What is the budget of earthquake rates in the upper plate?

Alexandra Hatem[1], Richard Briggs[1], Fred Pollitz[2], Nadine Reitman[1], Madeleine Tan[1]
1: U.S. Geological Survey, Golden, CO, USA; 2: U.S. Geological Survey, Seattle, WA, USA
ahatem@usgs.gov

Background

Geodetic moment, derived from observations of relative station velocities, is thought to represent deep-seated strain accumulation, whereas microseismicity and geologic slip rates represent short- and long-term records of earthquakes that accommodate the release of that accumulated strain. If geodetically derived strain is accommodated in crustal earthquakes, this strain should be recoverable by a combination of geologically and seismically derived strain. We test this hypothesis in the western United States to: (1) advance our understanding of crustal and regional tectonic processes, (2) determine any regions of under-characterized fault networks, and (3) assess the validity of off-fault deformation for use in future earthquake rupture forecasts and seismic hazard modeling.

A previous test of this hypothesis converted geodetic, geologic, and seismic strain rates to moment rates across the U.S., and found that there was a deficit of geologic moment (also referred to as "off-fault deformation") in regions with poorly defined geologic faults, such as the Basin and Range. In contrast, areas of well-defined fault networks, such as southern California, did not reveal a deficit of geologic moment rate. An outcome of this previous work was a greatly enhanced active fault inventory across the western U.S.

Since this original analysis, geodetic, seismic, and geologic datasets have been greatly expanded. These datasets were expanded to improve subsequent updates of the U.S. National Seismic Hazard Model (NSHM), particularly in the western U.S. Global navigation satellite system (GNSS) station density increased from ~1,800 stations used in the 2014 NSHM to nearly 5,000 stations used in the 2023 NSHM. The seismicity catalog considered for the 2023 NSHM has over 60,000 earthquakes, which naturally increases as the recording period continues. The updated fault network has doubled since the original test of this hypothesis, and now includes over 1,000 crustal fault sources. We use these updated 2023 NSHM datasets to compute geodetic, geologic, and seismic moment rates across the western U.S.

Methods

A geodetic strain rate field was derived using the expanded station network collated for use in the 2023 NSHM, incorporating stations representing primarily tectonic deformation. Once the second invariant field is generated, we apply three corrections to the strain rate field to account for: (1) interseismic creep on faults in California, (2) post-seismic transients following three major earthquakes in the western U.S. (1700 Cascadia, 1857 Fort Tejon, 1906 San Francisco), and (3) interseismic locking on the Cascadia subduction interface. Combined, these three corrections identify strain that can be attributed to sources other than interseismic locking on upper plate crustal sources. These corrections have spatially confined effects and can be very influential on the resulting strain rates. For example, correcting for Cascadia interseismic locking reduced strain rate by about a factor of 2 in the Pacific Northwest. We then converted the corrected strain rate field to a moment rate field using the Kostrov's formulation.

Geologic strain and moment rates were calculated using the geologic deformation model and fault sections database prepared for the 2023 NSHM. Geologic slip rates were projected onto dipping planes, and fault plane area is calculated from the sub-surface parameters listed in the fault sections database. Geologic moment rate was calculated by multiplying the geologic slip rate (i.e., strain rate) by the fault plane area.

Seismic moment rates were applied directly from the gridded seismicity field used in the 2023 NSHM. This seismicity field has earthquakes near mapped faults partially removed to avoid double counting of earthquakes that could contribute to geologic slip rates. We use the nucleation moment rate calculated within the branch-averaged "grand inversion" methodology used in the 2023 NSHM earthquake rupture forecast.

All moment rates are assessed on a common 0.1º x 0.1º grid across the western U.S. We subdivide the western U.S. into four regions: northern California, southern California, Basin and Range, and Northwest to compare results within tectonically similar regions.

Results

We find that the sum of geologic and seismic moment rates nearly equals, but is still less than, the geodetic moment rates across the four study regions. The ratio of geologic + seismic moment rates to geodetic moment rate ranges from 0.8 to 0.93, indicating that most of the far-field, deep signal of strain accumulation (geodetic moment rate) is accommodated by earthquakes (geologic + seismic moment rates). More locally, we find that areas of "complex" and under-characterized faulting, such as the Walker Lane (western Nevada & eastern California) are somewhat well-balanced between geodetic moment rate and the sum of seismic and geologic moment rate. In some places within the Walker Lane, the sum of seismic and geologic moment rates may exceed the geodetic moment rate, perhaps due to local influence of volcanic-related seismicity, overestimated geologic slip rates, or overestimated fault plane areas. Similarly, regions around the Yellowstone hotspot track (Idaho-Montana-Wyoming) indicate an overabundance of seismic moment rate relative to geologic and geodetic moment rates, perhaps due to the influence of volcanic earthquakes; by the same token, faults could be under-characterized in this region and a relative dearth of geodetic stations could be contributing to a potential underestimate of geologic and geodetic moment rate.

Discussion & Conclusions

The remaining ~7-20% of unaccounted geodetic moment rate at the regional scale may represent off-fault deformation. Processes that accommodate aseismic moment include folding, ductile flow, unidentified fault creep, unaccounted post-seismic transients, and (most likely) a combination of these factors as well as factors unknown. This percentage of off-fault deformation is consistent with previous estimates derived from field observations, boundary element numerical models, and analog modeling experiments of strike-slip faults. Understanding the role of off-fault deformation within dip-slip fault systems, particularly normal faults, is the topic of future study.

Our analyses indicate that off-fault deformation is present throughout the western U.S. at varying amounts, but is roughly 20% or less of the total geodetic budget. From the available data, we find that the total geodetic moment budget is not recorded by seismic or geologic evidence of earthquakes. This remaining ≤20% of geodetic moment rate should be carefully considered before implementation as "off-fault deformation" in updates to the U.S. NSHM and other earthquake rupture forecasting efforts, as we find that this remaining percent may not contribute to the damaging coseismic shaking forecasted by probabilistic seismic hazard models.

Continually reviewing and updating critical regional datasets using uniform methodology (including geodetic station velocities, seismicity catalogs, fault geometry and activities) will enable similar assessments in the future to test assumptions in modeling strain, and also serve several additional critical purposes (including accurate hazard analyses and public communication). Maintaining databases like the ones used in this study is a critical tool in answering fundamental, system-level questions that apply to a multitude of applications, including the driving question of this study: what is the earthquake rate budget?