and 2) the time-dependent pore pressure diffusion due to the permanent presence of water pressure at the bottom of the reservoir [*Roeloffs*, 1988] (auxiliary material). The magnitude of the undrained pressure change depends on rock compressibility and is proportional to the mean stress, is largest upon initial loading, and decays through time due to pore pressure diffusion. The rate of pore pressure change depends on the hydraulic diffusivity of the rocks, defined as the ratio of the hydraulic conductivity and specific storage [*Freeze and Cherry*, 1979].

3. Zipingpu Reservoir and Hypocenter Locations

[5] The Zipingpu Reservoir, with a capacity of 1×10^9 m^3, was impounded in September, 2005, 2.7 years before the May 2008 earthquake, raising the base water level elevation from 757 m to an average of 857 m (Figure 2). The maximum water level reached 877 m in December 2006. This average increase of 100 m of head caused an equivalent pressure increase of about 0.98 MPa at the bottom of the reservoir. The Zipingpu Reservoir is located close to the Yingxiu-Beichuan (YB) fault and a few kilometers west of the Guanxian-Anxian (GA) fault of the Longmen Shan fault zone (Figure 1). Both faults ruptured during the Wenchuan earthquake, but the locations of the hypocenters reported by the Chinese Earthquake Administration (CEA) and the U. S. Geological Survey (USGS) differ. Moreover, multiple event relocation analyses suggest that the actual hypocenter location is between 6 and

[1]Department of Geological Sciences, University of Colorado, Boulder, Colorado, USA.
[2]Department of Geological Sciences, University of Missouri, Columbia, Missouri, USA.
[3]Division of Engineering, Colorado School of Mines, Golden, Colorado, USA.
[4]U.S. Geological Survey, Denver, Colorado, USA.

0094-8276/09/2009GL040349$05.00

[5]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040349.

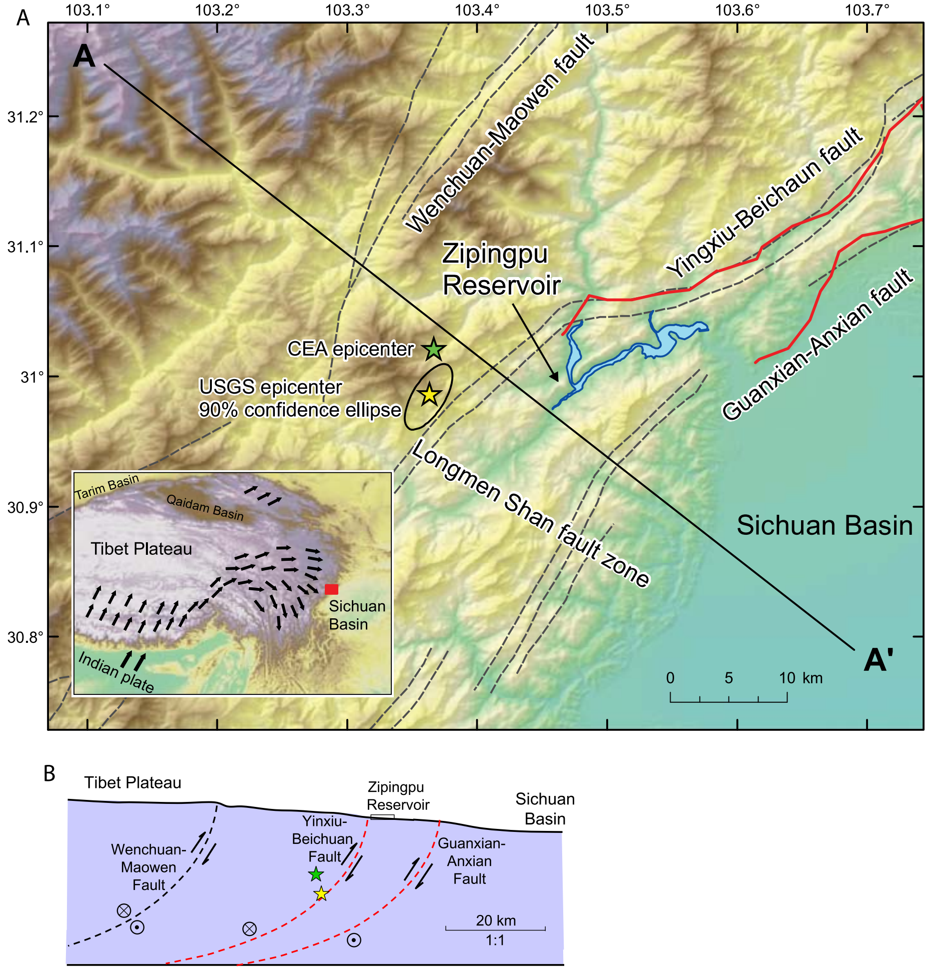


Figure 1. (a) Shaded relief map showing topography, faults (dashed lines), surface rupture (red lines) on the Yingxiu-Beichuan fault (YB) and the Guanxian-Anxian fault (GA), and epicenters from the U.S. Geological Survey (USGS - Lat. 30.986, Long. 103.364, yellow star) with the 90% confidence ellipse and the China Earthquake Administration (CEA - Lat. 31.021, Long. 103.367, green star) [*Li et al.*, 2008]. Fault rupture traces are modified from *Lin et al.* [2009]. The insert shows the location (red rectangle) of the shaded relief map and tectonic setting with the arrows indicating the relative crustal motion. (b) Schematic cross section across the Longmen Shan fault zone, the location of the cross section, A-A′, is shown in Figure 1a.

15 km to the west of those initially reported by the USGS and CEA [*Bergman and Engdahl*, 2008].

4. Impact of the Zipingpu Reservoir on Stress

[6] On the basis of the geologic and tectonic settings of the region [*Burchfiel et al.*, 2008], we constructed a two dimensional model to examine how the reservoir load changed the effective Coulomb stress in the fault zone. We first computed the mechanical effects on the static Coulomb stress, resulting from the 100-m water impoundment, using a finite element model [*Li et al.*, 2005]. These effects depend on the fault dip angle and rake. The geometry of the

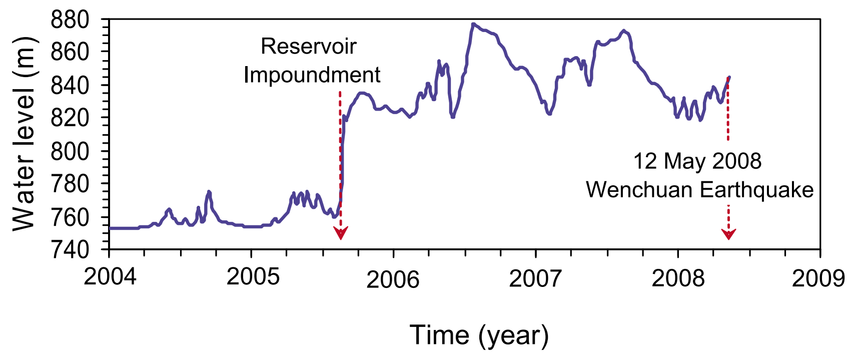


Figure 2. Water level history of the Zipingpu Reservoir [*Lei et al.*, 2008]. The water level is in meters above sea level.

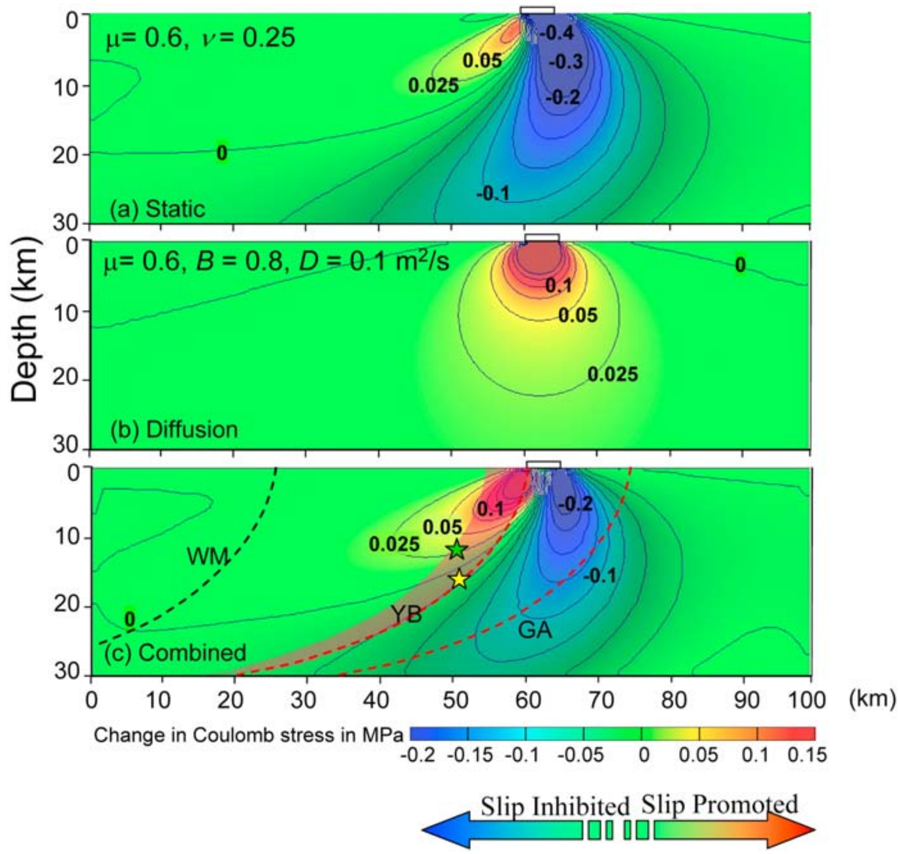


Figure 3. Simulated change in effective Coulomb stress due to the load from the Zipingpu Reservoir. (a) Coulomb stress change due to a static load of 100 m of water in the reservoir. (b) Hydrodynamic contribution to the Coulomb stress change 2.7 years after the impoundment. (c) Effective Coulomb stress change, the combined effects of static loading and hydrodynamic contribution. The black and red dashed lines in C indicate the locations of the WM, YB, and GA faults. The shaded band over the YB fault is the zone over which the effective Coulomb stress change is examined in more detail (Figure 4).

Longman Shan faults are generally listric with high angles near the surface [*Burchfiel et al.*, 2008], but the details are complex and vary along the strike of each fault [*Jia et al.*, 2009]. Here we simplified both the YB fault and the GA fault, assuming they dip at 80° to the west at the surface and gradually flattens to 10° at 30 km depth at a linear rate. Because of the two dimensional representation, we assumed the rakes to be up-slip (thrusting) on the footwall fault planes. For the crust outside these two faults, we used the same dips and rakes for potential receiver faults. Computed changes in Coulomb stress due to the static load from the reservoir range from +0.1 to −0.5 MPa (Figure 3a). The region directly below the reservoir experiences a negative change of the Coulomb stress, inhibiting failure from the static water loading. However, to the west of the reservoir the Coulomb stress change is positive where faults are brought closer to failure. The regions of positive Coulomb stress changes would be broader and negative Coulomb stress changes narrower, if the fault planes are steeper.

[7] We computed the transient hydrologic effects, ($\mu\Delta P$) in equation (1), including those from the undrained response and those from pressure diffusion using the reservoir level history (Figure 2) and a numerical model for pore pressure diffusion [*McDonald and Harbaugh*, 1988; *Waterloo Hydrogeologic, Inc.*, 2005]. Figure 3b shows the Coulomb stress change due to the hydrologic effects 2.7 years after the impoundment. The changes are all positive, as any increase in pore pressure acts to promote slip on the faults. In the upper 5 km, directly below the reservoir, the change in Coulomb stress is as large as 0.1 MPa. These results are independent of the dip angles of receiver faults, but their spatial-temporal variations are controlled by the hydraulic diffusivity [*Bell and Nur*, 1978; *Talwani*, 1997; *Chen and Talwani*, 1998, 2001; *Shapiro et al.*, 2005; *Rao and Singh*, 2008]. On the basis of the location and timing of the microseismicity presumably induced by the reservoir, we estimate the diffusivity in the reservoir region to be on the order of 0.1 to 1 m^2/s that is within the range of 0.1 to 10 m^2/s reported by *Talwani* [1997] (auxiliary material). We used the lower value of 0.1 m^2/s in this study because it is more consistent with crustal-scale hydrologic properties [*Manning and Ingebritsen*, 1999; *Saar and Manga*, 2004]. Sensitivity study using diffusivities from 0.01 to 10 m^2/s yielded similar temporal and spatial patterns and magnitudes of pore pressure increase 2.7 years after impoundment.

[8] The change in effective Coulomb stress (Figure 3c) is obtained by summing the changes due to static loading (Figure 3a) and hydrodynamic diffusion (Figure 3b). Although the spatial pattern of the effective Coulomb stress changes is similar to that caused by the static loading

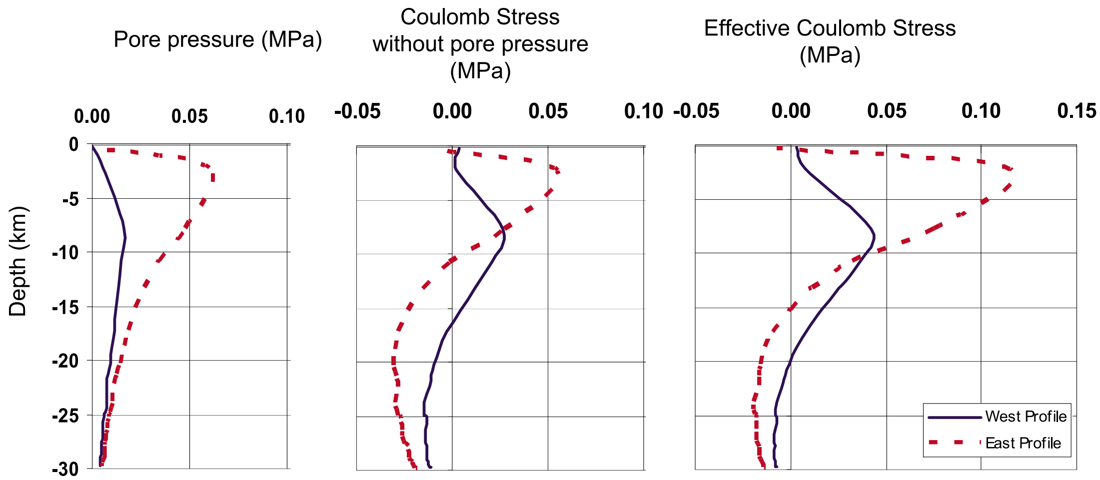


Figure 4. Stress change profiles over a 5–10 km YB fault zone shaded region in Figure 3c. Red lines are for the east boundary and blue the west boundary of the shaded region. (left) Pore pressure profiles over the YB fault zone at 2.7 years after the reservoir impoundment. (middle) Coulomb stress profiles without pore pressure. (right) Effective Coulomb stress profiles over the fault zone at 2.7 years after impoundment.

(Figure 3a), the values are augmented by the positive pore pressure values shown in Figure 3b. At 2.7 years after the impoundment of the Zipingpu Reservoir, changes of more than ±0.01 MPa are observed in a region extending 20 km west and 20 km below the reservoir. Such changes are comparable in magnitude to those induced by large earthquakes and that have been shown to trigger or delay subsequent earthquakes [*Reasenberg and Simpson*, 1992; *Stein*, 1999], and to the coseismic Coulomb stress changes by the Wenchuan Earthquake [*Parsons et al.*, 2008; *Toda et al.*, 2008].

[9] With the fault locations and geometry shown in Figure 3c, our results indicate that the GA fault is within a zone in which the change in effective Coulomb stress is negative, inhibiting slip. The YB fault, however, experiences positive Coulomb stress changes as deep as 20 km. Because the uncertainties of the exact locations of the rupture planes, and sensitivity of the predicted Coulomb stress changes to the fault location, we further examine the stress variations within a 5–10 km zone over the YB fault (shaded in Figure 3c). Figure 4 (left) shows the profiles of pore pressure change at 2.7 years after the reservoir impoundment and 4 (middle) the profiles of Coulomb stress without considering the influence of pressure. The effective Coulomb stress change profile (Figure 4, right) is the sum of the pore pressure (Figure 4, left) and Coulomb stress (Figure 4, middle). Increase in the effective Coulomb stress reaches a maximum of more than 0.1 MPa a few kilometers below the reservoir. At 10–20 km, the depth interval of reported hypocenters, the effective Coulomb stress varies from −0.02 to 0.05 MPa.

5. Discussion

[10] Anecdotal accounts by people in Dujiangyan, 6 km from the reservoir, suggest an increased level of seismicity after the impoundment [*Stone*, 2009]. Systematic microseismicity data near the reservoir, however, are lacking. The seismic data from the China Earthquake Administration do not contain sufficient miscroseismicity data in the vicinity of the reservoir. The microseismicity data recorded by the reservoir authority in the vicinity of the reservoir do not contain background data prior to 2004 or these data are currently unavailable to the public. Because sufficient microseismicity data are unavailable, a definitive correlation between microseismicity rate and Coulomb stress changes is impossible. Despite this challenge, this study demonstrates in detail how pore pressure diffusion could modify the effective Coulomb stress, which is a key to assessing the impact of the Zipingpu reservoir on the stress state in its vicinity. We acknowledge that the 2D model is an approximation of the real 3D system. For short time scales of a few years, however, there is little difference between 2D and 3D simulations of pore pressure distributions in the vicinity of the reservoir.

[11] Seismicity rates have been shown to increase in regions where Coulomb stress has been elevated by previous large earthquakes [*Stein*, 1999]. Coulomb stress increase of 0.01 MPa is considered a threshold that begins to affect seismicity [*Reasenberg and Simpson*, 1992; *Stein*, 1999]. Such a slight change in Coulomb stress can affect seismicity because active faults are critically stressed, and the stress drop associated with large earthquakes is typically only a few MPa. In the Longmen Shan fault zone, the recurrence interval for large earthquakes like the May 2008 Wenchuan event is estimated to be greater than 2000 years [*Burchfiel et al.*, 2008]. For a typical stress drop of 5–10 MPa for large earthquakes, this implies a stress rate of 0.0025–0.005 MPa/yr. The Zipingpu Reservoir, by elevating the Coulomb stress by 0.01–0.05 MPa, could have hastened the rupture of the YB fault by tens to hundreds of years.

[12] **Acknowledgments.** We thank Evelyn Roeloffs and Ross Stein for their insightful comments on earlier versions of this paper. The authors are grateful to Michael Manga, an anonymous reviewer, and Ruth Harris for their review comments that have helped to enhance the quality of the manuscript. Liu acknowledges partial support from US NSF/PIRE grant 0730154 and from the Chinese Academy of Sciences and the Chinese Ministry of Education.

References

Bell, M. L., and A. Nur (1978), Strength changes due to reservoir-induced pore pressure and stresses and application to Lake Oroville, *J. Geophys. Res.*, *83*, 4469–4483, doi:10.1029/JB083iB09p04469.

Bergman, E. A., and E. R. Engdahl (2008), The seismicity pattern of the 2008 Wenchuan, China, M_w 7.9 mainshock and aftershocks from a calibrated multiple event relocation technique, paper presented at the Bilateral Workshop under the Sino–US Earthquake Studies Protocol, Univ. of Colo., Boulder. (Available at http://www.iris.iris.edu/boulder/Abstracts/Bergman.new.poster.pdf)

Burchfiel, B. C., L. H. Royden, R. D. van der Hilst, and B. H. Hager (2008), A geological and geophysical context for the Wenchuan earthquake of May 12, 2008, Sichuan, People's Republic of China, *GSA Today*, *18*, 4–11, doi:10.1130/GSATG18A.1.

Chen, L., and P. Talwani (1998), Reservoir-induced seismicity in China, *Pure Appl. Geophys.*, *153*, 133–149, doi:10.1007/s000240050188.

Chen, L., and P. Talwani (2001), Mechanism of initial seismicity following impoundment of the Monticello Reservoir, South Carolina, *Bull. Seismol. Soc. Am.*, *91*, 1582–1594, doi:10.1785/0120000293.

Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, Prentice-Hall, Englewood Cliffs, N. J.

Gupta, H., and R. Chadha (1995), *Induced Seismicity*, *Pure Appl. Geophys.*, vol. 145, 217 pp., Birkhäuser, Boston, Mass.

Jia, D., Y. Li, A. Lin, M. Wang, W. Chen, X. Wu, Z. Ren, Y. Zhao, and L. Luo (2009), Structural model of 2008 Mw 7.9 Wenchuan earthquake in the rejuvenated Longmen Shan thrust belt, China, *Tectonophysics*, in press.

Kerr, R. A., and R. Stone (2009), A human trigger for the great quake of Sichuan?, *Science*, *323*, 322, doi:10.1126/science.323.5912.322.

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.

Lei, X. L., S. Ma, X. Wen, J. Su, and F. Du (2008), Integrated analysis of stress and regional seismicity by surface loading—A case study of Zipingpu Reservoir (in Chinese with English abstract), *Geol. Seismol.*, *30*, 1046–1064.

Li, Q., M. Liu, and E. A. Sandvol (2005), Stress evolution following the 1811–1812 large earthquakes in the New Madrid Seismic Zone, *Geophys. Res. Lett.*, *32*, L12S08, doi:10.1029/2004GL021524.

Li, X., Z. Zhou, M. Huang, R. Wen, H. Yu, D. Lu, Y. Zhou, and J. Cui (2008), Preliminary analysis of strong-motion recordings from the magnitude 8.0 Wenchuan, China, earthquake of 12 May 2008, *Seismol. Res. Lett.*, *79*, 844–854, doi:10.1785/gssrl.79.6.844.

Lin, A., Z. Ren, and X. Wu (2009), Co-seismic thrusting rupture and slide distribution produced by the 2008 M_w 7.9 Wenchuan earthquake, China, *Tectonophysics*, doi:10.1016/j.tecto.2009.02.014, in press.

Manning, C. E., and S. E. Ingebritsen (1999), Permeability of the continental crust: Implications of geothermal data and metamorphic systems, *Rev. Geophys.*, *37*, 127–150, doi:10.1029/1998RG900002.

McDonald, M. G., and A. W. Harbaugh (1988), A modular three-dimensional finite-difference ground-water flow model, *U.S. Geol. Surv. Tech. Water Resour. Invest., 06-A1*.

Parsons, T., C. Ji, and E. Kirby (2008), Stress changes from the 2008 Wenchuan earthquake and increased hazard in the Sichuan Basin, *Nature*, *454*, 509–510, doi:10.1038/nature07177.

Rao, R. R., and C. Singh (2008), Temporal migration of earthquakes in Koyna-Warna (India) region by pore-fluid diffusion, *J. Seismol.*, *12*, 547–556, doi:10.1007/s10950-008-9108-0.

Reasenberg, P. A., and R. W. Simpson (1992), Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake, *Science*, *255*, 1687–1690, doi:10.1126/science.255.5052.1687.

Roeloffs, E. A. (1988), Fault stability changes induced beneath a reservoir with cyclic variation in water level, *J. Geophys. Res.*, *93*, 2107–2124, doi:10.1029/JB093iB03p02107.

Saar, M., and M. Manga (2004), Depth dependence of permeability in the Oregon Cascades inferred from hydrogeologic, thermal, seismic, and magmatic modeling constraints, *J. Geophys. Res.*, *109*, B04204, doi:10.1029/2003JB002855.

Shapiro, S. A., S. Rentsch, and E. Rothert (2005), Fluid-induced seismicity: Theory, modeling, and applications, *J. Eng. Mech.*, *131*, 947–952, doi:10.1061/(ASCE)0733-9399(2005)131:9(947).

Stein, R. S. (1999), The role of stress transfer in earthquake occurrence, *Nature*, *402*, 605–609, doi:10.1038/45144.

Stone, R. (2009), Some unwelcome questions about big dams, *Science*, *324*, 714, doi:10.1126/science.324_714.

Talwani, P. (1997), The nature of reservoir-induced seismicity, *Pure Appl. Geophys.*, *150*, 473–492, doi:10.1007/s000240050089.

Toda, S., J. Lin, M. Meghraoui, and R. S. Stein (2008), 2008 M = 7.9 Wenchuan, China, earthquake calculated to increase failure stress and seismicity rate on three major fault systems, *Geophys. Res. Lett.*, *35*, L17305, doi:10.1029/2008GL034903.

Waterloo Hydrogeologic, Inc. (2005), Visual MODFLOW, Waterloo Hydrogeol. Inc., Waterloo, Ont., Canada.

S. Ge, Department of Geological Sciences, University of Colorado, Campus Box 399, Boulder, CO 80309, USA. (ges@colorado.edu)

J. W. Godt, U.S. Geological Survey, MS 966, Denver, CO 80225, USA.

M. Liu and G. Luo, Department of Geological Sciences, University of Missouri, 101 Geology Bldg., Columbia, MO 65211, USA.

N. Lu, Division of Engineering, Colorado School of Mines, 1600 Illinois St., Golden, CO 80401, USA.

Supplement

A. Effective Coulomb Stress Analysis

We assessed changes in Coulomb stress beneath reservoirs by the general theory of de-coupled linear poroelasticity [Biot, 1956; Roeloffs, 1988; Wang 2000; Cocco and Rice, 2002]. We define an effective Coulomb stress change ΔS_e in terms of the mechanical effect and hydrologic effect:

$$\Delta S_e(x,z,t) = \Delta\tau(x,z) - \mu\sigma_n(x,z) + \mu\,\Delta P_u(x,z,t) + \mu\,\Delta P_d(x,z,t) \tag{A1}$$

The first two terms represent the Coulomb stress change due to the static weight of the reservoir. The third term is the "undrained" pressure contribution that depends on change in the mean stress due to the static load of the reservoir. The last term reflects the contribution due to pressure diffusion or fluid flows into the rock from the bottom of the reservoir. The first three terms can be regrouped under the principle of effective stress and called the undrained part of the Coulomb stress change ΔS_u. The last term is referred to as the hydraulic diffusion part of the Coulomb stress change ΔS_d. Then (A1) becomes:

$$\Delta S_e = \Delta S_u + \Delta S_d \tag{A2}$$

The effective Coulomb stress change due to hydraulic diffusion ΔS_d is governed by the following diffusion equation:

$$D\nabla^2 P_d = \frac{\partial P_d}{\partial t} \tag{A3}$$

where D is the hydraulic diffusivity. For given initial and boundary conditions, equation (A3) is solved using a numerical model [McDonald and Harbaugh, 1988; WHI, 2005] for ΔP_d, which is then multiplied by the friction coefficient, μ, to obtain the time-and-space-dependent ΔS_d.

The effective Coulomb stress change due to the undrained part ΔS_u can be obtained from (A1) and (A2):

$$\Delta S_u(x,z,t) = \Delta\tau(x,z) - \mu\Delta\sigma_n(x,z) + \mu\Delta P_u(x,z,t) \quad \text{(A4)}$$

The initial spatial distribution of change in pore pressure ΔP_u upon a reservoir loading depends on the change in the mean stress. Through time, ΔP_u diffuses governed by the diffusion equation (A3) and hydraulic diffusivity D. If we assume $\Delta P_u = B\Delta\sigma_n$ with B being the Skempton constant, varying between zero and unity depending on rock type, equation (A4) becomes:

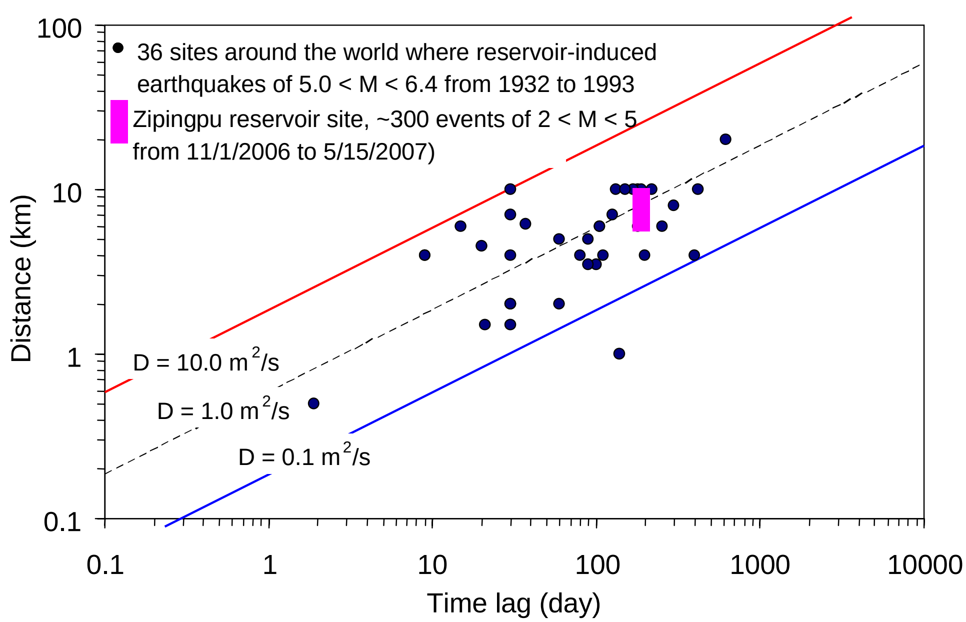
$$\Delta S_u(x,z,t) = \Delta\tau(x,z) - \mu(1-B)\Delta\sigma_n(x,z) = \Delta\tau(x,z) - \mu'\Delta\sigma_n(x,z) \quad \text{(A5)}$$

where $\mu' = \mu(1\text{-}B)$ is the effective or apparent friction coefficient [Cocco and Rice 2002]. It should be recognized that μ' is a convenient parameter but not a material property. Its use obscures the time-dependent nature of ΔP_u. The more rigorous solution of (A4) used in this study is obtained by setting ΔP_u $(x, z, 0) = B\Delta\sigma$ [Rice and Cleary, 1976] upon loading, at which time ΔP_u is at its maximum and so is ΔS_u. Over time, ΔP_u diminishes through diffusion and ΔS_u approaches its minimum.

In computing the effective Coulomb stress change defined in (A1), the first two terms are the stress changes from a static loading due to reservoir impoundment, computed by a numerical model [Li et al., 2005]. The third term has the initial value of $\Delta P_u(x,z,0) = B\Delta\sigma(x, z)$ that is obtained from the mean stress change. The fourth term is simulated using the numerical model with zero pressure boundary conditions everywhere except the time dependent pressure condition at the bottom of the reservoir.

B. Hydraulic Diffusivity Estimation

The hydraulic diffusivity beneath reservoirs has been extensively studied by using reservoir-induced seismicity data [Roeloffs, 1988; Kessels and Kuck, 1995; Talwani, 1997; Guha, 2000]. Based on 36 cases studies of reservoir-induced earthquakes, hydraulic diffusivity has been shown to vary between 0.1 and 10 m^2/s [Talwani et al., 2007], as shown in Supplementary Fig. 1. Based on approximately 300 seismic events within 50 km from the Zipingpu reservoir between November 1, 2006 to May 15, 2007 [Lei et al., 2008], we estimated the hydraulic diffusivity under the reservoir to be around 0.5 and 1.2 m^2/s, using the equation of $D = L^2/(4t)$ with L being either the vertical or dipping distances below the reservoir and t being the average lag time since September 2005 when the impoundment occurred. It should be noted that this approach tends to overestimate the diffusivity.



Supplement Figure 1. Inferred hydraulic diffusivity values from reservoir-induced earthquakes. Data shown in black dots are from Talwani et al. [2007] and pink bar the estimated range using the seismic events reported in Lei et al. [2008].

Reference

Biot. M.A. 1956, General Solutions of the Equations of Elasticity and Consolidation for a Porous Material. *J. Appl. Mech.* 23, 91-96.

Cocco, M. and Rice, J. R. 2000, Pore Pressure and Poroelasticity Effects in Coulomb Stress Analysis of Earthquake Interactions, *J. Geophys. Res.* 107(B2), 10.1029/2000JB000138.

Guha, S.K. 2000, *Induced Earthquakes*, Kluwer Academic Publishers, 314pp.

Kessels, K. and Kuck, J. 1995, Hydraulic Communication in Crystalline Rocks between the Two Boreholes of the Continental Deep Drilling Programme in Germany, *Int. J. Rock. Mech. Sci. Geomech. Abstr.* 32, 37-47.

Lei, X.L., Ma, S., Wen, X., Su, J., and Du F. 2008, Integrated Analysis of Stress and Regional Seismicity by Surface Loading – A Case Study of Zipingpu Reservoir. *Geol. Seismol.* 30(4), 1046-1064, (in Chinese with English abstract).

Li, Q., Liu, M. and Sandvol, E.A. 2005, Stress Evolution Following the 1811-1812 Large Earthquakes in the New Madrid Seismic Zone. *Geophys. Res. Lett.* 32, doi:10.1029/2004GL022133.

McDonald, M.G. and Harbaugh, A.W. 1988, *A modular three-dimensional finite-difference ground-water flow model*. US Geological SurveyTechniques of Water-Resources Investigations, 06-Al.

Rice, J.R. and Cleary, M.P. 1976, Some Basic Stress Diffusion Solutions for Fluid Saturated Elastic Porous Media with Compressible Constituents. *Rev. Geophys.* 14, 227– 241.

Roeloffs, E.A. 1988, Fault Stability Changes Induced beneath a Reservoir with Cyclic Variation in Water Level. *J. Geophys. Res.* 93(B3), 2107-2124.

Talwani, P. 1997, On the Nature of Reservoir-induced Seismicity. *Pure Appl. Geophys.* 150, 473-492.

Talwani, P., Chen, L. and Gahalaut, K. 2007, Seismogenic Permeability, k_s, *J. Geophys. Res.* 112, B07309, doi:10.10129/2006JB004665.

Wang, H.F. 2000, *Theory of Linear Poroelasticity*. Princeton University Press, Princeton, N.J. 287p.

WHI, 2005, Waterloo Hydrogeologic, Inc. *Visual MODFLOW*. Waterloo, Ontario, Canada.