Earthquake Forewarning in the Cascadia Region

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Executive Summary

This report, prepared for the National Earthquake Prediction Evaluation Council (NEPEC), is intended as a step toward improving communications about earthquake hazards between information providers and users who coordinate emergency-response activities in the Cascadia region of the Pacific Northwest. NEPEC charged a subcommittee of scientists with writing this report about forewarnings of increased probabilities of a damaging earthquake. We begin by clarifying some terminology; a "prediction" refers to a deterministic statement that a particular future earthquake will or will not occur. In contrast to the 0- or 100-percent likelihood of a deterministic prediction, a "forecast" describes the probability of an earthquake occurring, which may range from >0 to <100 percent. When the time window is short (days to months) and the forecast is formulated for operational utility, this term may be "operational earthquake forecasting." The subcommittee considered short-term forecasts only, herein referred to as "forewarnings," but not their formulation into messages or their applications, which will be addressed by NEPEC in subsequent activities.

The subcommittee considered "direct" and "indirect" forewarnings. Direct forewarnings originate with observed changes in geologic processes or conditions, which may include

- Increased rates of M>4 earthquakes on the plate interface north of the Mendocino region
- Changes in shallow seismicity patterns
- Increased rates of moderate earthquakes within the subducting plate
- Changes in the pattern of slow slip on the plate interface and other major faults

Indirect forewarnings are based largely on model predictions of increased earthquake-occurrence probabilities. In this context, "models" refers to simulations of the processes believed to affect earthquake occurrence, as implemented in computer software, laboratory experiments, or some analog natural system. These indirect forewarnings likely will be more uncertain and difficult to interpret than direct forewarnings. This report also highlights the challenges of assessing the significance of

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forewarnings, which mostly will be extraordinary events with little or no historical precedent in the Cascadia region.

Purpose

The authority for issuing earthquake warnings in the United States resides with the Director of the U.S. Geological Survey (USGS). For most earthquake-related situations, the National Earthquake Prediction Evaluation Council (NEPEC) advises the Director. NEPEC seeks to evaluate and, possibly, improve communications between earthquake scientists and the public, emergency managers, and government officials about the likelihood of an earthquake in the United States. To date, NEPEC's focus in the Cascadia region has been on the possibility of an *M*9 earthquake on the interface between the subducting and overlying plates. Such an earthquake would directly affect Washington, Oregon, California, and British Columbia.

Three specific forewarning events concern NEPEC. (1) Partly as a result of public statements by the Geological Survey of Canada, the public has been made aware of regularly recurring slow motions or "slip" across the plate interface and possible associated elevated probabilities of a major earthquake. (2) The California Earthquake Prediction Evaluation Council (CEPEC, composed of earthquake scientists and a representative from the California Emergency Management Agency) might issue an advisory of a heightened daily probability of a major Cascadia earthquake in rare, but not impossible, circumstances. For example, on the basis of statistics of California seismicity (not a subduction zone), the probability of an *M*9 earthquake following an *M*5 earthquake within a week is less than the likelihood of an *M*9 event occurring independently within a 300-year period. The probability of an *M*5 earthquake foreshadowing an *M*6 event is ~100 times greater and might warrant CEPEC's attention. Thus, official warnings of a dangerous Cascadia earthquake could be issued from either Canada or California. (3) The occurrence of an $M>4$ earthquake on the plate interface would undoubtedly generate significant speculation by both scientists and the public because no earthquakes have been detected anywhere on the Cascadia plate interface since the inception of modern monitoring networks, except for a recurring cluster beneath offshore Newport, Oreg., and in the vicinity of Cape Mendocino (Trehu and others, 2008; 2015).

Regional coordination on earthquake-related issues also is promoted in various venues between scientists, emergency managers, and public officials within the States and Province composing Cascadia, although no formal administrative entity focuses on forewarnings or predictions. One example of such coordination is the creation of a regional Cascadia Catastrophic Earthquake and Tsunami Response Plan under Federal Emergency Management Agency (FEMA) sponsorship. NEPEC considers that coordination among scientists, public officials, and emergency management personnel in the Cascadia region ought to be examined and any shortcomings addressed, to ensure that such coordination effectively crosses all State boundaries and international borders in the region.

NEPEC's first step toward achieving the aforementioned goals was to charge a subcommittee of scientists with writing this report, to serve as a basis for subsequent discussion with user communities. Specifically, NEPEC charged the subcommittee with creating a comprehensive list of potential geologic events envisioned as substantially increasing the probability of a large damaging earthquake in the Cascadia region. NEPEC allowed the subcommittee freedom to organize its activities and report in whatever way they deemed most appropriate.

Geography

The Cascadia geographic region extends from Cape Mendocino, near the city of Eureka in northern California, to northern Vancouver Island and mostly (but not exclusively) west of the Cascade Range and offshore where the subducting plate begins its descent. This region covers the spatial extent of significant shaking likely to result from a great "subduction zone" earthquake along the plate interface, like the recent events in Japan, Chile, and Sumatra, and includes the most densely populated urban centers. Earthquakes of concern originate not only along the plate interface but also deep within the subducting plate (like the 2001 Nisqually, Wash., earthquake) and at shallow depths within the crust of the overlying plate. In addition to occurring west of the Cascades, these crustal earthquakes may occur within and east of the Cascade Range; though not a primary focus, this area also should receive some consideration. Finally, earthquakes outside the Cascadia region could affect the probability of earthquakes within it, such as a major earthquake on the north end of the San Andreas Fault or the south end of the Queen Charlotte Fault.

Forewarnings typically come as a change in some measurement or observation, quantified as a ratio, which simplifies the task of identifying likely forewarnings because forewarning criteria need not be geographically specific. For example, the ambient or "normal" rate of crustal earthquakes in the Puget Sound area exceeds that in the Willamette Valley, and so the same increase in rate would require a jump to a higher value in the Puget Sound area than in the Willamette Valley. More generally, in one area the ambient and changed rates may differ from those in another, but the ratio of the changed to ambient rates may be far more similar.

Forewarning Events

Forewarning events should be defined on the basis of sound scientific analysis and expert advice. Signals indicative of forewarning events should be measurable or derived from a laboratory, mathematical, and (or) computer simulation. One category of potential forewarnings indicates accelerating motion along a fault or increased stressing or weakening of a fault; signals might include changes in earthquake activity and (or) measurements of slow deformation (for example, an uplifting or subsiding ground surface). Another category of potential forewarnings indicates changes in the physical environment that could weaken a fault, such as evidence for changes in fluid pressure.

"False alarm" forewarnings can result from misinterpretation of data, for example, changes in signals monitored for geologic purposes but caused by processes unrelated to earthquakes, such as heavy rainfall leading to measurable swelling of the ground surface, or subsidence associated with withdrawal of ground water. The subcommittee considered publicized nonscientific predictions outside the scope of its expertise.

Measurements

Detection of forewarning events requires continuously operating instruments, receipt of measurements from them without significant delay, and ready-to-use analytical tools. Once a possible forewarning event is detected, intensified evaluation of other information will be needed to verify and, possibly, quantify its meaning and significance. A protocol must be in place for prompt collaborative evaluation of all relevant information. Presently satisfying all of these requirements for all types of measurements remains a challenge. The classes of potential forewarnings include the following:

- *Seismic deformation* refers to relative motions across faults that occur fast enough that seismic waves radiate (time scales of seconds to minutes). In the Cascadia region, these events include ordinary earthquakes of all sizes and tiny sources that emit low-level seismic chatter or "tremor." Other types of seismic events have been documented elsewhere but not yet in the Cascadia region. Quantities diagnostic of forewarning events that are monitored continuously include catalog numbers and characteristics of earthquakes, and characteristics of the seismic signals themselves.

- *Aseismic deformation* refers to changes in the rocks and in the faults that bisect them that evolve over timescales of minutes to years and that may permanently alter their properties. These deformations occur slowly enough that they do not radiate measurable seismic waves, but like seismic waves, are continuously measured in the Cascadia region. Measurements of slow deformation come from the Global Positioning System (GPS), tiltmeters, coastal sea-level gages, and strainmeters. Different measurement types resolve details with differing spatial resolution. For example, spatially high-resolution views of ground deformation may be revealed in the differences between two images taken at different times from a satellite or airplane, such as from interferometric synthetic aperture radar (insar) or from light detection and ranging (lidar) imagery, although these images have poor temporal resolution because they are acquired only at intervals of days to years. Field observations of the rocks and topography can provide the highest spatial resolution of events that cause surface deformation, but they sample only the smallest areas; examples include densely spaced GPS monitoring in the immediate vicinity of well-located, significant active faults, such as the Seattle or Southern Whidbey Island Faults, or even mapping of geologic features by field geologists.
- *Physical conditions* measured include fluid pressures, temperatures, various rock properties, and others. Fluid pressures are now being monitored on the seafloor Neptune Observatory cable off of Vancouver Island, which extends from the Juan de Fuca Ridge onto the Continental Shelf.

Indirect Forewarning

Assessing the significance of enhanced earthquake probabilities predicted by means of computer, laboratory, or theoretical models requires an additional layer of uncertainty not faced when using direct observational evidence. Models commonly require simplifications, extrapolations, and untested assumptions absent in purely observation-based inferences, noting that many models use observations as guides or constraints and for validation. An example of these indirect forewarnings might be calculations of increased stresses on the Cascadia subduction-zone plate interface or on other surrounding fault systems, due to a major earthquake on the northern section of the San Andreas Fault or offshore within the Gorda plate and along the Blanco Fracture Zone. Studies that calculate stress changes caused by major earthquakes and their effects on the likelihood that nearby faults will fail in earthquakes within a specific time interval are now routinely conducted and sometimes reported in popular-science magazines (for example, Parsons and others, 2000). These types of forewarnings can be evaluated if the same criterion applied to observational changes is used: increased probability of a large earthquake must be demonstrated as objectively and quantitatively as possible.

Examples of Plausible Forewarning Events in the Cascadia Region

Here we provide several examples of forewarning events that might foreshadow a damaging earthquake. Although NEPEC requested a comprehensive list, we note a high probability that a foreshadowing event will be one that no one has anticipated! If no comparable events have been observed anywhere globally, no basis may exist for recommending actions. However, several obvious forewarning events may be identified in advance because of the somewhat unique features of Cascadia:

1. M>~*4 earthquakes on the plate interface*—The Cascadia plate interface has been nearly devoid of earthquakes during the instrumental era (mid-20th century), except perhaps for events near Cape Mendocino and in a few areas that have generated several clusters of *M*<4.9 earthquakes offshore of Oregon. Thus, the occurrence of multiple small earthquakes or a single moderate or larger earthquake on the plate interface north of the Mendocino area is likely to cause concern. In the next section, we describe an actual scenario in which an *M*7.3 event preceded an *M*9.0 earthquake along the plate interface in Japan, along with other forewarning signs. In the Cascadia region, these events would be more easily recognized as extraordinary, given that unlike Japan, the Cascadia plate interface is almost completely seismically silent.
2. *Changes in the pattern of slow slip on major faults*—Relative motions across deeper sections of the plate interface in the Cascadia region comparable to those resulting from an *M*~6.5 earthquake are regularly evident in GPS measurements, but occur so slowly (over days to weeks) that only tiny tremor seismic signals radiate. The regularity of these "episodic tremor and slow slip" (ETS) events in the Cascadia region makes identification of some forewarning events somewhat straightforward. The characteristics and patterns of these events have now been documented throughout the Cascadia region, such that significant deviation should be identifiable. For example, skipping or cessation of ETS events, or an ETS event that lasts longer than several weeks, locates elsewhere from where normally observed, simultaneously occurs over an unusually large area, or moves more than several centimeters, would all be considered extraordinary. In this case and others, the designation as "extraordinary" may be only a qualitative assignment. Any of these deviations would likely be considered a potential forewarning sign.
3. *Shallow crustal faults that slip slowly, without generating seismic waves but with measurable ground deformation*—Such faults have not yet been observed in the Cascadia region, and so such activity would be cause for concern if it was ascribable to a sufficiently large causative fault.
4. *Changes in shallow seismicity patterns*—The spatial patterns of shallow, small-magnitude earthquakes show no clear correlation with major, geologically mapped crustal faults in the Cascadia region. Many faults likely remain undiscovered, and the geometries at depth of even the best-mapped faults are uncertain. The repeat times for moderate to large earthquakes on these faults are likely thousands to many thousands of years. Thus, a sudden alignment of seismicity or other indications of motion across a single fault, or within a broader active fault zone, could be cause for concern. For example, localized swarms of small earthquakes elsewhere have provided evidence of larger-scale, slow, aseismic fault slip, which could elevate the stresses and potential for more significant earthquakes.
5. *Increased rates of moderate and larger intraplate earthquakes*—The occurrence of moderate earthquakes within the subducting plate itself is likely a cause for concern, as the damage and costs from the 2001 *M*6.8 Nisqually, Wash., earthquake demonstrated. Any such moderate earthquake also increases the probability of subsequent larger events on either the same intraplate fault and (or) on the plate interface itself. Some scientific studies have proposed increased earthquake rates as foreshadowing large earthquakes, and others decreased rates, highlighting the challenges in interpreting these types of changes.

Precedents for Forewarning Advisories

Several examples provide lessons about assessing possible increases in the probability of a damaging earthquake and issuing alerts. These examples come from past earthquakes in California and volcanoes nationwide. Forewarnings of volcanic unrest involve scientists issuing warnings cast as green to yellow, orange, and red threat levels; each level triggers a predefined set of actions by emergency managers (see http://volcanoes.usgs.gov/activity/alertsystem/). Once an alert has been issued scientists and emergency managers continue dialoguing until they reach a collective decision that the threat has expired (or the anticipated event occurs). Such consensus is key, so that both groups convey a uniform message to the public. The various threat levels are not necessarily based on quantitative criteria, and unlike earthquakes, volcanic eruptions most commonly follow measurable forewarnings lasting days to weeks.

The California Earthquake Advisory Plan provides another relevant example. This plan, which was adopted in 1991, is based on a series of statistical studies of the foreshocks and aftershocks of earthquakes in California. When an $M>5$ earthquake occurs the California State Geologist convenes CEPEC. If an alert is considered warranted CEPEC issues a statement to the Governor of California, the head of the California Office of Emergency Services, and the USGS, describing what has happened and the nature of the larger earthquake that may now be more probable.

How well has the California Earthquake Advisory Plan worked? A main shock has never occurred within the time window of any of the advisories issued, and several damaging earthquakes have occurred without any advisory being issued. Relative to the Pacific Northwest, California benefits (for the purpose of long-term assessments and more immediate forewarning) from a high rate of small earthquakes and lengthy records of past earthquakes that permit application of robust statistical methods. In the Cascadia region, similar methods may be applicable, but results have much larger uncertainties because input information has to come from places outside the region (presumed to be similar geologically) and because Cascadia's recent seismicity rates are much lower and its record of past earthquakes less complete relative to California. In addition, the differing plate-tectonic configurations of California and Cascadia result in a greater diversity of earthquake characteristics in the Cascadia region, where earthquakes occur on the plate interface, within the shallow crust of the overriding plate, and deep within the downgoing plate. The tectonic plates that split California move parallel to one another rather than converging, and so the part of the plate boundary that generates earthquakes lies only within the shallow crust. Cascadia's greater geologic complexity makes forecasting more challenging. Furthermore, the Cascadia region spans northern California, Oregon, and Washington States and extends well into Canada, leading to greater logistic challenges in the Pacific Northwest in coordinating rapid assessments of forewarnings of an increased probability of a damaging earthquake.

The Parkfield, Calif., prediction experiment provides another experience from which to glean lessons about forewarnings and issuing alerts, keeping in mind that testing the utility of these types of alerts statistically requires a compilation of the successes and failures (false alarms, unexpected earthquakes), and thus many years of records. A seemingly regular pattern of $M\sim6$ earthquakes along the section of the San Andreas Fault near the town of Parkfield led scientists to forecast another $M\sim6$ earthquake by 1993. In 1985 the USGS began setting out dense monitoring systems to observe the earthquake with unprecedented detail when it did occur. In addition, the USGS worked with the California Division of Mines and Geology and the California Office of Emergency Services to devise quantitative alert levels based on the information from these systems. Despite the fact that the earthquake did not occur until 2004, without any forewarnings and with somewhat different characteristics from those expected, the dense monitoring and intensive study of this area have led to significant scientific advances. Before 2004 alerts were issued to the media and public when forewarning signs caused increases in estimated probabilities of an *M*~6 earthquake. We note that though increased relative to background values, these alert-level probabilities were still very small.

Assessment of Earthquake Probabilities

Converting observations into quantitative estimates of increased probabilities of a future damaging earthquake still remains a major challenge. For example, over the 2 days preceding the March 11, 2011, *M*9 Tohoku, Japan, earthquake, a suite of observations clearly indicated that the probability of a large rupture might have become elevated, noting that interpretations of these observations benefit from hindsight. Sufficient measurements were available from global and Japanese networks to determine that (1) an *M*7.3 earthquake and a series of smaller aftershocks had occurred on the plate interface off Tohoku that increased the stress on surrounding parts of the interface; (2) a swarm of recurring very small earthquakes indicated that the plate interface fault was undergoing rapid, but still aseismic motion that was migrating along the fault; and (3) if it had occurred as rapidly as an earthquake, the amount of aseismic slip was equivalent to another *M*7 event (Kato and others, 2012). However, no well-established methodology existed for turning this information into quantitative probability changes related to the increased likelihood of a subsequent large earthquake.

A scenario similar to that leading up to the Tohoku earthquake plausibly could occur in the Cascadia region. Many of the scenarios mentioned in this report likely imply significant increases in the short-term probability of a damaging earthquake (for example, >100-percent increase in probability), but even the increased absolute probabilities remain very low (for example, <0.1-percent probability per day). How well can either the absolute probability or changes in probability be estimated? Some basis exists for estimating probability changes on the basis of foreshock activity. Reasenberg (1999) evaluated the foreshock probabilities for shallow subduction zones on the basis of earthquake catalogs (none from the Cascadia region) and estimated that the probability of a larger earthquake should generally increase significantly within 10 days and 75 km after an *M*>5 earthquake. However, experience with foreshock advisories in California indicates that longer-than-expected delays (that is, >10 days) may occur. No statistical techniques exist for estimating the probability changes associated with other forewarnings. Though instructive, the first published theoretical calculations of probability changes associated with ETS events in the Cascadia region (Mazzotti and Adams, 2004) are now recognized as oversimplified.

In short, establishing quantitative linkages between whatever is measured or calculated and earthquake occurrence remains a challenge in the Cascadia region. Even if we can identify extraordinary events, quantitative short-term forecasts will have huge uncertainties because they will be based on observations for which, by definition, no clear precedent exists. In some cases, only qualitative judgments may be possible. Nonetheless, more careful study of precedents set in other subduction zones globally, particularly those that have undergone damaging earthquakes, should reduce uncertainties in the Cascadia region. One useful outcome of this effort to plan for a response to forewarnings of damaging earthquakes will be for scientists and NEPEC to educate emergency managers and other emergency responders, policymakers, and the USGS Director about the certainty (or lack thereof) that can be ascribed to any forewarning scenario of a future earthquake. In turn these individuals will inform scientists about the certainty they would require before being notified or taking any action. Whatever the final products this process yields, both scientists and decision makers should benefit from the dialogues the process will require.

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