Aquifer Storage Properties Generated from Well Water Level Responses to Seismic Rayleigh Waves

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Abstract

Observation well water levels in confined aquifers may be sensitive to large global earthquakes, and commonly produce hydroseismograms with centimeter scale water level fluctuations. Regional broadband seismographs can generally provide excellent estimates of Rayleigh wave (LR) displacement. The sparse amount of hydraulic head data provided by most well recorders relative to seismological data makes direct spectral comparisons impractical because the spectral density of the water deflections cannot be calculated. To account for the sparse data collection interval, we propose a method to use water level records sampled on the scale of minutes during the passage of Rayleigh waves for the assessment of aquifer properties. To increase the precision of this method, adjustment for the wavelength and the borehole response is applied in the frequency domain. This reduces the influence of the longer wavelength (and typically higher amplitude) Rayleigh waves on the process and acts as a band-pass filter enhancing components near the resonant frequency of the borehole.

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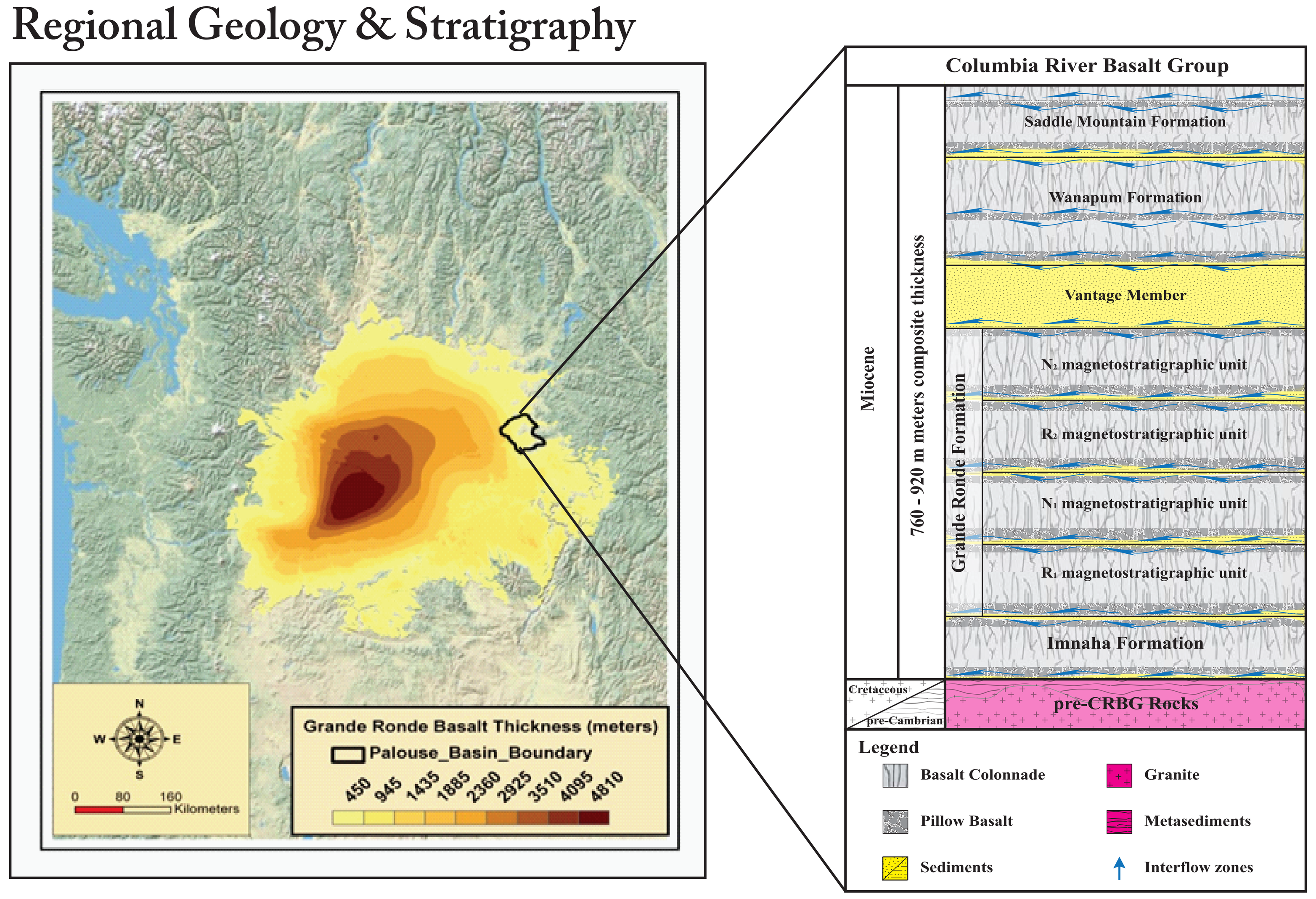

Figure 1: A. Areal extent of the Grande Ronde formation and thickness (Burns, 2011) with Palouse Groundwater Basin (PGB) boundary in black. B. Palouse Groundwater Basin stratigraphy with weathered flow tops acting as aquifer interflow zones.

Background

Seismological theory predicts that while a seismic Rayleigh wave of wavelength λ_o is passing, the relation between the vertical ground displacement and subsurface dilatation within a few hundred meters of the earth's surface is given by

$$\Delta o = -1.836\, \pi\, w_o / \lambda_o \qquad [1]$$

where Δo is the amplitude of the dilatation, and wo is the amplitude of vertical displacement of the LR of wavelength $\lambda_o >> z$ where z is the depth of the aquifer (Cooper et al., 1965; Shih, 2009).

For a confined aquifer, dilatation (the change in aquifer volume per unit volume) can be expressed in terms of specific storage (S_s) and water level change in an open borehole:

$$\Delta o = -S_s\, h_o / R_o \qquad [2]$$

where ho is the amplitude of the water level oscillation and Ro is the borehole amplification factor (Cooper et al., 1965). The borehole response can be estimated using the following formula (Cooper et al.,1965):

$$R_o = [\, (1 - \{\pi r^2 / T\tau\}\, \mathrm{Kei}\,\alpha - 4\pi^2 H_e / \tau^2 g)^2 + (\{\pi r^2 / T\tau\}\, \mathrm{Ker}\,\alpha)^2\,]^{-1/2} \qquad [3]$$

where $\alpha = r(\omega S / T)^{1/2}$, r is the radius of the borehole, S is storativity, T is transmissivity, τ is wave period, ω is angular frequency of the wave, He is the effective height of the water column, and g is the gravitational acceleration. Ker and Kei are Kelvin functions of the second kind of order zero(eg http://keisan.casio.com).

Combining equations (1) and (2), one obtains, in theory, a connection between the water level oscillation in the borehole and the Rayleigh wave displacement on the surface:

$$h_o = (1/S_s)\,(5.77\, R_o\, w_o / \lambda_o) \qquad [4]$$

With the exception of S_s, all the variables in the above equation are functions of frequency. In practice, spectral methods need to be employed to transform the LR displacements (Figure 2A) and the water level fluctuations (Figure 2B) into their constituent frequency components to get useful results. Results can be validated by earth tide spectral analysis (Bredehoeft, 1967; Merritt, 2004). However, accurate spectral methods require sampling of water levels on a scale similar to that of seismograph data (less than 1 sample per second). Large earthquakes produce high amplitude surface waves for an hour or more after the shock.

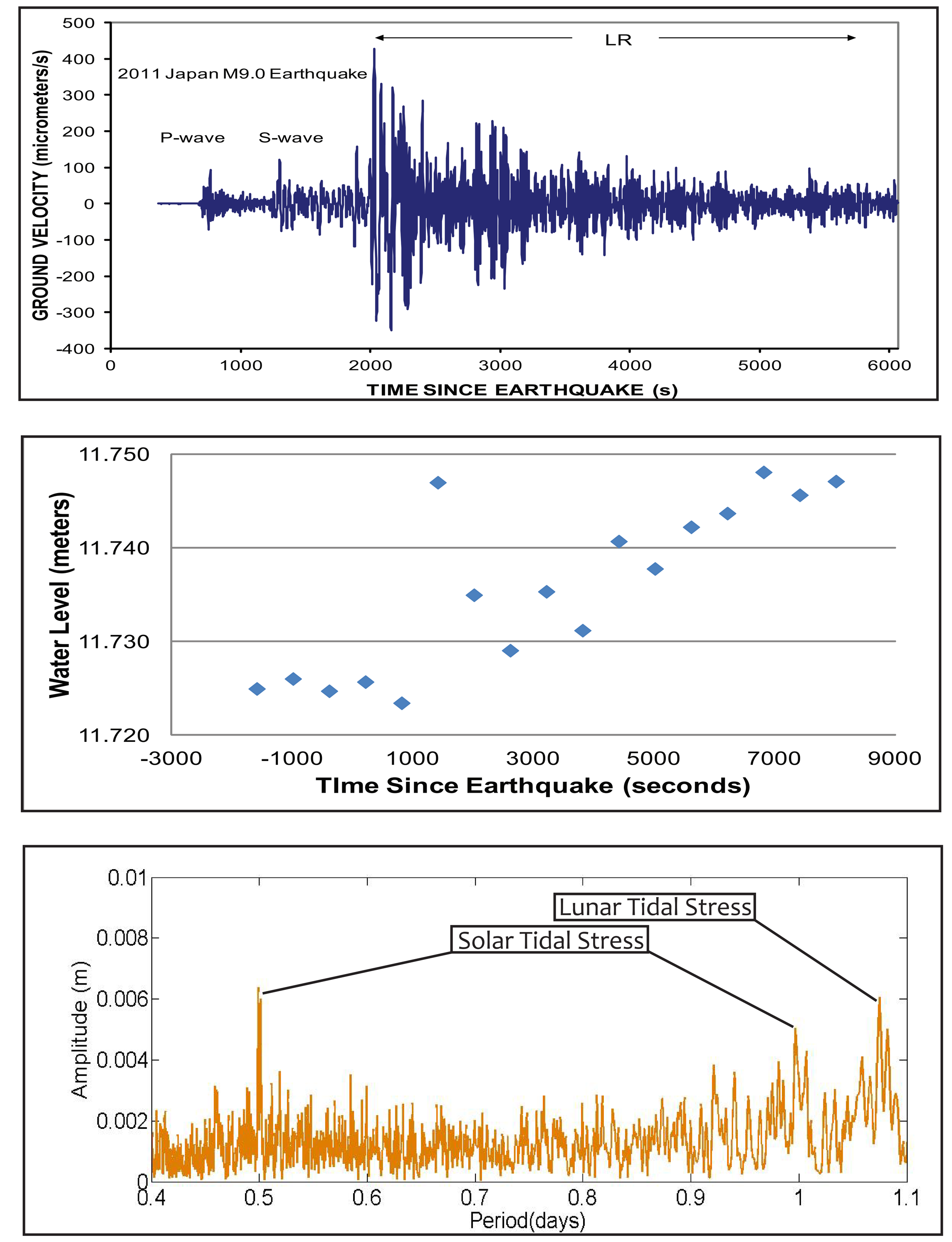

Figure 2: A. Vertical ground displacement at PUW based on station BRAN. The Rayleigh wave arrives 2000 seconds after the earthquake at 21:46:23 PST. The Rayleigh wave analyzed in this study extends over 4095 seconds as illustrated by the arrows.

B. Water levels measured in Washington State Department of Ecology (DOE) observation well in the Grande Ronde Aquifer during the passage of Rayleigh waves from the the 2011 Japan M9 Earthquake. The sample interval for the Japan event was 10 minutes.

C. Amplitude spectrum of water fluctuations in the DOE well based on a year of well recorder data sampled at 5 minute intervals. The data are noisy due to nearby pumping; however, the lunar diurnal peak at 1.076 days is apparent with an amplitude of over 5 mm.

Methodology

In terms of the discrete Fourier transform F , equation [4] can be written as follows, taking note that λ and R are dependent on frequency as indicated by the subscript k.

$$F\{h\} = (1/S_s)\,(5.77\, R_k / \lambda_k)\, F\{w\} \qquad [5]$$

Now the complex conjugate of [5] is taken:

$$F\{h\}^* = (1/S_s)\,(5.77\, R_k / \lambda_k)\, F\{w\}^* \qquad [6]$$

Multiplying [5] times [6], and dividing by the number of samples N in the time sequences:

$$H_k = (1/S_s^2)\,(33.3\, R_k^2 / \lambda_k^2)\, W_k \qquad [7]$$

where: H_k is the spectral density of the predicted water level deflections, defined by:

$$H_k = F\{h\}\, F\{h\}^* / N \qquad [8]$$

and W_k is simply the spectral density of w, defined by:

$$W_k = F\{w\}\, F\{w\}^* / N \qquad [9]$$

This adjustment $(33.3\, R_k^2 / \lambda_k^2)$ for the wavelength and the borehole response is applied in the frequency domain and acts partly like a high-pass filter, reducing the influence of the longer wavelength (and typically higher amplitude) Rayleigh waves on the process and partly as a band-pass filter enhancing components near the resonant frequency of the borehole.

Dividing both sides of [7] by N, and using Parseval's theorem, one finds that the mean squared water deflection can be predicted from the mean value of the Rayleigh wave displacement spectral density after adjustment for wavelength and borehole effects. That is,

$$E\{h^2\} = E\{\,(1/S_s^2)\,(33.3\, R_k^2 / \lambda_k^2)\, W_k\,\} = E\{H_k\} \qquad [10]$$

where: the expected value operator E represents an average value over the sample interval.

The above equation can be used to compare a time domain measurements of the mean-squared water level fluctuations (Figure 3) to an appropriately filtered spectral measurement of overall seismic LR displacement (Figure 4). Thus by comparing time domain measurements of water level fluctuations to spectral measurements of the LR displacement, an estimate of specific storage can be obtained for each observed seismic event (Figure 5).

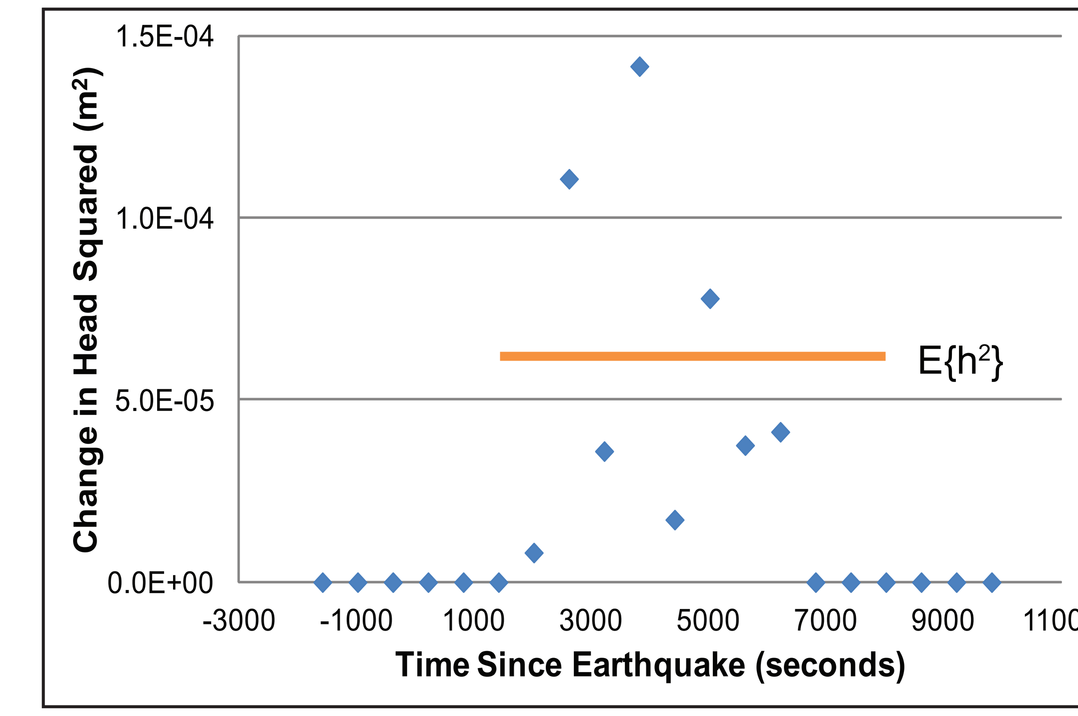

Figure 3: DOE well Mean Squared Water Level Deflection ($E\{h^2\}$)

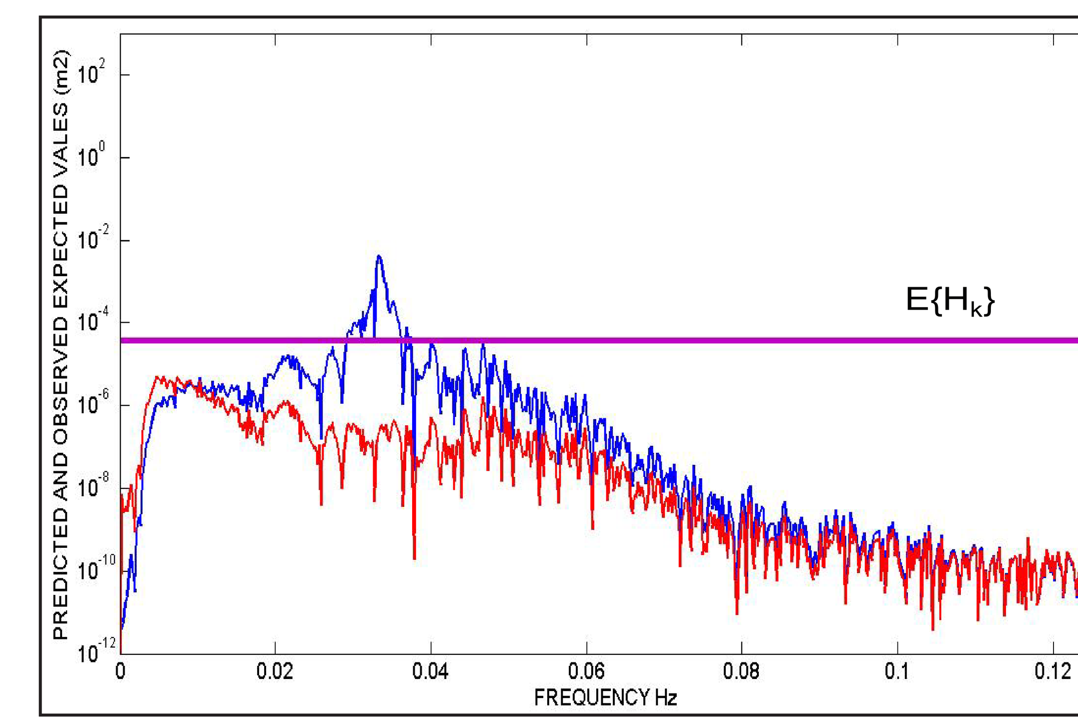

Figure 4: Spectral density W_k of the Rayleigh wave displacement for the Chile earthquake (red curve) and spectral density H_k of the predicted water level fluctuation for a trial value of S_s (blue curve). The horizontal line is $E\{H_k\}$, the mean value of H_k used for comparison with time domain measurements of $E\{h^2\}$.

Conclusions

1. Valuable tool to complement and validate aquifer property estimates from more conventional methods.

2. The discrepancy between the results for the two quakes at DOE might be an indication that the aquifer is not fully confined.

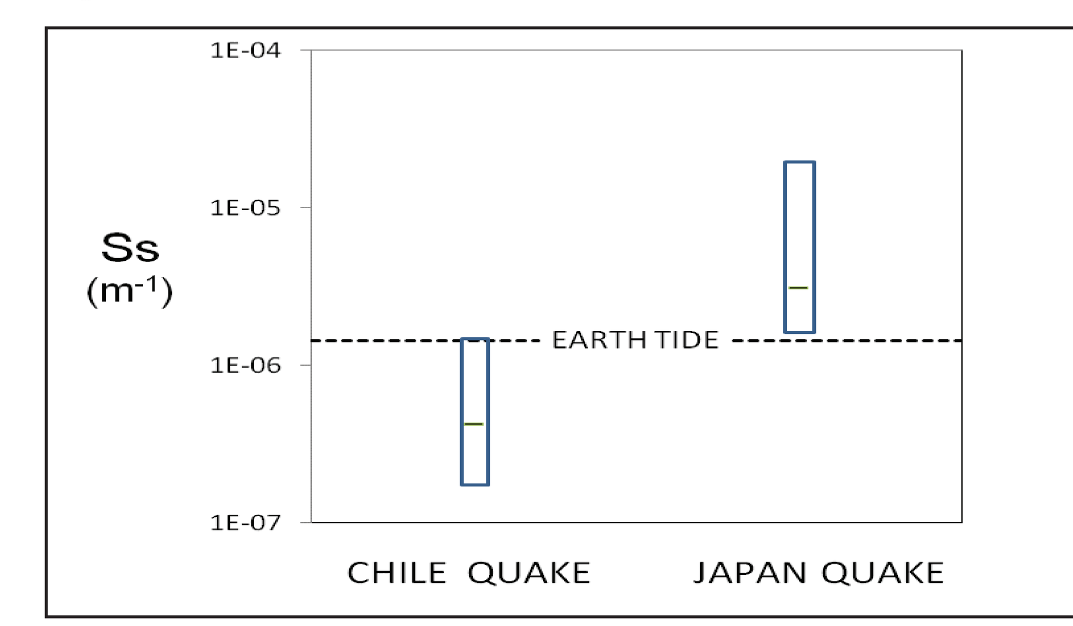

Figure 5: Specific storage results for the two earthquakes analyzed. The bars show 80% fudicial limits on the results for each event. The specific storage of 1.44×10^{-6} m^{-1} found from the earth tide analysis.

Acknowledgements

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