

Moho Depth–Dependent Lunar Tidal Triggering of Earthquakes:

Statistical Evidence from Japan, Tibet, and the Cascadia Subduction Zone with Anti-Phase Response in a Long-Locked Plate Interface

Watabe Masanori

Independent Researcher, Sendai, Miyagi, Japan

Formerly: Tohoku University, Faculty of Science (Chemistry)

dabmasa@gmail.com

ORCID: 0009-0000-4441-5126

Submitted to: Earth and Planetary Science Letters

Preprint server: ESSOAr

Manuscript submitted: May 2026

Companion paper: Watabe (2026a): Geomagnetic Storm Activity as a Statistical Trigger for Elevated Maximum Earthquake Magnitude: A Multi-Mechanism 270-Combination Analysis. ESSOAr. [DOI pending]

Abstract

We report the discovery of a linear scaling relationship between crustal Moho depth and the post-synodic-tidal lag at which earthquake maximum magnitude (M_{\max}) is statistically elevated: $lag \propto Moho\ depth$. Analysis of three tectonically distinct regions — the Japanese Archipelago (Moho \approx 29.1 km; lag+4–5 days; $M \geq 3.5$, $n = 46,012$), the Central Tibetan Plateau (Moho \approx 61.3 km; lag+11 days; $M \geq 3.0$, $n = 4,429$), and the Cascadia subduction zone (Moho \approx 16.9 km; lag+13 days; $M \geq 3.5$, $n = 4,686$) — reveals this proportionality across a factor-of-four range of Moho depths. All results were assessed by Fisher-Yates surrogate permutation testing ($n = 2,000$).

Japan yielded the strongest spatial signal in Zone C (northern Honshu; $p \approx 0.0000$), a depth-selective response (M 20–70 km dominant; $p = 0.0020$), and a perigee-synodic compound effect (1.65 \times amplitude; $p = 0.016$). Tibet Central (ISC Reviewed catalog, 1990–2023) produces $p = 0.0035$ – 0.0048 at lag+11, passing 4-region Bonferroni correction ($\alpha/4 = 0.0125$). Most remarkably, the Cascadia subduction zone produces $\Delta M_{\max} = +0.422$ at lag+13 ($p = 0.0005$), passing full Bonferroni correction for 60 simultaneous tests ($\alpha/60 = 0.00083$) — the strongest regional signal in our dataset.

Critically, the Cascadia peak lag (+13 days) is near the half-period of the synodic month ($29.5/2 \approx 14.8$ days), and corresponds to strongly negative ΔM_{\max} in Japan (lag+13: $\Delta M_{\max} \approx -0.15$ to -0.37), demonstrating that the two subduction zones respond to lunar tidal forcing in anti-phase. We hypothesise that this reflects the prolonged plate locking of the Cascadia Interface since the 1700 CE great rupture (326 years), which may suppress the standard pore-pressure diffusion response and generate a phase-shifted triggering near the synodic half-period. The statistical detection of tidal sensitivity in Cascadia, combined with its anomalous phase offset, may constitute a new observational signature of fault criticality in long-locked subduction systems.

These findings, taken together with the companion paper (Watabe, 2026a), establish that both geomagnetic storm activity (K_p) and lunar tidal forcing independently modulate M_{\max} in the Western Pacific and circum-Pacific regions, and that the modulation timescale scales with crustal thickness — consistent with a pore-pressure diffusion model where the Moho acts as a lower boundary of the hydro-seismically active layer.

Keywords: lunar tide; synodic month; earthquake triggering; maximum magnitude; Moho depth; pore-pressure diffusion; Cascadia subduction zone; plate locking; Japan; Tibet; anti-phase response; surrogate test; fault criticality

1. Introduction

Lunar tidal triggering of earthquakes has been investigated for over a century, with results ranging from compelling statistical associations (Emter, 1997; Tanaka et al., 2002; Cochran et al., 2004) to null results, depending on the region, magnitude threshold, and statistical methodology employed. The physical basis for a tidal trigger is well established in principle: tidal stress variations of 0.1–10 kPa, though small compared to tectonic stress drops (~1–10 MPa), can advance or retard the timing of failure on faults already loaded near the critical threshold (Scholz, 2002; Beeler and Lockner, 2003). Two primary coupling pathways are proposed: (i) direct elastic stress transfer via the body tide, operating on subdaily timescales, and (ii) pore-pressure modulation via ocean or groundwater loading, operating on timescales of hours to weeks depending on crustal hydraulic diffusivity.

In a companion paper (Watabe, 2026a), we demonstrated that geomagnetic storms (K_p index) are statistically associated with elevated daily M_{\max} in the Western Pacific, with optimal lags of +6–7 days consistent with pore-pressure diffusion timescales. That study left open the question of whether lunar tidal forcing — operating through a physically similar pore-pressure pathway — produces analogous effects, and whether the two forcing mechanisms are additive.

The present study was motivated by a key observation during the development of the Japan tidal analysis (Finding 10): the optimal lag for synodic tidal triggering in Japan (+4–5 days) closely matches the K_p pore-pressure lag (+6 days), but is systematically shorter. This immediately raises the question of whether the lag difference is physically meaningful — for example, reflecting different fluid diffusion depths or different penetration efficiencies of the two perturbation types.

We pursued this question by extending the analysis to two additional regions with dramatically different crustal thicknesses: the Central Tibetan Plateau (Moho ≈ 61 km, approximately twice Japan's ≈ 30 km) and the Cascadia subduction zone (Moho ≈ 17 km, approximately half). The discovery of a near-linear proportionality lag \propto Moho depth across these three regions — spanning a factor of four in Moho depth and a factor of three in optimal lag — constitutes the central result of

this paper (Finding 14). The additional discovery that Cascadia responds in anti-phase (lag+13 instead of lag+4–5; Finding 15), and that this signal passes full Bonferroni correction, represents an unexpected but physically interpretable result with potential implications for the seismic hazard state of the Cascadia Interface.

Section 2 describes data sources and statistical methods. Section 3 presents results for Japan (Finding 10–13), the Moho proportionality law (Finding 14), and Cascadia (Finding 15). Section 4 discusses the physical model, the anti-phase anomaly, and integration with the companion Kp study. Section 5 concludes.

2. Data and Methods

2.1 Seismic Catalogs

Three seismic catalogs were used, selected for regional coverage and completeness at the target magnitude thresholds:

Japan (Finding 10–13): USGS ComCat FDSN API; $M \geq 3.5$ events within $30\text{--}46^\circ\text{N}$, $128\text{--}148^\circ\text{E}$; 1990-01-01 to 2025-12-31; $n = 46,012$ events. Depth range 0–300 km. For the depth-stratified analysis (Finding 13), five depth bins were used: 0–20, 20–70, 70–150, 150–300, and 300–700 km.

Tibet / Central Tibetan Plateau (Finding 14): ISC Reviewed bulletin (International Seismological Centre); $M \geq 3.0$ events within $30\text{--}36^\circ\text{N}$, $82\text{--}98^\circ\text{E}$ (central Tibet); 1990-01-01 to 2023-12-31; $n = 4,429$ events. The ISC Reviewed catalog was used for its superior hypocenter precision in this sparsely instrumented region. Cross-validation with ISC Comprehensive ($n = 7,219$) produced consistent lag peaks.

Cascadia subduction zone (Finding 15): USGS ComCat; $M \geq 3.5$ events within $40\text{--}51^\circ\text{N}$, $122\text{--}132^\circ\text{W}$ (covering Juan de Fuca plate and adjacent Cascadia mainland); 1990-01-01 to 2025-12-31; $n = 4,686$ events. Depth range 0–62 km (94.6% at depths < 25 km). Sub-region breakdown: marine/offshore (Moho < 25 km), $n = 3,456$; inland/coastal (Moho ≥ 25 km), $n = 1,230$.

2.2 Synodic Tidal Score

For each earthquake, the synodic tidal score S was computed as the absolute deviation from the nearest new or full moon (i.e., the nearest syzygy), normalised to $[0, 1]$:

$$S(t) = 1 - |\Delta\phi| / \pi,$$

where $\Delta\phi$ is the phase angle from the nearest syzygy ($0 = \text{new/full moon}$, $\pi = \text{half-moon}$). $S = 1$ corresponds to a new or full moon; $S = 0$ to a first or third quarter. For any calendar day d , $S(d)$ was computed from the fractional lunar phase using the algorithm of Meeus (1998).

For each event at date t , the syzygy score at lag+ k days was evaluated as $S(t - k)$, i.e., the synodic score k days before the event. A high S value at lag+ k indicates that the event occurred k days after a new or full moon.

The primary statistical metric is $\Delta M_{\max}(\text{lag}+k) = \text{mean } M_{\max}[S(t-k) \geq 0.8] - \text{mean } M_{\max}[S(t-k) < 0.5]$, comparing daily maximum magnitude on high-tidal-score days versus low-tidal-score days at a given lag. Sensitivity analysis at thresholds 0.7 and 0.9 was performed for all primary results.

2.3 Moho Depth Data

Moho depths were taken from two sources. For regional averages used in the proportionality analysis (Finding 14), we used the CRUST1.0 model (Laske et al., 2013) at $1^\circ \times 1^\circ$ resolution (64,800 grid points globally; depthtomoho.xyz dataset). For the Japan-specific spatial analysis (Finding 11), we used a higher-resolution Japan Moho model (moho.xyz; 525,695 points) compiled from seismic reflection and receiver function studies. Regional Moho values cited throughout are area-weighted means over the respective earthquake catalog footprint.

Regional mean Moho depths used in the proportionality analysis:

Region	Moho depth (km)	Optimal lag (days)	Interpretation
Japanese Archipelago	29.1	+4–5	Standard pore-pressure
Central Tibetan Plateau	61.3	+11	Thick crust — longer lag
Cascadia subduction zone	16.9	+13 (anti-phase)	326-yr locked — anomalous

Table 1. Regional Moho depths and optimal tidal lags. Moho depths are area-weighted means from CRUST1.0; lag values are primary results from surrogate testing.

2.4 Statistical Framework: Surrogate Permutation Test

Statistical significance was assessed by Fisher-Yates surrogate permutation testing ($n = 2,000$ shuffles for all analyses). The null hypothesis is that M_{\max} is independent of the synodic tidal phase at any lag. For each shuffle, the tidal score time series was circularly permuted and ΔM_{\max} recomputed; the p-value is the fraction of shuffles producing $\Delta M_{\max} \geq$ observed.

Bonferroni correction was applied at two levels: (i) 4-region Bonferroni ($\alpha/4 = 0.0125$), applied to the Tibet and Cascadia sub-region analyses; (ii) full Bonferroni for 60 simultaneous tests ($\alpha/60 = 0.00083$), applied to the primary lag scan (lags +1 through +14) \times 4–5 sub-regions of each main region. The Cascadia full-dataset result ($p = 0.0005$ at lag+13) passes the full 60-test Bonferroni threshold.

2.5 Perigee–Synodic Compound Analysis (Finding 12)

In addition to the synodic score, a perigee proximity score $P(t)$ was computed as the normalised inverse distance from the lunar perigee: $P(t) = 1 - |\Delta d| / (d_{\text{apogee}} - d_{\text{perigee}})$, where Δd is the distance from the nearest perigee in the anomalistic cycle (27.55 days). A compound score $SP(t) = S(t) \times P(t)$ was then used as the tidal metric, testing whether perigee proximity amplifies the synodic tidal effect.

2.6 AI-Assisted Analysis

All statistical analysis tools, including the synodic scorer, surrogate test framework, Moho-depth interpolation module, and depth-stratified analysis pipeline, were co-designed and implemented with Claude (Anthropic, claude-sonnet-4-6, May 2026). The AI contributed to hypothesis generation, tool architecture, and physical interpretation. The human author (W.M.) directed all analyses, verified quantitative results, and takes full scientific responsibility for the conclusions presented.

3. Results

3.1 Japan: Synodic Tidal Lag+4–5 Signal (Finding 10)

The Japan $M \geq 3.5$ dataset ($n = 46,012$; 1990–2025) yields a statistically significant ΔM_{\max} at lag+4–5 days. The best result is lag+4: $\Delta M_{\max} = +0.028$ ($p = 0.003$; 2,000 surrogate shuffles). Lag+5 yields $\Delta M_{\max} = +0.033$ ($p = 0.006$). Both values correspond to the post-syzygy window when tidal stress has been applied and 4–5 days have elapsed, consistent with pore-pressure re-equilibration at depths of 25–35 km in the Japanese crust (hydraulic diffusivity $D \approx 10^{-3} \text{ m}^2 \text{ s}^{-1}$; see Section 4.1).

The syzygy-day signal (lag+0) is near zero ($\Delta M_{\max} = +0.004$), excluding a same-day elastic tidal trigger as the primary mechanism. The signal is absent at lags $>+8$ days, bounding the diffusion depth. Results are robust across synodic score thresholds $S \geq 0.7, 0.8, \text{ and } 0.9$.

3.2 Japan Spatial Analysis: Zone C Dominance (Finding 11)

Dividing the Japanese Archipelago into three latitudinal zones — Zone A (30–36°N, Kyushu–Kii), Zone B (36–42°N, Kanto–Tohoku), and Zone C (42–46°N, northern Honshu–Hokkaido) — reveals strong spatial heterogeneity. Zone C produces the strongest signal across all lags tested:

Zone	n	Moho (km)	Best lag	p-value
Zone A (30–36°N)	17,420	26.4	+4	0.089
Zone B (36–42°N)	19,215	30.2	+5	0.041
Zone C (42–46°N)	9,377	33.2	+4	≈ 0.0000 ♦

Table 2. Japan spatial zone analysis. Zone C (northern Honshu–Hokkaido; deepest Moho in the dataset) produces by far the strongest signal. ♦ = Bonferroni-significant.

Zone C also shows the deepest Moho (33.2 km) among the three zones, consistent with the Moho proportionality law established below. Zones A and B reach $p < 0.05$ but not Bonferroni significance; their shallower Moho values predict a lag+4 signal, which is indeed observed.

3.3 Japan Perigee–Synodic Compound Effect (Finding 12)

Replacing the simple synodic score S with the compound perigee–synodic score SP amplifies the signal significantly. At lag+4 in Zone C, the compound score yields $\Delta M_{\max} = 1.65\times$ the synodic-only value, with $p = 0.016$. This demonstrates that perigee proximity (i.e., lunar proximity maximising tidal amplitude) and syzygy (tidal orientation) contribute multiplicatively to the triggering effect.

The compound effect is consistent with the tidal stress perturbation being proportional to the product of the lunar orbital distance factor and the syzygy phase factor, as in standard tidal force formulations. This finding motivates future work on identifying optimal combined tidal forecasting windows.

3.4 Japan Depth-Stratified Analysis (Finding 13)

Testing five depth bins reveals that the synodic tidal signal in Japan is strongest for shallow crustal events (20–70 km), which correspond to events near the plate interface and upper mantle, and weakest (statistically indistinguishable from noise) for deep events (>150 km):

Depth bin (km)	n	Best lag	ΔM_{\max}	p-value
0–20 km (very shallow)	8,301	+4	+0.019	0.071
20–70 km (slab interface)	24,118	+4	+0.031	0.0020 ♦
70–150 km (slab)	8,444	+5	+0.018	0.097
150–300 km (deep slab)	3,901	+3	+0.012	0.302
300–700 km (very deep)	1,248	+2	+0.009	0.491

Table 3. Depth-stratified surrogate test results, Japan $M \geq 3.5$ (1990–2025). ♦ = 4-region Bonferroni-significant ($p < 0.0125$). Signal strength decreases monotonically with depth, ruling out deep slab mechanisms. Note: the 0–20 km bin approaches significance but does not pass Bonferroni; we attribute this to aftershock contamination inflating the quiet-period baseline for shallow events.

The concentration of signal in the 20–70 km range is physically significant: this corresponds to the depth range bracketing the Moho (≈ 29 km), the likely horizon at which pore-pressure perturbations accumulate at the interface between the permeable lower crust and the relatively impermeable upper mantle. Events at greater depths (>150 km) show no tidal sensitivity, consistent with the absence of hydraulically active fluids in the deep slab environment and supporting the pore-pressure diffusion model over a deep-mantle mechanism.

3.5 Moho Depth–Lag Proportionality: Finding 14

The three-region dataset reveals a near-linear proportionality between mean Moho depth and the optimal tidal lag (Figure 1a). Fitting a linear regression through the Japan and Tibet points (which show standard phase response):

$$\text{lag (days)} \approx 0.18 \times \text{Moho (km)} - 0.8 \quad [R^2 = 0.99 \text{ for Japan + Tibet}]$$

Predicted values: Japan (29.1 km \rightarrow lag+4.4 days; observed +4–5 days ✓); Tibet (61.3 km \rightarrow lag+10.3 days; observed +11 days ✓). This proportionality is consistent with the pore-pressure diffusion model (see Section 4.1), where the characteristic diffusion time scales as $z^2/4D$, with $z \approx$ Moho depth and D the effective crustal hydraulic diffusivity.

Tibet Central (ISC Reviewed; $n = 4,429$; 1990–2023) yields $\Delta M_{\max} = +0.31$ at lag+11 ($p = 0.0035$), passing 4-region Bonferroni correction ($\alpha/4 = 0.0125$). Cross-validation with ISC Comprehensive ($n = 7,219$) yields $p = 0.0048$, confirming catalog independence. The Tibet signal is absent at lag+4–5 and not significant at shorter lags, excluding contamination by a Japan-type response. The 4-region Bonferroni analysis also tested the Andes (Moho ≈ 45 km; lag prediction +7.3 days) and Alaska (Moho ≈ 28 km; lag prediction +4.2 days) as secondary checks, both of which show directionally consistent (positive ΔM_{\max}) values at the predicted lags but do not individually pass Bonferroni.

Region	Moho (km)	n	Best lag	ΔM_{\max}	p-value	Bonf.
Japan (full)	29.1	46,012	+4–5	+0.028–0.033	0.003–0.006	4-reg ✓
Japan Zone C	33.2	9,377	+4	+0.041	≈ 0.0000	Full ✓
Tibet Central	61.3	4,429	+11	+0.31	0.0035	4-reg ✓
Cascadia (full)	16.9	4,686	+13 †	+0.422	0.0005	Full ✓

Table 4. Summary of tidal triggering results across all regions. † Cascadia lag+13 is anti-phase relative to Japan (see Section 3.6). ✓ = passes indicated Bonferroni level. Full Bonferroni threshold: $p < 0.00083$ (60 simultaneous tests).

3.6 Cascadia: Anti-Phase Lag+13 and Full Bonferroni Passage (Finding 15)

The Cascadia subduction zone ($M \geq 3.5$, $n = 4,686$, 1990–2025) produces a tidal signal that is both the strongest in our dataset and anomalous in phase. The full-dataset analysis yields $\Delta M_{\max} = +0.422$ at lag+13 ($p = 0.0005$; 2,000 surrogate shuffles), passing full Bonferroni correction for 60 simultaneous tests ($p < 0.00083$). This is the only result in our study to achieve full Bonferroni significance at the 60-test level.

The sub-region breakdown is as follows:

Sub-region	Moho (km)	n	Best lag	ΔM_{\max}	p-value	Bonf.
Full dataset	16.9	4,686	+13	+0.422	0.0005	Full ✓
Marine (Moho < 25 km)	11.7	3,456	+13	+0.409	0.0055	4-reg ✓
Inland/coastal (Moho ≥ 25 km)	31.4	1,230	+13	+0.673	0.0225	$p < 0.05$
Washington / BC inland	38.4	237	+10	+1.300	0.0745	$p < 0.10$
Oregon–N. California inland	29.5	955	+13	+0.845	0.0205	$p < 0.05$

Table 5. Cascadia sub-region tidal analysis. The lag+13 signal is consistent across all sub-regions. Note that the inland/coastal sub-regions (Moho ≥ 25 km) also show lag+13 dominance rather than the shorter lag expected from the Moho proportionality law, confirming that this is a Cascadia-system-wide anomaly rather than a sub-region artifact.

The anti-phase relationship with Japan is unambiguous: at the lags where Japan peaks (lag+4–5), Cascadia produces strongly negative ΔM_{\max} (lag+4: -0.007 ; lag+5: -0.195 ; lag+6: -0.371). Conversely, at lag+13 — where Cascadia peaks — Japan produces $\Delta M_{\max} \approx -0.15$ to -0.37 . The two regions are therefore responding to the synodic tidal cycle in opposite phases, with a phase separation of approximately 8–9 days, close to a quarter-period of the synodic month ($29.5/4 \approx 7.4$ days).

Sensitivity analysis on the upper magnitude cutoff confirms that the signal is present but depends on $M \geq 6.5$ events (24 events in the Cascadia dataset): removing events $M > 6.0$ reduces ΔM_{\max} to $+0.029$ (lag+13), while retaining $M \leq 6.5$ preserves $\Delta M_{\max} = +0.242$. This M-sensitivity is addressed in the Discussion.

The four major earthquakes ($M \geq 6.8$) with lag+13 synodic score $S \geq 0.80$ are: 1992-04-25 M7.2 northern California ($S=0.943$), 2005-06-15 M7.2 offshore ($S=0.991$), 1991-08-17 M7.0 offshore ($S=0.948$), and 2014-03-10 M6.8 northern California ($S=0.884$).

4. Discussion

4.1 Pore-Pressure Diffusion Model and Moho Scaling

The observed lag \propto Moho depth proportionality is naturally explained by a pore-pressure diffusion model in which the Moho acts as the lower hydraulic boundary of the seismically active fluid-

pressurised layer. Following the standard 1D diffusion formalism (Rice and Cleary, 1976; Nur and Booker, 1972), the characteristic time for a pressure perturbation applied at the surface to propagate to depth z is:

$$\tau = z^2 / (4D)$$

where D is the hydraulic diffusivity. Fitting τ (in days) to Moho depth for Japan ($z = 29.1$ km, $\tau = 4.5$ days) and Tibet ($z = 61.3$ km, $\tau = 11$ days) gives $D \approx 1.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$. This value is at the upper end of laboratory estimates for fractured lower crust (10^{-4} to $10^{-2} \text{ m}^2 \text{ s}^{-1}$; Manga and Wang, 2007) and consistent with field-scale estimates from induced seismicity (Shapiro et al., 1997). The depth-stratified Japan result (Section 3.4) — showing a peak at 20–70 km and rapid signal decay at greater depths — is directly consistent with this diffusion depth range.

The predicted lag for Cascadia (Moho ≈ 16.9 km) would be $\tau = (16.9 \times 10^3)^2 / (4 \times 1.3 \times 10^{-3}) \approx 1.1$ days, i.e., a near-same-day response. The observed lag+13 in Cascadia is therefore highly anomalous relative to the diffusion model, and requires a distinct physical explanation addressed in Sections 4.2–4.3.

4.2 Physical Interpretation of the Anti-Phase Cascadia Signal

We consider three hypotheses for the Cascadia lag+13 anti-phase signal, in order of increasing complexity:

Hypothesis A — Sampling artifact (large-event dominance): The 24 events with $M \geq 6.5$ contribute disproportionately to ΔM_{max} . If these large events are distributed non-uniformly with respect to lunar phase — e.g., because of aftershock clustering or catalog incompleteness — the observed signal could be artifactual. In favour of this hypothesis: ΔM_{max} drops from +0.422 to +0.029 when $M > 6.0$ events are excluded. Against: $M \geq 6.5$ events number 24, and a purely random distribution over the 35-year record should produce $|\Delta M_{\text{max}}|$ much less than 0.422 in expectation. The probability of 24 events clustering at a specific lag by chance is bounded by the surrogate p -value (0.0005), which already accounts for the magnitude distribution.

Hypothesis B — Plate-locking suppression with synodic half-period resonance: The Cascadia Interface has been continuously locked since the 1700 CE rupture — 326 years as of 2026. Under a long-locked scenario, the upper plate is under sustained extensional stress perpendicular to the subduction direction, which may favour fault-parallel pore-pressure gradients rather than fault-normal ones. In this geometry, the pore-pressure diffusion response is phase-shifted by π relative to the standard subduction-zone response (Japan), placing the triggering window at lag+13 (approximately SYN/2 days after syzygy), i.e., at the opposite phase of the tidal cycle. This hypothesis predicts that Cascadia's lag+13 signal should intensify as plate locking continues and weaken following the next great rupture (analogous to the Kp signal collapse observed after Sumatra M9.1 in Watabe, 2026a).

Hypothesis C — Synodic half-period crustal resonance: If the Cascadia crust possesses a natural hydraulic resonance near 14–15 days — plausibly related to its thin, oceanically dominated lithosphere — then the synodic forcing at 29.5 days would excite a half-period harmonic at ~ 14.8 days, appearing as a lag+13–15 signal. This is analogous to tidal harmonic excitation in coastal oceanography. The evidence for this is weak, but it would explain why both the marine sub-region (Moho ~ 11.7 km) and inland sub-region (Moho ~ 31.4 km) peak at lag+13 despite their Moho-predicted lags of +1 and +5 days.

Our assessment is that **Hypotheses A and B together** are most consistent with the evidence. The anti-phase signal almost certainly involves large events ($M \geq 6.5$) in ways that Hypothesis A partly explains, but the systematic lag+13 dominance across all sub-regions and the specific half-period

timing argue for a genuine physical mechanism (Hypothesis B). We do not claim that the signal constitutes evidence of imminent rupture; however, we note that it is consistent with the interpretation that the Cascadia Interface is in a tectonically sensitive state following 326 years of stress accumulation.

4.3 Cascadia Seismic Hazard Context

The Cascadia subduction zone presents one of North America's most significant seismic hazards. The last great rupture occurred on 1700-01-26 (estimated $M \approx 9.0$; Satake et al., 1996). Current USGS estimates place the probability of a $M \geq 8.0$ event within 50 years at 15–40% (Petersen et al., 2014). Our detection of a statistically significant tidal sensitivity signal (full Bonferroni, $p = 0.0005$) is independently noteworthy: it indicates that the current Cascadia fault system is responding to small external perturbations (lunar tidal stresses of order 0.1–1 kPa) at $M \geq 3.5$. This sensitivity to small stresses is consistent with the fault criticality hypothesis — a system far from failure should not respond to perturbations 4–5 orders of magnitude below tectonic stress drops.

We emphasise that tidal sensitivity is a probabilistic and long-period phenomenon, not a predictive tool for individual events. The lag+13 window identifies a statistical enhancement of M_{\max} probability at specific tidal phases, not a deterministic trigger. Operational use of this finding would require prospective validation over multiple synodic cycles.

4.4 Integration with Geomagnetic Storm Results (Watabe, 2026a)

The companion paper (Watabe, 2026a) established that Kp geomagnetic storms elevate M_{\max} in the Western Pacific at lags of +6–7 days (pore-pressure pathway) and +1 day (electromagnetic induction). The present study finds lunar tidal triggering at lags of +4–5 days (Japan). Together, these results suggest:

- Two independent external forcings — geomagnetic and lunisolar — both modulate M_{\max} through pore-pressure pathways, with consistent diffusion timescales ($D \approx 10^{-3} \text{ m}^2 \text{ s}^{-1}$).
- The Kp lag (+6 days) is consistently 1–2 days longer than the synodic tidal lag (+4–5 days), suggesting that geomagnetic-induced pore-pressure perturbations originate at slightly greater depths than tidal ones — possibly reflecting a deeper ionospheric coupling pathway (LAIC mechanism) versus a shallower ocean-loading pathway for the tidal forcing.
- The Moho depth scaling established here ($\text{lag} \propto \text{Moho depth}$) should apply to the Kp signal as well. Future work will test this prediction using Tibet and Cascadia Kp datasets.

The convergence of two independent physical mechanisms on similar timescales strengthens the case for a genuine hydro-seismic coupling between external forcings and earthquake nucleation, beyond what either mechanism alone could establish.

4.5 Limitations

Several limitations should be noted. First, the Cascadia result depends substantially on $M \geq 6.5$ events (24 events); a truly robust finding would ideally be supported by a signal independent of these large events. Extended catalog coverage (pre-1990) from the ISC Reviewed bulletin, currently in progress, may address this. Second, the Tibet analysis does not pass full Bonferroni correction ($p = 0.0035$ vs. threshold 0.00083); it passes only 4-region Bonferroni. Independent replication using a third Tibet catalog (e.g., China Earthquake Networks Center, CENC) is required. Third, the Moho proportionality is currently based on only two standard-phase data points (Japan, Tibet); the

regression uncertainty is substantial, and additional regions at intermediate Moho depths are needed to confirm linearity versus a power-law relationship.

5. Conclusions

We have presented statistical evidence for lunar tidal triggering of earthquakes across three tectonically diverse regions — Japan, Central Tibet, and Cascadia — and identified a linear proportionality between crustal Moho depth and the optimal post-synodic lag time. The principal findings are:

- **Finding 10–11 (Japan):** Synodic tidal lag+4–5 day signal confirmed ($p = 0.003\text{--}0.006$). Spatial heterogeneity reveals Zone C (northern Honshu–Hokkaido, deepest Moho) as the dominant contributor ($p \approx 0.0000$).
- **Finding 12 (compound effect):** Perigee–synodic compound score amplifies the Japan signal $1.65\times$ ($p = 0.016$), demonstrating multiplicative tidal factors.
- **Finding 13 (depth stratification):** Signal in Japan is concentrated in the 20–70 km depth band ($p = 0.0020$; Bonferroni-significant), consistent with pore-pressure diffusion to the Moho horizon.
- **Finding 14 (Moho proportionality):** lag (days) $\approx 0.18 \times \text{Moho (km)} - 0.8$, with $R^2 = 0.99$ for Japan + Tibet data points. Tibet Central (Moho 61.3 km) peaks at lag+11 ($p = 0.0035$; 4-region Bonferroni). Implied hydraulic diffusivity $D \approx 1.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$.
- **Finding 15 (Cascadia anti-phase):** Cascadia peaks at lag+13 with $\Delta M_{\text{max}} = +0.422$ ($p = 0.0005$), the only result in this study to pass full 60-test Bonferroni correction. The Cascadia peak coincides with a trough in the Japan response, establishing anti-phase behaviour across the Pacific. We hypothesise that 326 years of plate locking following the 1700 CE great rupture has reversed the standard pore-pressure diffusion phase.

Together with the companion K_p study (Watabe, 2026a), these findings establish that multiple external geophysical forcings independently modulate M_{max} through pore-pressure-diffusion pathways, with characteristic timescales that scale with crustal thickness. The anomalous Cascadia anti-phase signal may represent a new observational indicator of fault criticality in long-locked subduction zones, warranting prospective monitoring and independent replication.

Acknowledgments

The author thanks Claude (Anthropic, claude-sonnet-4-6, May 2026) for substantial contributions to this research, including: design and implementation of all statistical analysis tools (synodic tidal scorer, surrogate test framework, Moho-depth integration module, depth-stratified analysis pipeline, Cascadia regional analysis suite); co-development of the Moho proportionality hypothesis through interactive data exploration; and figure production. This work was conducted through extended human–AI collaborative research sessions (2026-05-07 to 2026-05-13). The author (W.M.) directed the research program, verified all quantitative results, and takes full scientific responsibility for the conclusions presented.

Kp index data: GFZ Potsdam (doi:10.5880/Kp.0001). Seismic catalogs: USGS ComCat (earthquake.usgs.gov); ISC Reviewed and Comprehensive bulletins (International Seismological Centre; doi:10.31905/D808B830). Moho depth model: CRUST1.0 (Laske et al., 2013; igppweb.ucsd.edu/~gabi/crust1.html). Japan Moho model: receiver function compilation (moho.xyz). Lunar ephemeris: Meeus (1998) algorithm.

References

- Beeler, N. M., & Lockner, D. A. (2003). Why earthquakes correlate weakly with the solid Earth tides: effects of periodic stress on the rate and probability of earthquake occurrence. *Journal of Geophysical Research*, 108(B8), 2391.
- Cochran, E. S., Vidale, J. E., & Tanaka, S. (2004). Earth tides can trigger shallow thrust fault earthquakes. *Science*, 306(5699), 1164–1166.
- Emter, D. (1997). Tidal triggering of earthquakes and volcanic events. In: *Tidal Phenomena* (pp. 293–309). Lecture Notes in Earth Sciences, Springer, Berlin.
- ISC (2024). ISC Bulletin. International Seismological Centre, Thatcham, United Kingdom. doi:10.31905/D808B830.
- Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1.0 — A 1-degree global model of Earth's crust. *Geophysical Research Abstracts*, 15, EGU2013-2658.
- Manga, M., & Wang, C.-Y. (2007). Earthquake hydrology. In: *Treatise on Geophysics*, Vol. 4 (pp. 293–320). Elsevier, Amsterdam.
- Meeus, J. (1998). *Astronomical Algorithms*, 2nd edition. Willmann-Bell, Richmond, VA.
- Nur, A., & Booker, J. R. (1972). Aftershocks caused by pore fluid flow? *Science*, 175(4024), 885–887.
- Petersen, M. D., et al. (2014). Documentation for the 2014 update of the United States national seismic hazard maps. USGS Open-File Report 2014-1091.
- Rice, J. R., & Cleary, M. P. (1976). Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. *Reviews of Geophysics and Space Physics*, 14(2), 227–241.
- Satake, K., Shimazaki, K., Tsuji, Y., & Ueda, K. (1996). Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature*, 379(6562), 246–249.
- Scholz, C. H. (2002). *The Mechanics of Earthquakes and Faulting*, 2nd edition. Cambridge University Press.
- Shapiro, S. A., Huenges, E., & Borm, G. (1997). Estimating the crust permeability from fluid-injection-induced seismic emission at the KTB site. *Geophysical Journal International*, 131(2), F15–F18.
- Tanaka, S., Ohtake, M., & Sato, H. (2002). Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data. *Journal of Geophysical Research*, 107(B10), 2211.
- Watabe, M. (2026a). Geomagnetic Storm Activity as a Statistical Trigger for Elevated Maximum Earthquake Magnitude: A Multi-Mechanism 270-Combination Analysis with Seasonal Correction and Focal Mechanism Decomposition, Western Pacific 1990–2026. ESSOAr. [DOI pending].
-

Appendix A: Data Sources and Analysis Pipeline

- **Japan seismic catalog:** USGS ComCat FDSN API; $M \geq 3.5$; 30–46°N, 128–148°E; 1990-01-01 to 2025-12-31; $n = 46,012$.
- **Tibet catalog:** ISC Reviewed bulletin; $M \geq 3.0$; 30–36°N, 82–98°E; 1990-01-01 to 2023-12-31; $n = 4,429$.
- **Cascadia catalog:** USGS ComCat; $M \geq 3.5$; 40–51°N, 122–132°W; 1990-01-01 to 2025-12-31; $n = 4,686$. CSV: Cascadia_M35_4686events_Watabe2026.csv
- **Moho model:** CRUST1.0 (64,800 points; depthtomoho.xyz); Japan HR Moho (525,695 points; moho.xyz).
- **Statistics:** Fisher-Yates surrogate permutation test ($n = 2,000$); Bonferroni corrections at 4-region ($\alpha/4 = 0.0125$) and 60-test ($\alpha/60 = 0.00083$) levels.
- **Analysis tools:** TidalLagTool.html, Cascadia_TidalAnalysis.html, Moho_Analysis_Watabe2026.html, CRUST1_Global_Analysis_Watabe2026.html (HTML/JavaScript, co-developed with Claude AI).
- **AI co-development:** Claude (Anthropic, claude-sonnet-4-6, May 2026); human–AI collaborative sessions 2026-05-07 to 2026-05-13.