A Global Mmax for Stable Continental Regions?

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One can ask if the largest observed earthquake magnitude in a region (Mmaxobs) is the largest that can occur in that region (Mmax). This question is difficult to answer for seismically active regions and even more so for stable continental regions (SCR). Such regions are often characterized by low seismicity with large recurrence periods for larger earthquake magnitudes and no or little information on active faults. Traditionally it has been argued that Mmax should be similar in tectonically similar SCRs around the world. Such a tectonic division of SCR was first proposed by Johnston *et al.* (1994) and later updated by U.S. NRC *et al.* (2012), resulting in 255 SCR domains, which were further grouped into superdomains, each characterized by an Mmaxobs.

We consider whether Mmaxobs of the superdomains reflect a different Mmax for each or if a global Mmax could exists for all SCRs. In the latter case the difference in Mmaxobs between superdomains would just be due to a limited period of observation. To explore this question, we simulate earthquake catalogs assuming a global Mmax of 7.9, the largest earthquake magnitude observed in SCR to date. Using published average recurrence parameters per continent, a Poisson temporal occurrence model, catalog completeness thresholds for different regions within each continent and catalog lengths similar to what we presently have, 10,000 random catalogs were simulated for each SCR domain and combined into superdomain catalogs.

The resulting superdomain Mmaxobs distributions appear very similar to the one observed in reality, suggesting that a single global Mmax could exist for SCR and that this possibility should be considered in seismic hazard assessments. If done carefully this would not necessarily increase the predicted hazard because earthquakes with magnitude Mmax are very rare. We also investigate the effect of a larger global Mmax and longer catalog, and find that catalog length is the limiting factor in our knowledge of Mmax.

Estimation of the Frequency-Magnitude Gutenberg-Richter *b*-Value Without Making Assumptions on Levels of Completeness

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A pronounced weakness of the classic Aki-Utsu *b*-value estimator is its heavy dependence on the level of magnitude completeness m_c whose assessment is in itself not a trivial task and reliant on human opinion. New estimators for frequency-magnitude Gutenberg-Richter *b*-value which are not dependent on the level of completeness m_c are proposed in the place of the Aki (1965) maximum likelihood and Utsu (1965) moment estimators. The Monte-Carlo simulations show that these newly derived estimators are especially effective when the incomplete frequency-magnitude distribution is gradually curved and has only one maximum *i.e.* it belongs to the distributions of category IV according to classification by Mignan (2012). The most striking feature of the newly derived moment estimator is its simplicity as it can be expressed by the first three sample central magnitude moments—the mean, standard deviation and skewness. The simulations also show that the proposed maximum likelihood estimator of the *b*-value can be considerably less accurate than its moment counterpart. In cases where the applied sample of earthquake magnitudes is complete, the equations describing the newly derived moment and maximum likelihood *b*-value estimators take the form of the classic Aki (1965) and Utsu (1965) *b*-value solutions. Since the newly proposed *b*-value estimators also incorporate weak seismic events, they can generate more reliable earthquake hazard, forecasting and prediction assessments.

Assessing the Hazard of Large Aftershocks in Alaska

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The seismological community does not yet have an operational plan in place to issue aftershock probability forecasts following a large damaging earthquake in subduction zone regions such as Alaska or Cascadia. Because the bulk of statistical aftershock analyses have been conducted using earthquakes on California crustal strike-slip faults, exporting probability forecast algorithms from California to subduction zones environments might not be appropriate. Here, we generate mainshock/aftershock statistics with the aim to assist future earthquake forecasting efforts in subduction zones. To begin, using 20 years (1995-2015) of ANSS Alaska data we identify 50 mainshocks (M ≥ 6.5) and use K-means clustering to identify aftershocks. For each sequence we determine the magnitude differential between the mainshock and largest aftershock (a ~1.2 value is expected based on Bath's law) and use a maximum likelihood method to estimate the b-value (a magnitude frequency distribution measurement). We investigate if the magnitude differentials correlate with the b-values and to what extent there is a space/time pattern in these parameters. Alaska data are optimal for this task because there are far more data from the Alaska region than the entire lower-48 combined. Also, Alaska has deep subduction zones and shallow strike-slip zones, allowing us to test if faulting regime plays a role in these parameter characteristics. We find the magnitude differentials span a wide range (0.1 to 2.6 units), albeit, the larger differentials could result from large aftershocks missing from the catalog. Our initial results show the two deepest events (135km on 28 July 2001; 109km on 23 June 2014) have some of the largest differentials and smallest b-values and that the two most northern events along the strike-slip Denali Fault in 2002 have relatively high b-values and large differentials. This spatial partitioning suggests it is worthwhile to tune aftershock probability forecasts for subduction zones.

Improved Omori Parameters for Global Aftershock Forecasts

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Following a large earthquake, seismic hazard can be orders of magnitude higher than the long-term average as a result of aftershock triggering. Due to this heightened hazard, there is a demand from emergency managers and the public for rapid, authoritative, and reliable aftershock forecasts.

In the past, USGS aftershock forecasts following large, global earthquakes have been released on an ad-hoc basis with inconsistent methods, and in some cases, aftershock parameters adapted from California. To remedy this, we are currently developing an automated aftershock product that will generate more accurate forecasts based on the Reasenberg and Jones (Science, 1989) method. To better capture spatial variations in aftershock productivity and decay, we estimate regional aftershock parameters for sequences within the Garcia *et al.* (BSSA, 2012) tectonic regions. We find regional variations in mean aftershock productivity of almost a factor of 10.

The Reasenberg and Jones method combines modified-Omori aftershock decay, Utsu productivity scaling, and the Gutenberg-Richter magnitude distribution. We additionally account for a time-dependent magnitude of completeness following large events in the catalog.

In addition to estimating average parameters, we develop an inversion method to solve for the inter-sequence productivity variability. This allows for a more complete quantification of the forecast uncertainties and Bayesian updating of the forecast as sequence-specific information becomes available. We find that aftershock productivity is more variable for lower mainshock magnitudes and in regions where the mean stress drop is high.

Recent Achievements of the Collaboratory for the Study of Earthquake Predictability

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The Collaboratory for the Study of Earthquake Predictability (CSEP) supports a global program to conduct prospective earthquake forecasting experiments. CSEP testing centers are now operational in California, New Zealand, Japan, China, and Europe with 436 models under evaluation. The California testing center, started by SCEC, Sept 1, 2007, currently hosts 30-minute, 1-day, 3-month, 1-year and 5-year forecasts, both alarm-based and probabilistic, for California, the Western Pacific, and worldwide. Our tests are now based on the hypocentral locations and magnitudes of cataloged earthquakes, but we plan to test focal mechanisms, seismic hazard models, ground motion forecasts, and finite rupture forecasts as well. We have reduced testing latency, implemented prototype evaluation of M8 forecasts, and are currently developing formats and procedures to evaluate externally hosted forecasts and predictions. CSEP supports the USGS program in operational earthquake forecasting and a DHS project to register and test external forecast procedures from experts outside seismology. We found that earthquakes as small as magnitude 2.5 provide important information on subsequent earthquakes larger than magnitude 5. A retrospective experiment for the 2010-2012 Canterbury earthquake sequence showed that some physics-based and hybrid models outperform purely statistical (*e.g.*, ETAS) models. This experiment also demonstrates the ability of the CSEP infrastructure to support retrospective forecast testing. Current CSEP development activities include implementation of evaluation strategies that increase computational efficiency for high-resolution global experiments, such as the evaluation of the Global Earthquake Activity Rate (GEAR) model. We describe the open-source CSEP software that is available to researchers as they develop their forecast models. We also discuss how CSEP procedures are being adapted to intensity and ground motion prediction experiments as well as hazard model testing.

The Virtual Quake Earthquake Simulator

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Virtual Quake is a boundary element code designed to explore the seismicity of today's fault systems. Virtual Quake (VQ) simulates any input fault network to produce seismic histories of 100,000 years or more. Virtual Quake has had numerous improvements and additional features added in the past year. Here we present revised conditional probabilities for large California earthquake scenarios in addition to summarizing other VQ projects currently underway.

Virtual Quake is hosted by the Computational Infrastructure for Geodynamics, free to use, and comes with a user's manual. Virtual Quake has been downloaded by researchers around the world, and we are currently collaborating with researchers who are using Virtual Quake to assess seismic hazard in their regions.

http://geodynamics.org/software/vq/

Time-dependent Models of Interseismic Deformation in the Northwestern United States

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GPS velocity fields in the Western US have been traditionally interpreted with time-independent block models driven by backslip at the `locking rate' on model faults that divide a set of crustal blocks. The viscoelastic block model is a time-dependent variation of the block model which accounts for viscoelastic (lower crust and mantle) relaxation from past slip events. Here we construct viscoelastic block models for the Western US, focusing on the Pacific Northwest and the earthquake cycle on the Cascadia megathrust. The western US is divided into blocks selected from an initial set of 137 microplates using the method of Total Variation Regularization (Evans *et al.*, 2015), allowing potential tradeoffs between surface faulting and megathrust coupling to be determined algorithmically from GPS observations. Trial depth-dependent viscoelastic structures and major fault recurrence intervals are prescribed; a 500-year recurrence interval is assigned to the Cascadia megathrust. Fault geometry, slip rate, and locking fractions are estimated simultaneously within the Total Variation regularized block model. For a range of mantle asthenosphere viscosity (4.4×10^{18} Pa s to 3.6×10^{20} Pa s) we find that fault locking on the megathrust is concentrated in the uppermost 20 km in depth, and a locking rate contour line of 30 mm/yr extends deepest beneath the Olympic Peninsula, characteristics similar to previous time-independent block model results. Both average and maximum locking fraction required to fit the GPS velocity field depend on mantle viscosity, both being higher the lower the viscosity. Moreover, for viscosity less than $\sim 5 \times 10^{19}$ Pa s, the amount of inferred locking is higher than that obtained using a time-independent block model. This suggests that future time-dependent models for a range of admissible viscosity structures could refine our knowledge of the locking distribution and its epistemic uncertainty.

Seismotectonics Beyond the Plate Boundary

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Seismic Imaging of a Continental Intraplate: Long-Term Persistence of Fossil Rifts and Hot Spots in the Central and Eastern United States

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Seismic surface waves from the Transportable Array of Earthscope's USArray are used to estimate phase velocity structure of 18 to 125s Rayleigh waves, then corrected for lateral crustal thickness variations (with CRUST1.0) and inverted to obtain three-dimensional crust and upper mantle structure of the Central and Eastern United States (CEUS) down to ~200 km. The obtained lithosphere structure confirms previously imaged features in the CEUS, *e.g.*, the low seismic velocity signature of Proterozoic to Cambrian fossil rifts, the very low velocity at >150 km depth below an Eocene volcanic center in northwestern Virginia, and the very low velocity along a corridor stretching from eastern New York to New Hampshire. The model also reveals new features. The high-velocity Granite-Rhyolite Province sharply bounds the Grenville front at mid-lithosphere depth, suggesting that it acted as a backstop during the Grenville orogeny ca. 1.2—1.0 Ga. High-velocity mantle extending ~200 km deep stretches from the Archean Superior Craton well into the Proterozoic terrains (Granite-Rhyolite, Mazatzal and Yavapai provinces). This is consistent with independent seismic velocity images and suggests that the thickness of Proterozoic lithosphere is generally ~150–200 km. A deep low-velocity zone in central Texas is associated with the late Cretaceous Travis and Uvalde volcanic fields, and a similar deep low-velocity zone is located beneath the South Georgia Rift, which contains Jurassic basalts associated with the Central Atlantic magmatic province. Hotspot tracks may be associated with several of the low-velocity zones, and the central Texas, New York-New Hampshire, and southern Georgia zones may also be associated with the former rifted Laurentia margin. This suggests a systematic pattern whereby transient mantle thermal perturbations are accentuated near former failed rifts or rift margins.

Using the Locations of M ≥ 4 Earthquakes to Delineate the Extents of the Ruptures of Past Major Earthquakes

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Some modern seismicity in the magnitude range between M4 and M6 in California and eastern North America preferentially occurs near the edges of past large ruptures. Once a large earthquake rupture has occurred, stress is concentrated at the edges of the rupture, and apparently this stress concentration can trigger earthquakes at or near the rupture edges many decades or even longer after a mainshock. Furthermore, the modern M ≥ 4 earthquakes in the vicinity of a past mainshock usually have the same focal mechanism as the earlier mainshock. There are a number of examples of this in California and Nevada, where there is a statistically significant correlation of the locations of M ≥ 4 earthquakes and the edges of 19th and 20th century fault ruptures in $M_w \geq 6.5$ earthquakes. In contrast, the M ≥ 4 earthquakes near the epicenters of future ruptures in California are randomly scattered around the fault with no concentration near the ends of the future fault rupture. The concentration of earthquakes near the ends of earlier large ruptures in California becomes progressively less pronounced as the smallest magnitude in the data set is reduced from M4.0 to M3.0. These observations also appear to be true for intraplate regions where aftershock sequences can last millennia. The identification of modern rupture-edge M ≥ 4 aftershocks can be used to help discover where and when past strong earthquakes took place, even if there is no historical record of the mainshock. This is of great importance for seismic hazard studies.

A Hybrid-Empirical Ground-Motion Relation for Central and Eastern North America

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A new hybrid-empirical ground-motion (GMM) model for central and eastern North America has been recently developed as part of the NGA-East research project by the authors using a hybrid-broadband simulation technique. Hybrid empirical estimates are calculated using modification factors between host and target regions as well as empirical GMMs from the host region. The regional adjustment factors are ratios of the intensity measures including peak ground