18 Hydrologic Modulation of Seismicity in Western China 1991–2013

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Introduction

Deep drilling projects and induced seismicity suggest that much of the earth's crust—even deep in continental interiors—is near critically stressed and prone to fail after small (<1 MPa) stress changes (*e.g., Zoback and Harjes,* 1997). It has been suggested that stresses due to hydrologic loading from rain and snow (*e.g., Heki*, 2003), changes in pore fluid pressure (*e.g., Hainzl et al., 2006)*, solid earth tides (*e.g., Knott, 1897)*, and thermally induced stresses due to thermal expansion (*e.g., Hainzl et al., 2013)* may produce stresses sufficient to generate earthquakes. Because many of these stresses are periodic or quasi-periodic, periodicity in seismicity may be widespread and provide insight into how earthquakes nucleate.

Periodic modulation of earthquakes has been observed in the High Himalaya in Nepal (*Bollinger et al.*, 2007; *Bettinelli et al.*, 2008; *Ader and Avouac*, 2013), the San Andreas fault near Parkfield, CA (*Christiansen et al.*, 2007; *Ben-Zion and Allam*, 2013; *Amos et al.,* 2014), Mt. Hochstaufen in Germany (*Hainzl, 2006; 2013*), mountains in Japan (*Heki*, 2003), and some hydrothermal systems (*Saar and Manga*, 2003; *Christiansen et al.*, 2005; *Braunmiller et al.*, 2013, *Rydelek et al.*, 1988; *Gao et al.*, 2000; *Wilcock*, 2001.) Unlike past studies which focused on seismicity over small areas, we examine apparently similar modulation in seismicity from 1991–2013 throughout an ~100,000 km^2 area including the Tibetan Plateau, Altyn Tagh, Tarim Basin, and Tien Shan. This diversity of tectonic and climatic setting allows us to assess different mechanisms and statistical tests.

Data

We analyze earthquakes between 20^o and 60^o N and between 105^o and 70^o E from two catalogs: the Annual Bulletin of Chinese Earthquakes (ABCE) 1991 to 2005 (n=22,513) and the China Earthquake Networks Center Catalog (CENC) 2006 to 2013 (n=5,162.) We also compare background seismicity in the ABCE catalog to repeating earthquakes in the ABCE catalog (n=2,379) as identified by *Schaff and Richards* (2011). Using the Gutenberg-Richter relationship between earthquake occurrence and magnitude we assess catalog completeness for 1991-2005 and 2009–2013 after the 2008 M_w 7.9 Wenchuan earthquake and aftershock sequence. Although both seismic catalogs are incomplete for $M_w < 5$ the catalog completeness does not change seasonally, meaning that the seasonal modulation we observe is not simply due changes in station coverage and, therefore, both catalogs are used in whole.

We use three methods to see if the seasonal modulation is observable in background seismicity or only in foreshocks and aftershocks. First, we compare seismicity to a global catalog of $M_w > 8$ and a local catalog of $M_w > 7$. We also test two declustering methods. The Reasenberg (1985) method identifies the likelihood that earthquakes are related in a spatial-temporal window based on Omori's Law. In contrast the stochastic epidemic-type aftershock sequence (ETAS) declustering method of *Zhuang et al.* (2002) calculates the likelihood that each earthquake is a background event.

Results and Discussion

Seismicity in the Tibetan Plateau and surrounding areas suggests seasonal modulation (Figure 2.18.1). This seasonality is only visible in the shallowest earthquakes (< 5 km) making hydrologic loading, pore fluid pressure changes, and thermal elastic expansion all plausible causes (Figure 2.18.2).

We use three tests to quantify the statistical significance of the seasonal modulation. The most common test, the Schuster test (*Schuster*, 1897), calculates a p-value for one frequency at a time comparing the observed correlation with the likelihood of the correlation appearing wholly by chance. We also use a novel multi-frequential approach (*Dutilleul*, 2001), which finds the frequencies that add together to best fit the time series. This approach could allow us to identify different mechanisms as different frequencies. Finally, we use a simple analysis of variance test (ANOVA), which calculates the statistical difference between the mean seismicity of different seasons. All of these approaches show statistically significant ~12 month periods for both declustered and complete catalogs. The phase of this period varies spatially (Figure 2.18.1b and c) and the amplitude changes significantly year to year.

We show that loading on either side of the Plateau is significant (Figure 2.18.1a) and that seismicity correlates with peak hydrological loading determined from GRACE gravity-change measurements (Figure 2.18.1b and c). If surface loading is the primary mechanism for modulating seismicity, it should suppress thrust and strike-slip faulting and therefore negatively correlate with nearby seismicity. In contrast, if normal faults dominate or if pore fluid pressures rather than loading modulate seismicity, nearby seismicity will positively correlate with GRACE data. In the future we hope to further explore the spatial variation in seasonality and fault type and compare the potential contributions of earth tides, pore fluid pressures, and thermoelastic expansion.

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References

Ader, T., Avouac, J., Detecting periodicities and declustering in earthquake catalogs using the Schuster spectrum, application to Himalayan seismicity, *Earth and Planetary Science Letters*, 908-34, 2013.

Amos, C. B., P. Audet, W. C. Hammond, R. Bürgmann, I. A. Johanson, and G. Blewitt, Contemporary uplift and seismicity in central California driven by groundwater depletion, *Nature*, v. 509, 2014.

Ben-Zion, Y, Allam, A.A. Seasonal Thermoelastic Strain and

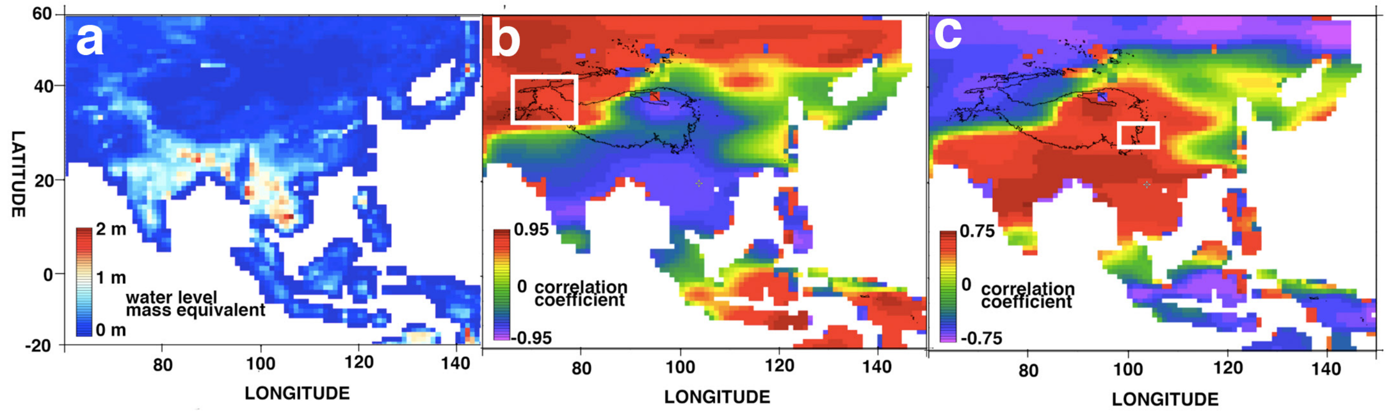

Figure 2.18.1a: Map of average annual change in mass storage in water equivalent thickness from GRACE satellites (http://grace.jpl.nasa.gov/data/). This shows over 1 m of annual loading along the foot of the Himalaya and almost 1 m along the western and northern edge of the Tibetan Plateau; b and c) Map of correlation coefficient comparing the monthly earthquake time series (1991–2005) in the white boxes to monthly GRACE loading data (2002–2013.) b shows the region where peak water storage in the fall corresponds with peak seismicity in the fall while c) shows where peak water storage in the spring corresponds with peak seismicity in the spring.

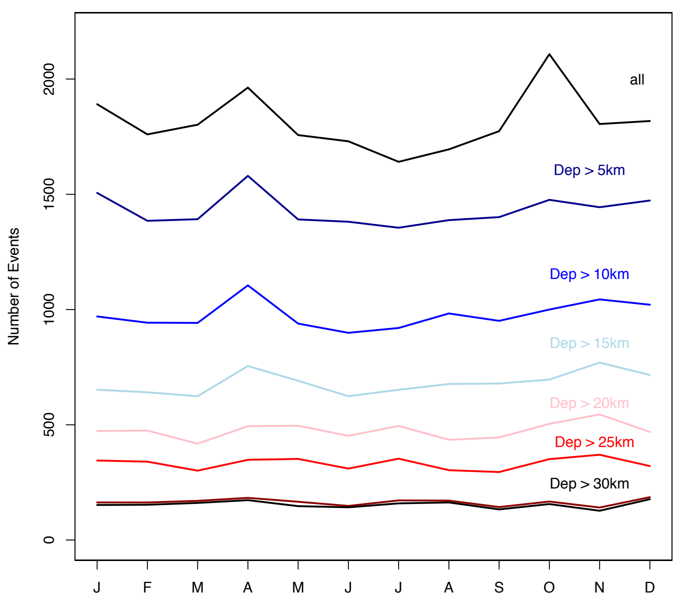

Figure 2.18.2: Cumulative monthly seismicity for different depths. Seaonal modulation is strongest at shallow depths.

Postseismic Effects in Parkfield Borehole Dilatometers, *Earth and Planetary Science Letters.*

Bettinelli, P., Avouac, J.-P., Flouzat, M., Bollinger, L., Ramillien, G., Rajaure, S., Sapkota, S., Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. *Earth and Planetary Science Letters v.* 266, 332, 2008.

Bollinger, L., Perrier, F., Avouac, J.-P., Sapkota, S., Gautam, U., D.R., Tiwari, Seasonal modulation of seismicity in the Himalaya of Nepal. *Geophysical Research Letters v.* 34, 2007.

Braunmiller, J. , Nabelek, J, Trehu, A., A seasonally modulated earthquake swarm near Maupin, Oregon, *Geophys. J. Int., 2014.*

Christiansen, L, Hurwitz, S, Saar, M, Ingebritsen, S, Annual modulation of seismicity along the San Andreas Fault near Parkfield, CA, *Geophysical Research Letters, v.* 34, 2007.

Christiansen, L.B., S. Hurwitz, M.O. Saar, S.E. Ingebritsen, and P.A. Hsieh, Seasonal seismicity at western United States volcanic centers, *Earth Planetary Science Letters,* 240, 307-321, 2005.

Dutilleul, P., Multi-frequential periodogram analysis and the detection of periodic components in time series*. Communications in Statistics-Theory and Methods* v. 30, 2001.

Gao, S.S., Silver, PG, Linde, A.T. Sacks, I.S., Annual modulation of triggered seismicity following the 1992 Landers earthquake in California, *Nature*, 406, 2000.

Hainzl, S., T. Kraft, J. Wassermann, H. Igel, and E. Schmedes, Evidence for rainfall triggered earthquake activity, *GRL.* v 33, 2006.

Hainzl, S., Y. Ben-Zion, C. Cattania, and J. Wassermann, Testing atmospheric and tidal earthquake triggering at Mt. Hochstaufen, Germany, *Journal of Geophysical Res. v.* 118, 2013.

Heki, K., 2003, Snow load and seasonal variation of earthquake occurrence in Japan, *Earth Planet. Sci. Lett.*, 207, 159–164, 2003.

Knott, C., On Lunar Periodicities in Earthquake Frequency. *Proceedings of the Royal Society of London* 60, 457, 1897.

Reasenberg, P., Second-Order Moment of Central California Seismicity, 1969-1982. *Journal. Geophysical Research* v. 90, 1985.

Saar, M.O., and Manga, M., Seismicity induced by seasonal groundwater recharge at Mt. Hood, Oregon, *Earth Plan. Sci. L.,* v 214, 2003.

Schaff, D., and Richards, P., On finding and using repeating seismic events in and near China, *J of Geophysical Research*, v. 116, 2011.

Schuster, A., On Lunar and Solar Periodicities of Earthquakes. *Proceedings of the Royal Society of London* v. 61, 455, 1897.

Zoback, M., Harjes, HP, Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany, *Journal of Geophysical Research*, v. 102, 1997.