# Can We Forecast the Detailed Characteristics of Repeated Mega-earthquakes on Subduction Zones?

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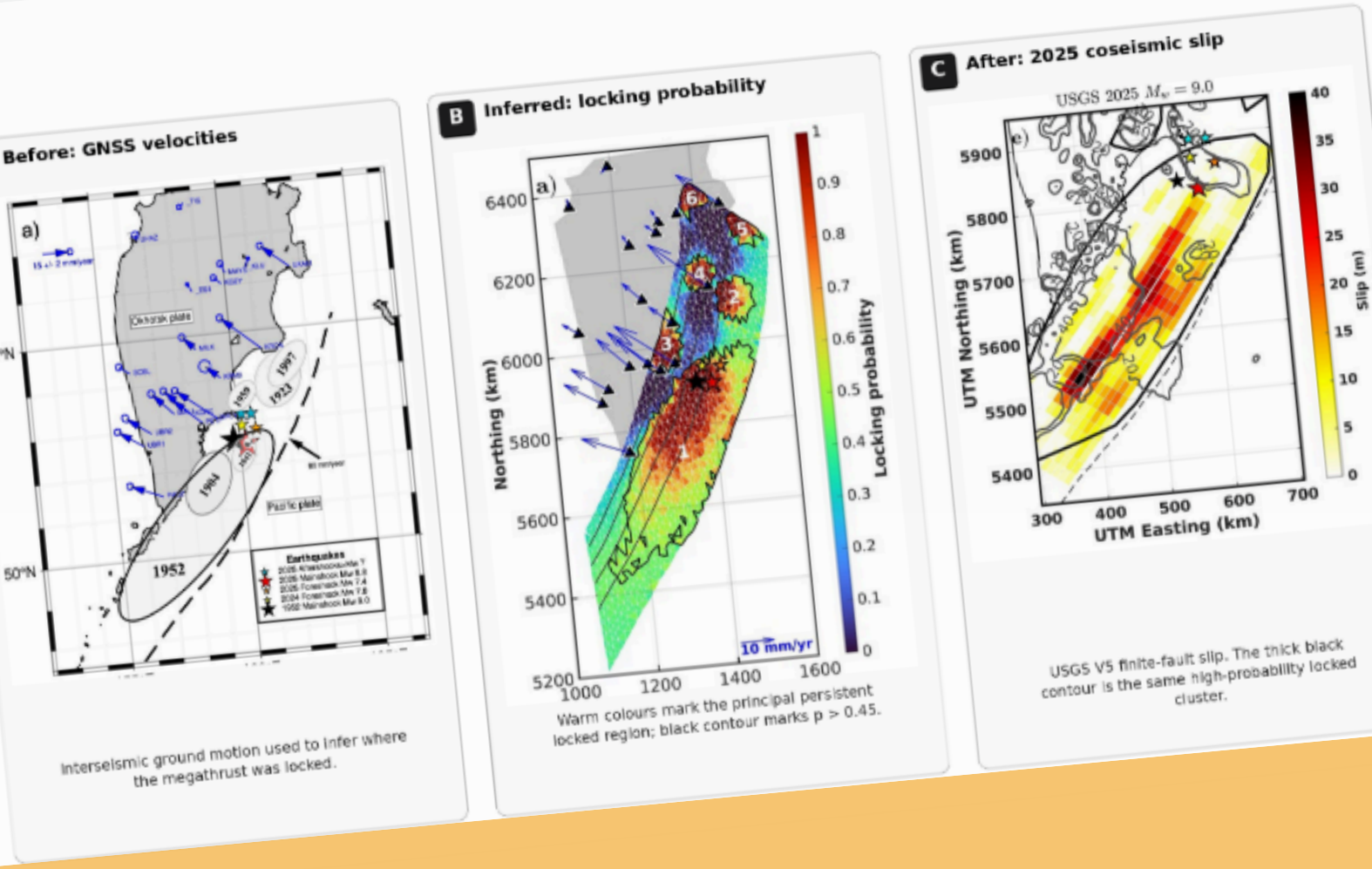


**Briefing note 535**

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# Introduction

Every so often, earthquake science produces a result that seems to move an old question slightly closer to an answer: can we identify where the next great rupture is most likely to occur? Periollat and Funning (2026) provide one of the more compelling recent tests of that idea. Using deformation measured before the 30 July 2025 moment magnitude (Mw) 8.8 Kamchatka earthquake, they reconstruct where the megathrust was strongly locked and compare that pattern with the rupture that followed. The result is important because the pre-earthquake deformation contained a recognisable spatial signal of the later rupture. But the study does not provide a date, or even a short time window, for when that rupture would happen.

## Mapping where strain is accumulating

At subduction zones, the largest earthquakes occur when a locked part of the plate interface finally releases strain that has accumulated over many years. While the fault remains locked, continued plate convergence slowly deforms the surrounding crust. That surface deformation is measurable, and it gives seismologists an indirect way of identifying strongly locked fault patches, or asperities, even when much of the fault lies offshore.

Periollat and Funning use horizontal Global Navigation Satellite System (GNSS) velocities to turn those surface measurements into an estimate of locking on the Kamchatka megathrust. Their boundary element model is coupled with a modified Metropolis-Hastings sampling algorithm, which repeatedly tests alternative patterns of fault locking against the observations. An important feature of the method is that the asperities are not drawn in beforehand. Instead, the analysis estimates how strongly the data support locking on individual fault elements, subject to the assumptions and resolution of the model. Figure 1 brings these elements together visually, showing the pre-earthquake GNSS deformation field, the inferred high-locking region and its relationship to the area that ultimately ruptured in 2025.

The spatial result is more specific than the broad locked region. The model identifies six high probability locking regions using a probability threshold of 0.45. The largest, described as the principal locked cluster, covers roughly 100,000 square kilometres of the megathrust and contains 618 triangular fault elements. Across the model ensemble, a typical realisation has about 423 of those elements locked, or around 68 percent. The same principal locked zone coincides with much of the megathrust area that slipped in both 1952 and 2025. Within it, hierarchical clustering resolves five smaller subregions. The two highest probability subregions, with mean locking probabilities of at least 0.88, lie close to the areas where the 1952 and 2025 ruptures began. In physical terms, the picture is of a large zone of long term strain accumulation that contains more compact patches where rupture initiation may be concentrated.

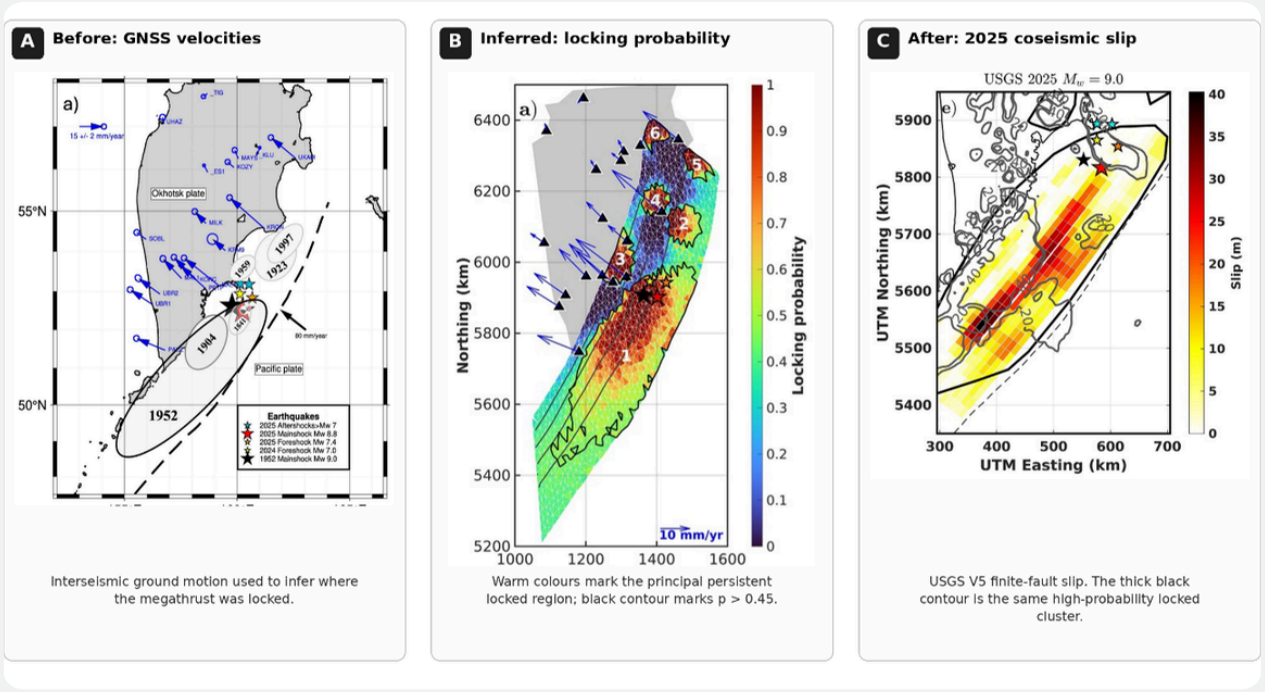


Figure 1: Relationship between pre-earthquake interseismic GNSS deformation, inferred megathrust locking and the 2025 Mw 8.8 Kamchatka rupture. This composite figure was prepared by the authors by extracting, cropping, and relabelling selected panels from Periollat and Funning (2026). The GNSS velocity field is based on Bürgmann et al. (2005), the probabilistic locking distribution is from Periollat and Funning (2026), and the 2025 coseismic slip distribution is based on the USGS finite-fault solution reported therein. Adapted from Periollat and Funning (2026), Geophysical Research Letters, under the Creative Commons Attribution (CC BY) licence.

Figure 2 puts the moment budget comparison in scale. Roughly 80 millimetres per year of convergence sustained over 73 years corresponds to about 5.8 metres of slip deficit on fully locked elements. Under the study's illustrative rigidity assumptions, that accumulated deficit is equivalent to about moment magnitude (Mw) 8.85 to 9.00, close to the observed moment magnitude (Mw) 8.84 event. The comparison is informative because it shows that the stored strain was of the right order to support an earthquake of that size. It is not, however, a unique prediction of either magnitude or rupture footprint.

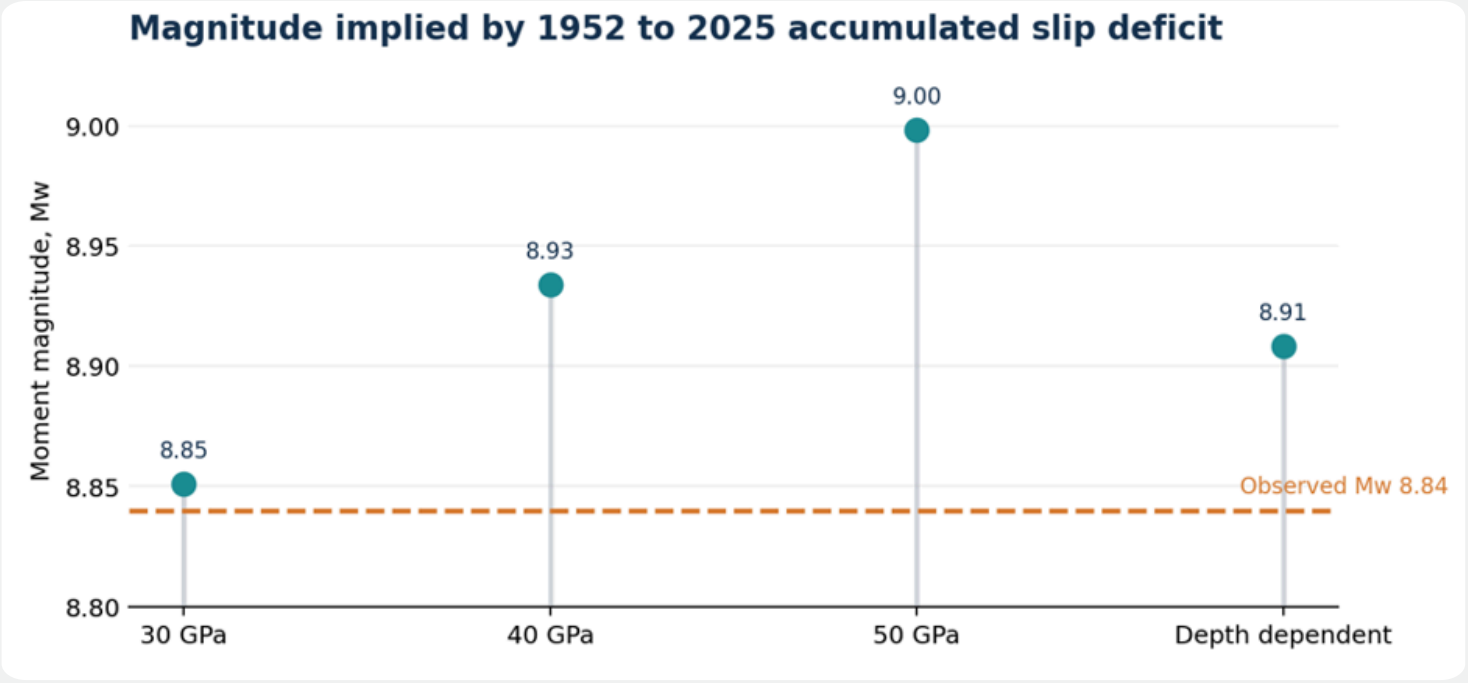


Figure 2. Equivalent moment magnitudes associated with the post-1952 accumulated slip-deficit budget under alternative rigidity assumptions (locking threshold=0.45), compared with the observed Mw 8.84 magnitude of the 2025 Kamchatka earthquake. The figure was prepared by the authors using the moment and magnitude estimates reported by Periollat and Funning (2026). These values represent model-based scenarios and should not be interpreted as a forecast range for the magnitude of a future earthquake.

## Forecasting, not Prediction

Prediction, forecasting and early warning are often discussed together, but they answer different questions. A conventional earthquake prediction would specify, in advance, where an earthquake will occur, how large it will be and when it will happen. No method can currently do that reliably. Forecasting is more modest: it estimates probabilities for defined regions, magnitude ranges and time windows. Seismic hazard describes the shaking that may happen at a place; seismic risk goes a step further by combining that hazard with exposure and vulnerability (United States Geological Survey, n.d.; Mizrahi et al., 2024).

For Kamchatka, the Global Navigation Satellite System (GNSS) observations themselves predate the 2025 earthquake, which is an important point. Even so, the comparison presented in the 2026 paper is retrospective which has inferred locking pattern is judged against a rupture whose location and slip distribution are now known. The study therefore demonstrates that useful spatial information was present before the earthquake, while it does not indicates of any time specific prediction issued beforehand.

This distinction is easy to miss, that a probability of locking is not a probability of rupture within a specified period. A segment can be very strongly locked and remain that way for decades. Periollat and Funning tell us something about where strain is being stored, but not when it will be released, or which locked segment will fail next. For now, the most defensible application is better earthquake source characterisation rather than short term public warning.

## The Kamchatka earthquake was unusually informative

The overlap between the 1952 and 2025 rupture regions makes Kamchatka an unusually informative natural experiment. It allows us to ask whether persistent asperities help organise successive great earthquakes on the same subduction margin. The answer appears to be yes, at least in a broad spatial sense. But the two ruptures were not replicas of one another: Periollat and Funning show important differences in shallow slip and identify areas where displacement in 2025 exceeded the slip deficit accumulated since 1952.

Figure 3 provides an independent check from a different geodetic model. Xiao et al. (2026). They estimate an average post 1952 slip deficit of about 2.56 metres, compared with average 2025 coseismic slip of about 3.06 metres, while the corresponding peak values are about 5.77 metres and 7.60 metres. Dynamic overshoot, release of older residual deficit, or a combination of the two may explain the excess. In other words, accumulated slip deficit is a valuable physical constraint, but it should not be read as a precise forecast of future fault displacement

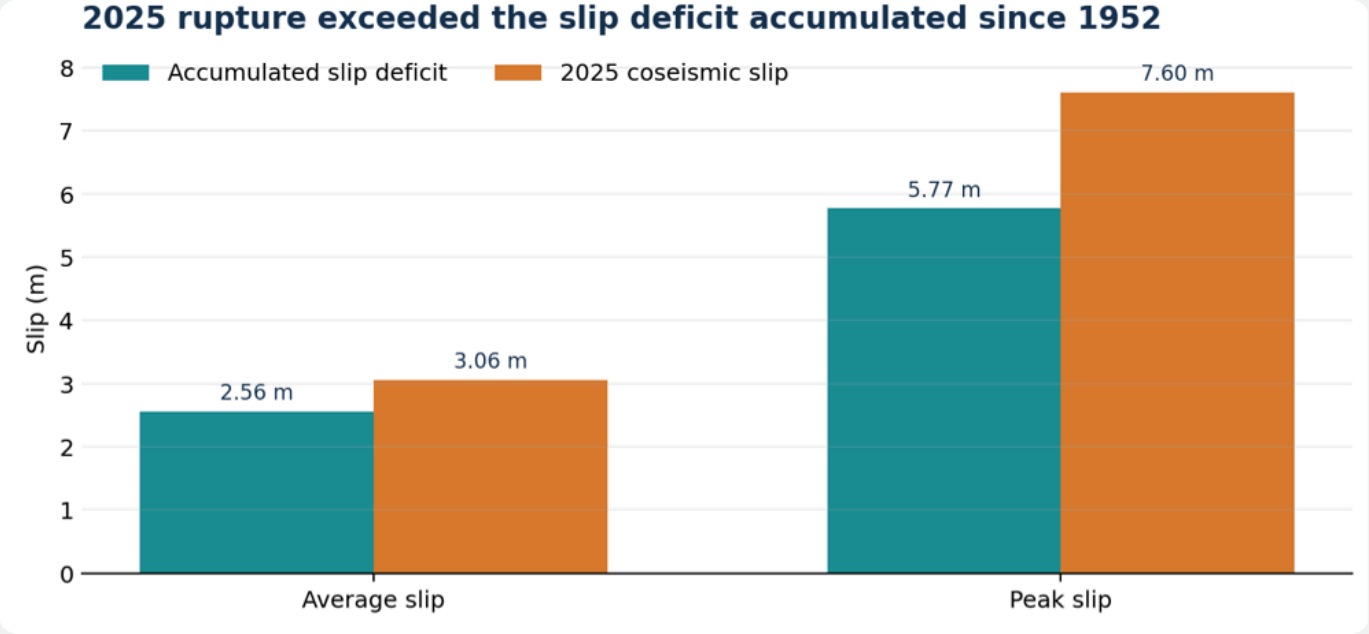


Figure 3. Comparison of modelled post-1952 accumulated slip deficit with coseismic slip during the 2025 Kamchatka earthquake. The figure was prepared by the authors from the average and peak slip-deficit and coseismic-slip values reported by Xiao et al. (2026). Both the average and peak coseismic slip exceed the corresponding accumulated slip-deficit estimates in that model. Values are specific to the Xiao et al. (2026) and should not be directly compared with local maxima derived from other rupture models.

For tsunami risk, this distinction matters even more. The larger near trench slip inferred for the 1952 earthquake contrasts with the more limited shallow slip in 2025. Knowing that a megathrust is locked does not tell us exactly how far a future rupture will propagate toward the trench, how much shallow slip it will generate, or how much water it will displace. Those details strongly influence tsunami generation and remain an important source of uncertainty.

## A related New Zealand thread

New Zealand provides a useful comparison because recent work there covers four different problems that are easily blurred together in public discussion: producing operational probability forecasts, testing whether those forecasts actually perform, estimating long term recurrence from geological records, and issuing early warning once rupture has begun. Keeping these categories separate is important because they operate on very different time scales. None amounts to knowing the exact time and place of the next great earthquake.

At the operational end, Matt Gerstenberger coauthored the Hybrid Forecast Tool (HFT), described by Kenny Graham and colleagues in 2024. The Hybrid Forecast Tool (HFT) brings short, medium and long term earthquake models into one software environment. After a significant earthquake, the statistical picture changes quickly as aftershocks occur and more data arrive. Automating that workflow reduces the manual effort needed to update probability estimates and helps agencies publish them more consistently. Its achievement is therefore operational speed and reproducibility, especially for aftershock forecasting, rather than deterministic prediction (Graham et al., 2024a).

Producing a forecast is only half the problem; the other half is showing that it works. A second collaboration led by Graham, again involving Gerstenberger, expanded pyCSEP, the Python toolkit developed within the Collaboratory for the Study of Earthquake Predictability (CSEP). The updated system makes it easier to draw on authoritative earthquake catalogues, work with different spatial grids, and compare forecasts using standard statistical tests and benchmark models (Graham et al., 2024b). This matters because an apparently convincing model can perform well simply because it has been examined after the event. Applied to Kamchatka, the lesson is clear, if fault locking probabilities are used to change where future earthquakes are weighted, they should eventually be tested prospectively, using earthquakes that were not available when the model was built.

The Hikurangi work operates on a much longer time frame. There, the question is not what will happen next week, but how often very large earthquakes may recur over decades to centuries when the geological record is sparse. The Smart Ideas project highlighted by East Coast Life at the Boundary (East Coast LAB), with Ting Wang as science lead and Mark Stirling as impact lead, approaches this problem using paleoseismic evidence, including traces of past earthquakes preserved in sediments, coastal deformation and fault records (East Coast Life at the Boundary, 2024). Wang et al. (2024) compared five recurrence models across 93 fault segments worldwide and then used Bayesian model averaging to carry uncertainty in the choice of model forward. That is important because a subduction margin may preserve only a handful of great earthquakes over many centuries. With so few observations, one mathematical recurrence law can appear plausible without being uniquely supported by the data. The practical message for Hikurangi is therefore one of disciplined uncertainty, that the long term probabilities can be refined, but they should not be

Machine learning and data science form another strand of the New Zealand effort. Research initiated at the Institute of Geological and Nuclear Sciences (GNS Science), now part of Earth Sciences New Zealand, has explored how automated methods can improve earthquake catalogues, identify patterns in large data sets and support probabilistic modelling (GNS Science, n.d.). The attraction is obvious, as the modern catalogues contain far more information than can be inspected manually. But a machine learning model is only as useful as the data and tests behind it. Apparent patterns can disappear when the catalogue changes, when the model is applied to another region, or when rare large earthquakes are poorly represented in the training data. For forecasting, out of sample testing and credible uncertainty estimates remain essential (Mizrahi et al., 2024).

Early warning sits at the opposite end of the time scale because it begins only after rupture has started. Jen Andrews and colleagues tested the Finite Fault Rupture Detector (FinDer) in New Zealand using the GeoNet national geological hazard monitoring network (Andrews et al., 2026; first published online in 2025). The Finite Fault Rupture Detector (FinDer) compares the evolving spatial pattern of recorded ground motion with precomputed rupture templates to estimate the developing fault's location, length and orientation. For a large earthquake, that information can improve rapid estimates of where strong shaking is likely to arrive next. The warning may amount to seconds or tens of seconds, and sites very close to the rupture may receive little or none. This is why early warning should be described as rapid detection and consequence forecasting, not prediction of the earthquake before it begins. Beheshtian and Somerville (2026) make the same distinction in Risk Frontiers' discussion of the Venezuela doublet.

### Implications for catastrophe risk

For catastrophe modelling, the Kamchatka result is potentially important, but it is better viewed as an evolution than a revolution. Geodetic locking estimates could provide additional physical constraints on rupture scenarios, source geometry and seismic moment budgets. Turning those constraints into event rates or scenario weights requires another layer of modelling and validation. In particular, the probability that a fault element is locked should not be treated as though it were an annual probability of earthquake occurrence.

The broader modelling principle is already familiar in catastrophe risk. Risk Frontiers' briefing on the 2023 update of the Australian National Seismic Hazard Assessment (NSHA23), by Somerville, Evans and Beheshtian (2024), shows how improvements to earthquake catalogues, source models and ground motion models feed into probabilistic hazard assessment. Australia's tectonic setting is very different from Kamchatka, but the modelling lesson is similar, better physical information is valuable when it narrows uncertainty without pretending to remove it.

Integrating a probabilistic geodetic method of this kind into catastrophe modelling pipelines will not be straightforward, with one of the main constraints being the availability and quality of the observations on which the method depends. Land based Global Navigation Satellite .

System (GNSS) measurements do not resolve every shallow part of a subduction interface equally well, particularly near the trench. Seafloor geodesy is therefore important if the Kamchatka approach is to be tested and extended elsewhere. Just as importantly, the method will need independent applications and prospective evaluation before we can say how much forecasting skill it adds.

Periollat and Funning do not give us a timetable for the next great earthquake, and that is not a weakness of the study so much as a reminder of what the method is designed to do. It gives us a stronger physical basis for identifying where the strain capable of producing a great earthquake is accumulating. For earthquake risk assessment, that is a meaningful advance, provided the information is used to improve probabilistic models rather than to replace uncertainty with false precision.

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