When Water, Temperature, and Earthquakes impact shallow seismic velocities: Decadal records in California and Mexico City

Marine Denolle (1), Tim Clements (2), Laura Ermert (1)

(1) University of Washington, (2) Harvard University

Long abstract

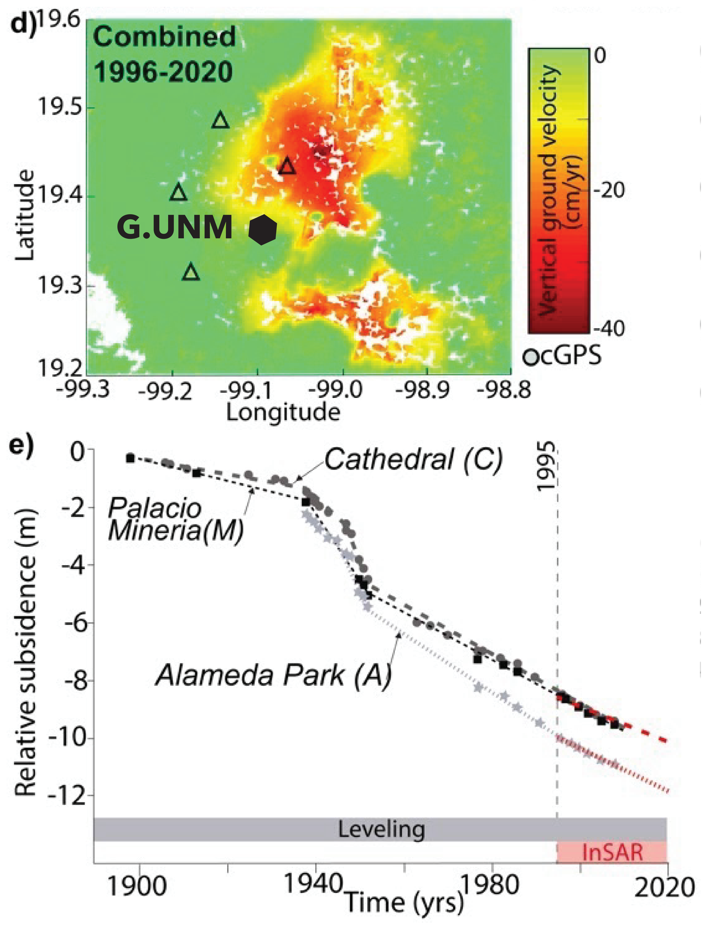
The Earth's near-surface is the buffer zone between the atmosphere and the solid Earth. It is greatly affected by atmospheric conditions (e.g., temperature, pressure, precipitation), shallow hydrology, and the transient effects of seismic activity. To sample the upper ~ 350 m of the near-surface, we use the relatively high-frequency content of ambient seismic field single-station cross-correlations. In this presentation, we present a 20+ year record of seismic velocity changes in the state of California and in the Mexico City sedimentary basin. We then analyze each day-stacked correlations to extract changes in the arrival time of phases in the coda and generate time series of perturbation in seismic velocity. In California, we find a highly diverse behavior across the state. We interpret the rainfall impact by fitting several hydrological models and find that sites may experience anywhere between fully drained and undrained poroelastic responses. Sites close to lakes exhibit a more substantial influence from lake levels, including the long-term drying of the Salton Sea. We also find heterogeneity in the contribution between hydrological strains and thermo-elastic strains. Removing these effects allow us to characterize tectonic effects better, and we find that some sites are still recovering from the 1999 Hector Mine Earthquake. In Mexico City, we find a linear increase in seismic velocities that corresponds well to the linear subsidence over the past 25 years. The measurements are likely sensitive to the depth at which occurs the pumping of the main groundwater aquifer that feeds Mexico City. Our data processing involves cloud-based workflows, unsupervised learning, and efficient scripting for memory and I/O management.

Subsidence in Mexico City: Changing in Site Effects

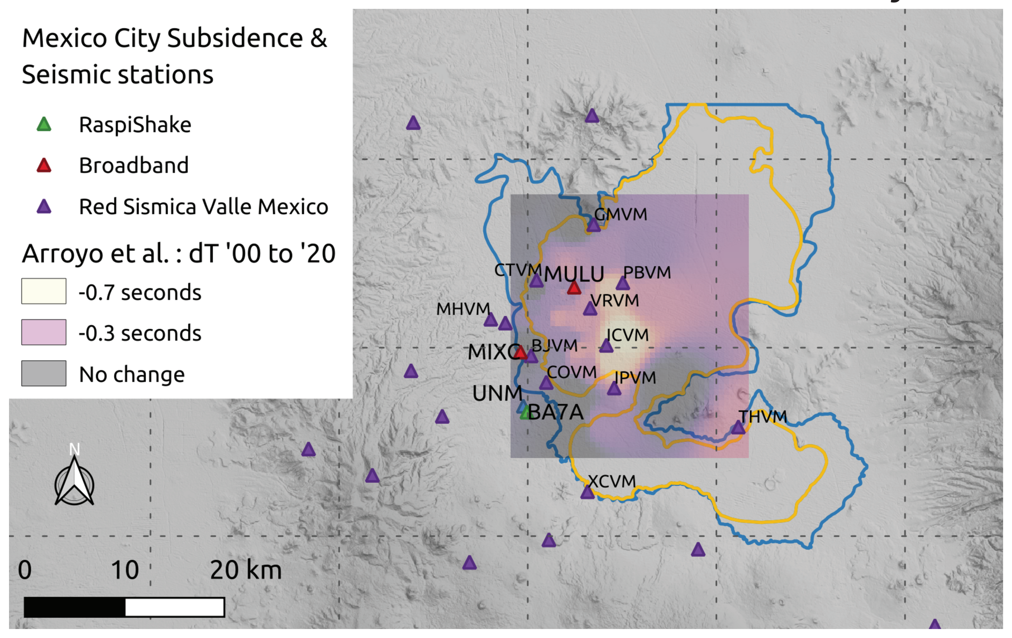
Lead: Laura Ermert

Mexico City is being drained for groundwater use. Subsidence has been linear since 1900 (Chaussard et al, 2014). Changes in site effects have been observed between the 1985 Michocoacan earthquake and the 2017 La Puebla earthquake (). The subsidence rates are extreme so that Arroyo et al (2013) predict a change in resonance frequency/period by up to 1 s in 25 years.

Chaussard et al, 2021



This study area



G.UNM: 1995-2021
TO.TEPE, TO.ESTA, TO.CIRE, TO.MULU (MASE array, 2006-2007)
RSVM stations: 2017-2021 *results not shown here (pending collaborator authorization)

Seismic Noise Characteristic in Mexico City

We perform single-station pure cross correlations of the seismograms (instrumental response removed). Urban environment are prone to fluctuations in high frequency waves. We use Viens and Iwata (2020) to cluster the shapes of the cross correlations and find diurnal patterns and detect outliers. We focus on "day-time" clusters for the waveform consistency.

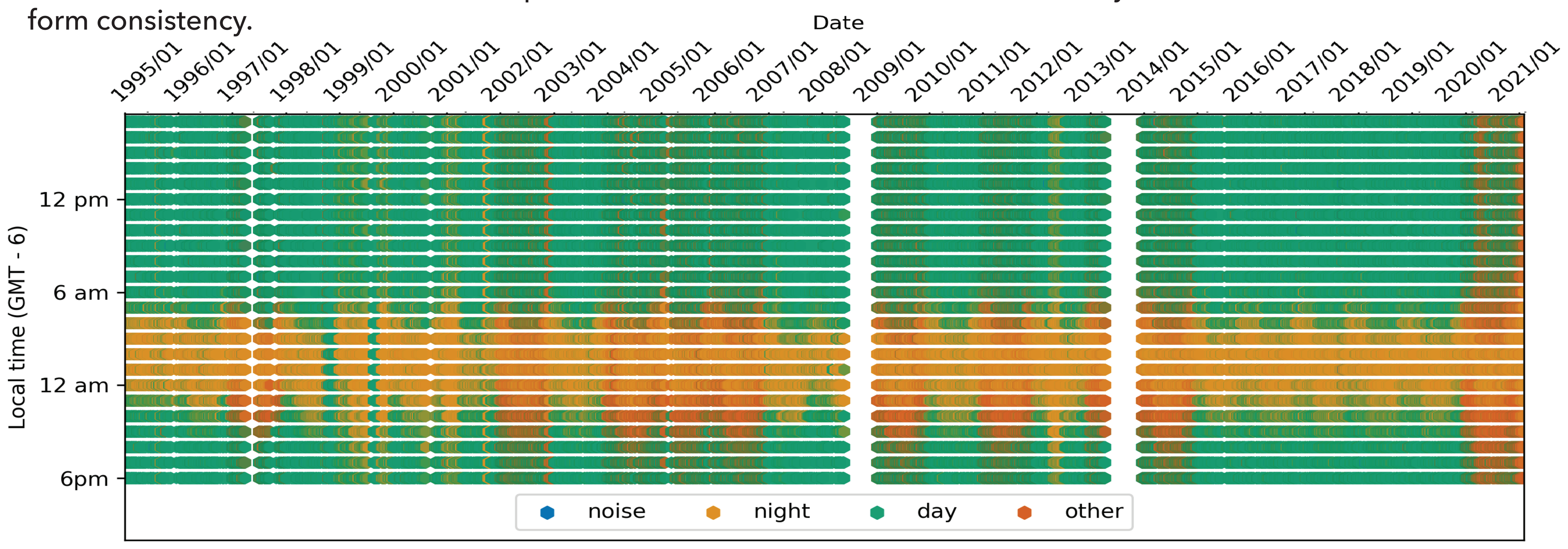


Figure: cluster ID per local hour for ZN component, 0.5-1.0 Hz at G.UNM. Annual fluctuations relate to day-saving times.

We use stretching in time domain of band-pass filtered cross correlations. Waveform become incoherent over the decades, so we proceed with a "stitching method". We generate several running "reference" stacks, calculate dv/v, and join the dv/v time series by a L2-norm misfit minimization of the dv/v values that overlap for a month.

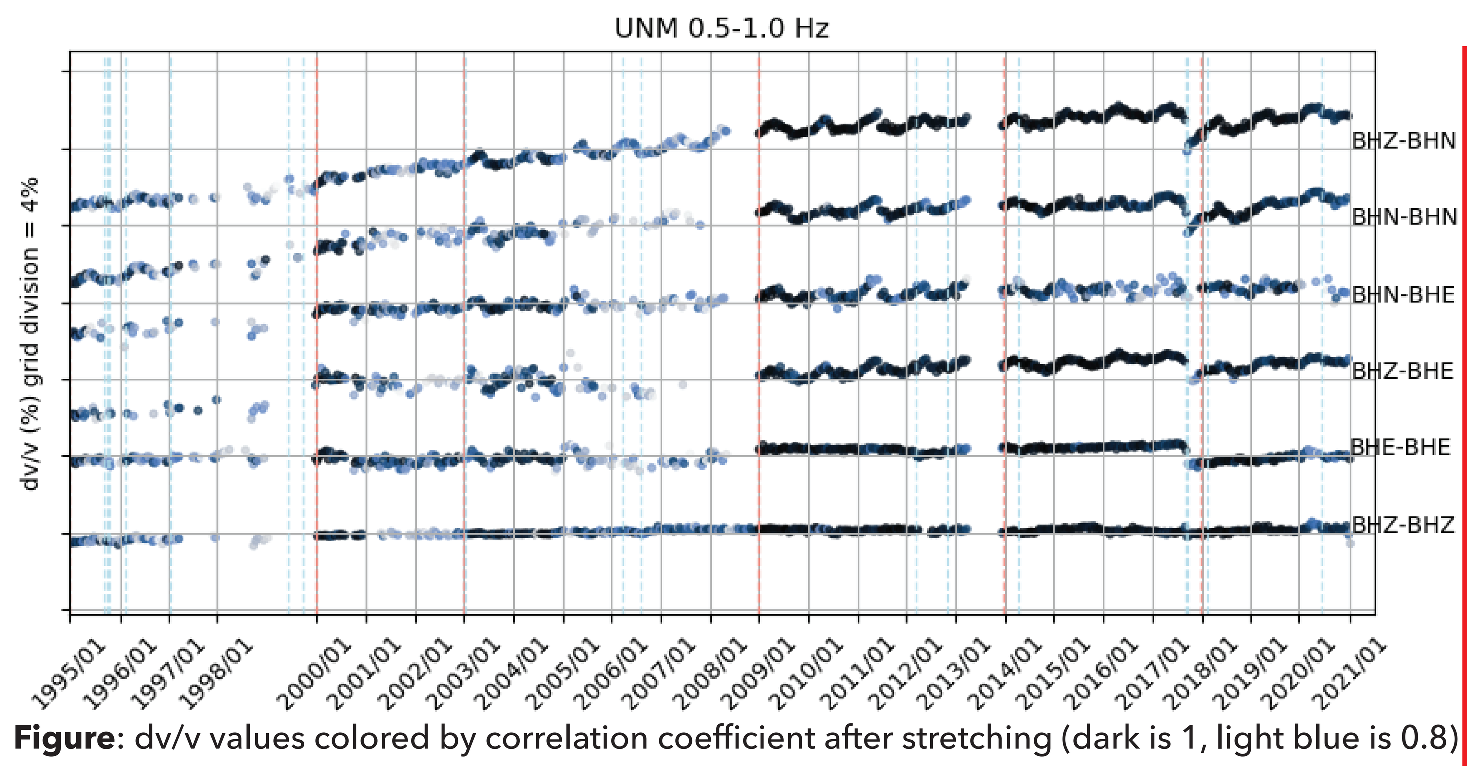


Figure: dv/v values colored by correlation coefficient after stretching (dark is 1, light blue is 0.8)

Message

dv/v+4% in 25 years at the edge of the basin.

La Puebla 2017 earthquake rest by ~1%

Only horizontal waves see a change in velocity=> mostly shear waves affected?

Peaks in H/V ratios confirm 5% change.

What is dv/v ?

dv/v is the relative change in seismic velocities obtained by relative measurements of phase lags. We measure the phase lag dt at lag t, and dv/v = - dt/t, assuming that the length of the ray (L=vdt) remains constant. Good references to read on the measurements are Sens-Schonfelder and Wegler 2006; Wegler and Sens-Schonfelder 2007; Clark et al, 2011; Yuan et al., 2021.

Seismic velocities relate to the elastic moduli of Earth materials. Linear elastic rheology relates the stresses and strains through a linear relation with constant elastic moduli. Non-linear elasticity relates stresses σ with strains ϵ and non-linear operations on strain such as strain squared (Ostrovsky and Johnson, 2001): $\sigma = M(\epsilon + \beta\epsilon^2)$

Under a nonlinear elastic rheology, the local sound velocity is given by Ostrovsky189and Johnson (2001) as, $v = \sqrt{\rho^{-1} d\sigma/d\epsilon} \approx v_0(1+\beta\epsilon+\ldots)$.

The perturbation in velocity $dv/v = \frac{v - v_0}{v_0}$ for a hydrostatic stress becomes $dv/v = \beta\epsilon_{kk}$.

Several studies have estimated β on the order of - 1E4 (Takano et al. 2014, Sens-Schonfelder and Eulenfeld 2019, Mao et al. 2019).

We assume that the total strain, and the total dv/v, is a linear combination of strains (dv/v) due to thermoelasticity $(dv/v)_T$, hydrology $(dv/v)_h$, transient tectonic $(dv/v)_{eq}$:

$$dv/v = a + b\,(dv/v)_T + c\,(dv/v)_h + d\,(dv/v)_{eq}$$

Other loads/strains may play a role, but in the following examples only these three matter. We measure a time series of dv/v, and fit each term with specific functional forms. Typically in measurements done at the surface,

$(dv/v)_T$ is a cosine function (Tsai, 2011).

$(dv/v)_{eq}$ is often a Heaviside function and a combination of logarithmic and exponential functions for "healing", "relaxation", "afterslip" responses (depending on the mechanism).

$(dv/v)_h$ is in general successfully modeled with groundwater levels (GWL). GWLs are difficult to measure (you need a well everywhere!) but are infered from rainfall, surface deformation, gravity measurements. A choice of rheology (undrained, drained, ...) is also necessary to model.

The Seismic Signature of California's Extreme Events

Lead: Tim Clements

We compute 1999-2021 year of single-station cross correlations using the SCEDC+NCEDC+IRIS data using a native cloud workflow. SCEDC is stored as an opendata on AWS. We downloaded NCEDC+IRIS data on AWS. We compute the single station cross correlations for 718 stations, 6 components. We cross correlation 30-min windows, overlapped by 75%.

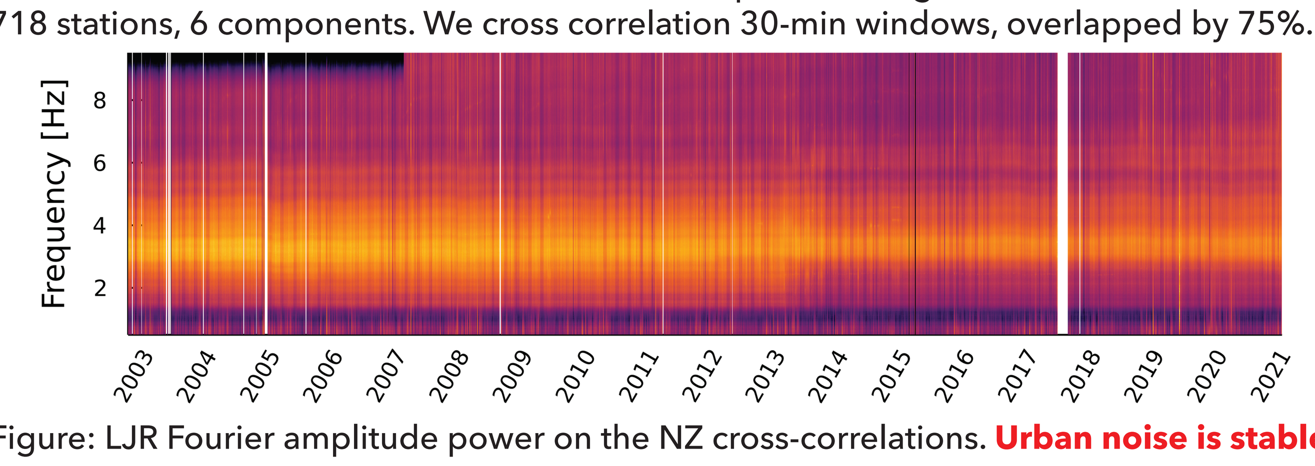


Figure: LJR Fourier amplitude power on the NZ cross-correlations. **Urban noise is stable over decades**

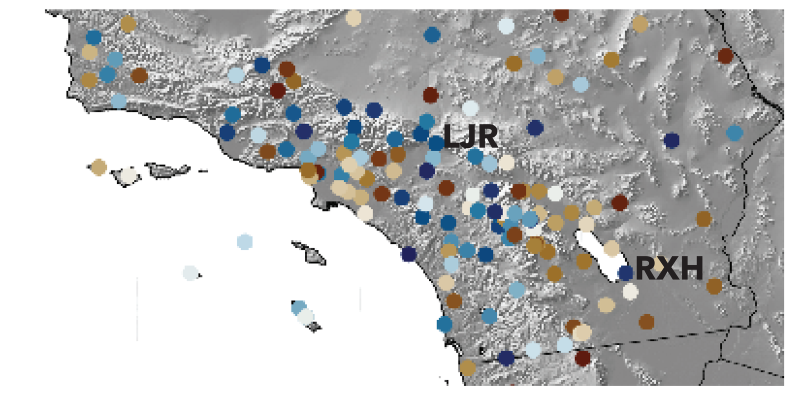


Figure: thermoelastic strains dominate dv/v in flat areas (Tsai 2011); water effects dominate dv/v in mountianeous region.

dv/v is explained by long term decline in water levels

Ground water levels fluctuate due to rainfall (source), lake levels (natural or maintained), water extraction (see the left panel!). Sites located in close proximity to lakes (characteristic distance depends on local geology/permeability), the lake level control the GWL underneath the seismic stations. For example, Taira et al, 2018 suggests a long term effects in station RXH near the Salton Sea due to geothermal activities, we instead correlate the **dv/v** with the **long term decline in the Salton Sea levels** (left figure below). We use **3 hydrological models** (baseflow, poroelastic, empirical) and use the best fit as the winner.

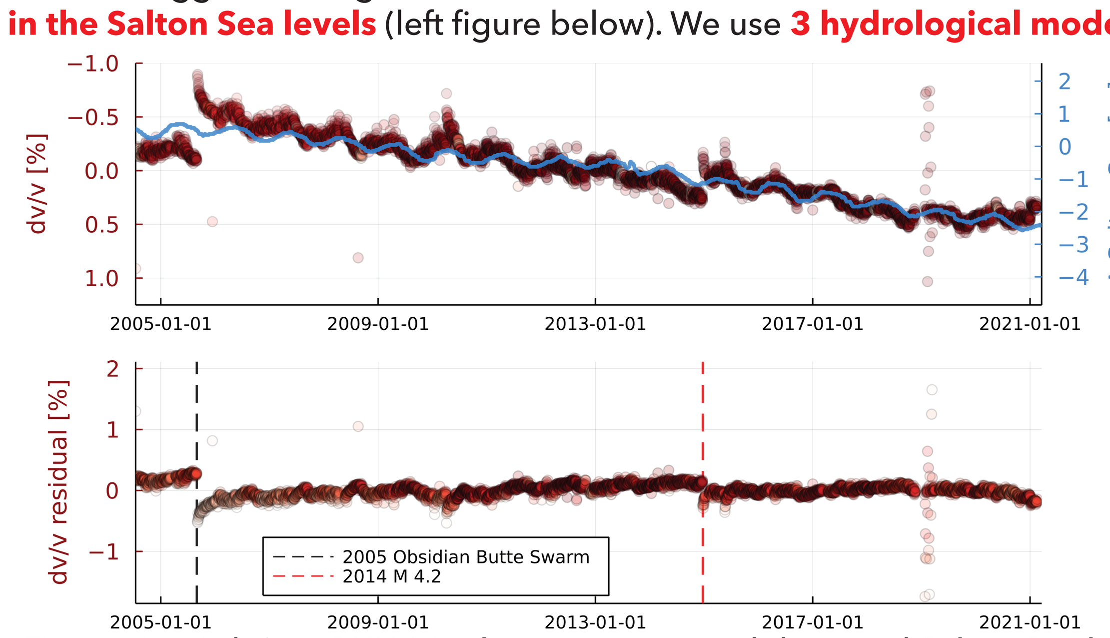


Figure: (top) dv/v at RXH (single component, red dots) and Salton Sea lake level (blue curve). (bottom) effect of level level removed and residuals showing earthquak damage.

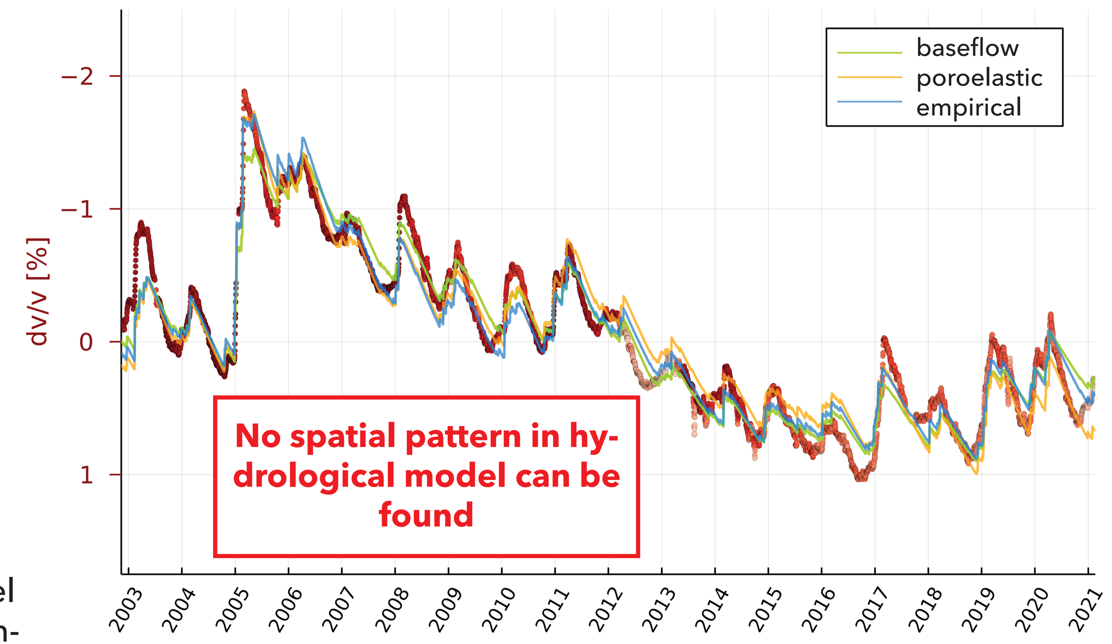


Figure: hydrological model fitting at LJR

dv/v is explained by earthquake damage and decadal relaxations

After removing thermoelastic and hydrologic terms, we analyze specific earthquake effects.

We find ~ 1% of velocity change nearby the fault, it's relatively small, but we averaged over days.

All sites experience on-going relaxation, including the M7.1 Hectore Mine earthquake.

Figure (right): (A) Map of the three earthquakes, focal mechanisms, fault traces (USGS), PGV map (USGS), location of a nearby GPS (red circle), and nearby seismic stations (blue triangle). (B-D): dv/v time series after removal of temperature and hydrological effects (blue dots), sqrt(N^2+E^2) GPS displacements (red curves), fit of the post seismic response with a logarithmic (purple line) and an exponential (yellow line) functions..

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