What are ground-motion simulations missing?

Validation-based insights into systematic site effects, sedimentary basins, and crustal tomography in New Zealand

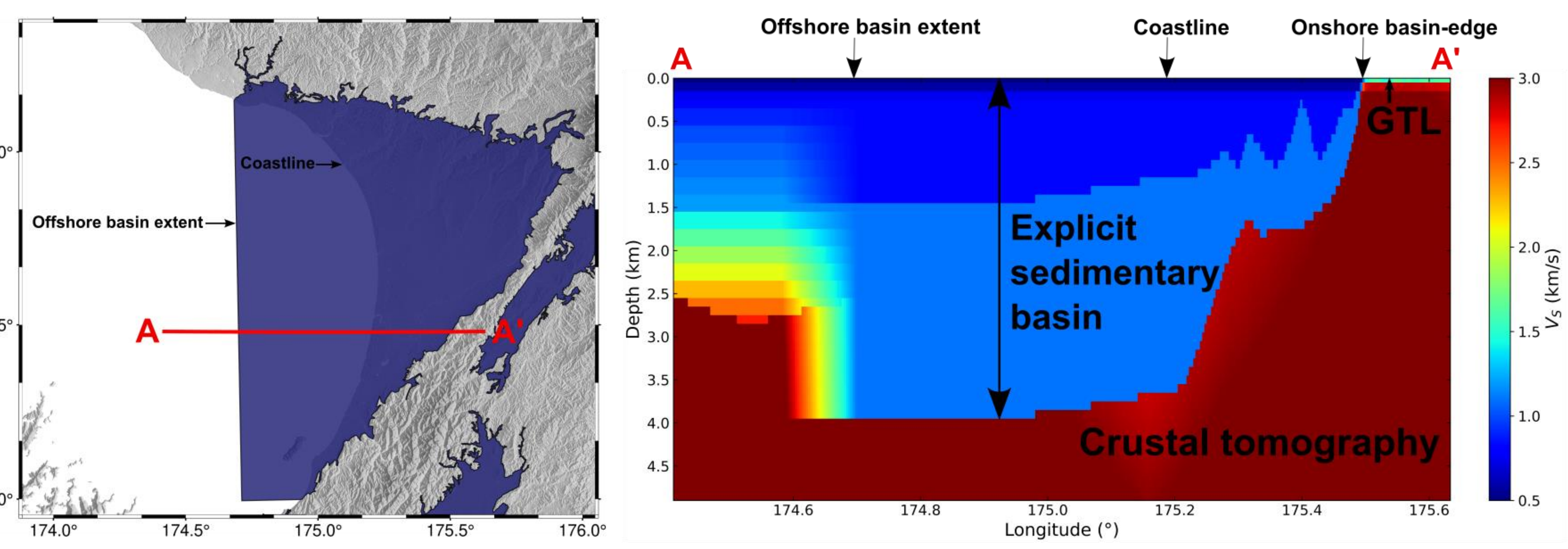
Ayushi Tiwari, Brendon A. Bradley, Robin L. Lee, Felipe Kuncar, Christopher A. de la Torre, Jake Faulkner, Cesar Pajaro Miranda

Civil and Environmental Engineering, University of Canterbury | Contact: ayushi.tiwari@pg.canterbury.ac.nz

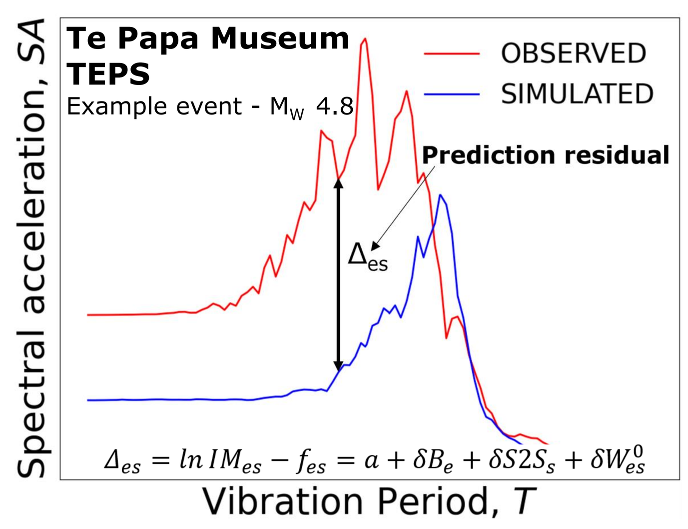
1. RESEARCH OVERVIEW

Ground-motion simulations estimate shaking from past and potential future earthquakes and are increasingly used for seismic hazard assessment. In the hybrid broadband approach, 3D wave propagation through the New Zealand Velocity Model (NZVM) provides the low-frequency component ($f \leq 1$ Hz), which is combined with stochastic high-frequency motions. Validation against recordings reveals systematic prediction bias and repeatable site effects, guiding empirical adjustments and physical improvements to the velocity model. **Figure 1** summarizes the NZVM components and residual-based validation framework.

(A) NZVM components: Palmerston North example



(B) Observations vs. simulations (C) Systematic site residuals



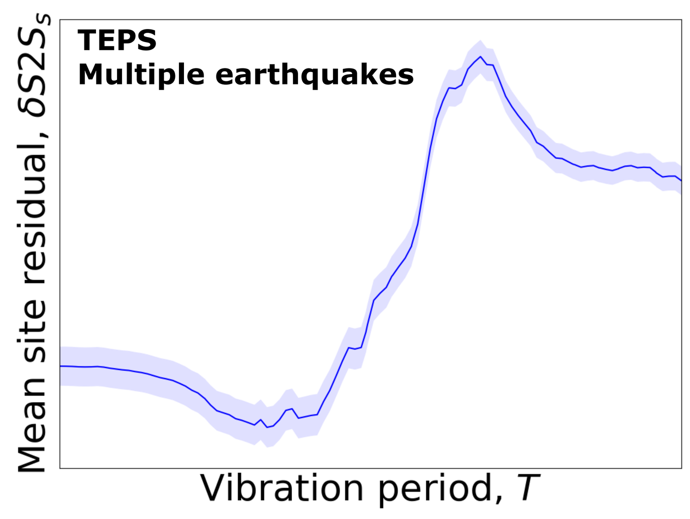


Figure 1. NZVM components and residual-based simulation validation: (A) crustal tomography, an explicit sedimentary basin, and the geotechnical layer (GTL) near Palmerston North; (B) observation-simulation prediction residual; and (C) repeatable site-to-site residual estimated from multiple earthquakes.

Research Questions

1. **Examine systematic site effects:** Where do simulations systematically mispredict site response, and can the missing effects be empirically corrected?
2. **Improve basin representation:** Do explicit basin models outperform a $V_{S,30}$-based GTL, and what controls the improvement?
3. **Evaluate crustal tomography:** How does tomography affect predictions, and do recent model refinements improve performance?

2. NATIONWIDE MODELS AND VALIDATION DATA

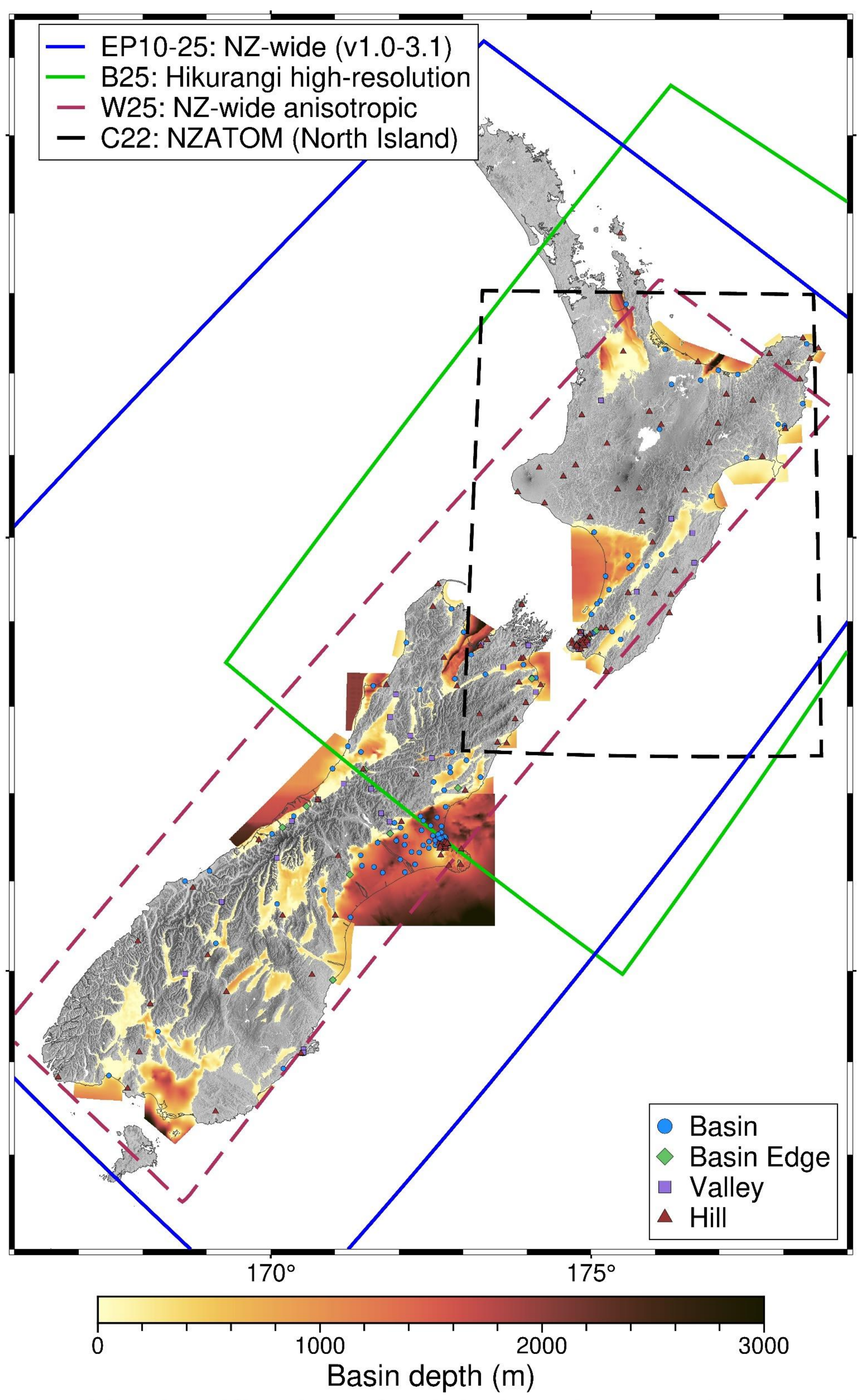


Figure 2. Nationwide classification of validation sites, modeled sedimentary-basin depths, and crustal tomography domains considered in this research.

3. VALIDATION RESULTS

3.1 Systematic site effects: Diagnosis and empirical adjustment

The validation dataset comprised 479 earthquakes and 212 sites. We classified the sites as Basin, Basin Edge, Valley, or Hill (**Figure 2**), then combined this geomorphic classification with NZVM basin coverage to distinguish modeled and unmodeled basin sites. Hill/Non-Basin sites exhibit the greatest variability at short periods, whereas Unmodeled Basin sites dominate at moderate-to-long periods (**Figure 3A**). Their residuals relate to relative elevation (H_{1250}) and fundamental site period (T_0), respectively; we used these relationships to develop the empirical adjustments shown in **Figure 3B**.

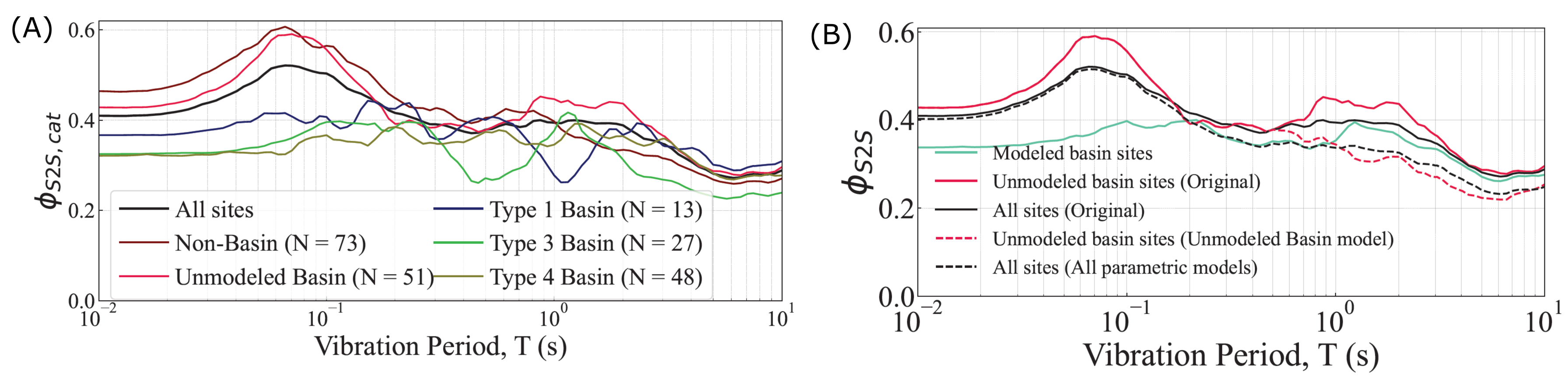


Figure 3. Site-to-site variability: (A) category-specific $\varphi_{S2S,cat}$; and (B) original and empirically adjusted φ_{S2S} for Unmodeled Basin sites and all sites.

3.2 Sedimentary basin models: Development and validation

We developed **37 new** sedimentary basin models and refined existing NZVM v2.02 basins, producing **45** explicit basin models in NZVM v2.09 (**Figure 2**). Validation used 73 earthquakes recorded at 300 sites. The new basin models were constructed primarily from widely available regional geology, geological cross-sections, and topography, providing a consistent first-order representation of nearly all major sedimentary-basin regions across New Zealand. Validation against the conventional $V_{S,30}$-based GTL shows that explicit basin representation improves predictions primarily at intermediate-to-long periods and low frequencies (**Figure 4A**). The improvement increases with modeled sediment depth, $Z_{1.0,sim}$, and shifts to longer periods for deeper basins, consistent with basin-specific resonance (**Figure 4B**). Shallow/narrow structures show limited change, likely because they are poorly resolved by the 100 m grid.

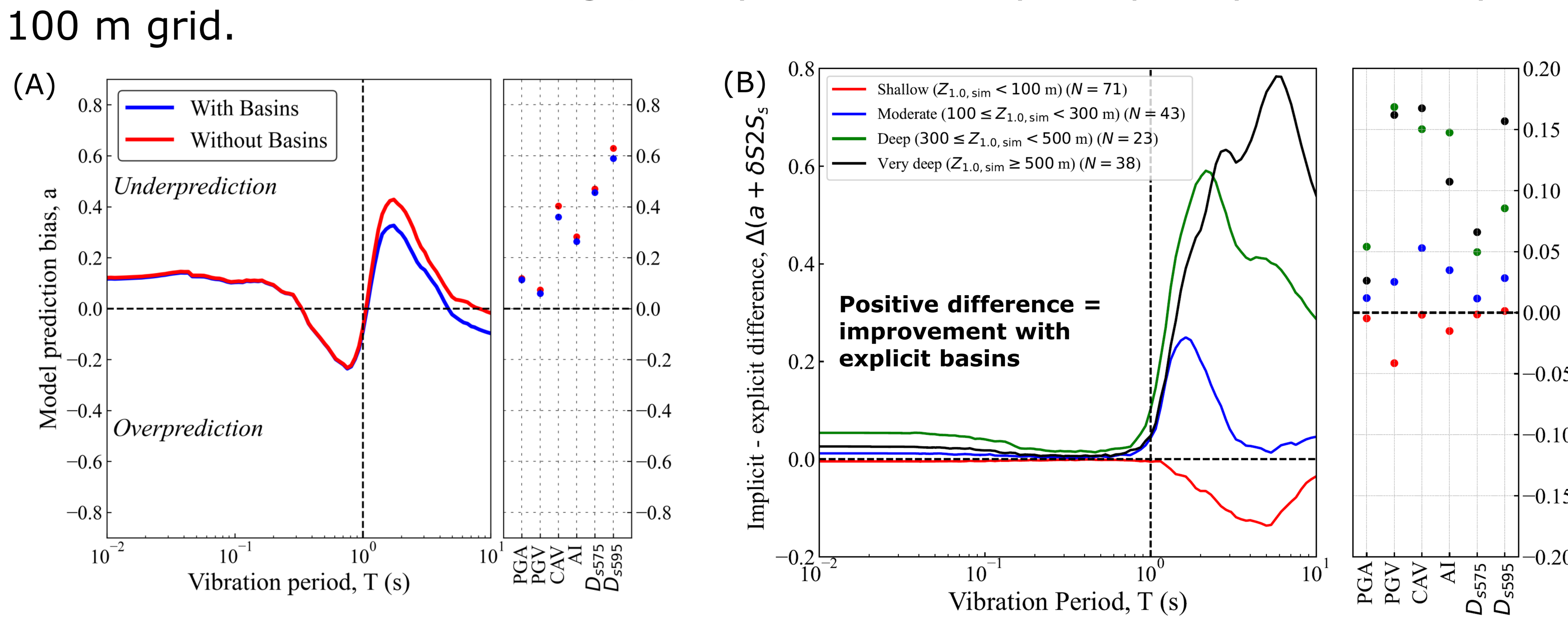


Figure 4. (A) Prediction bias with and without explicit basins; (B) implicit-minus-explicit site residuals grouped by modeled sediment depth, $Z_{1.0,sim}$.

3.3 Crustal tomography models: Comparative validation

We implemented **six** crustal tomography models with different spatial extents, resolutions, datasets, and inversion methods within the NZVM framework (**Figure 2**). Validation used low-frequency simulations for 28 earthquakes at 137 sites. Their shared short-period bias indicates causes beyond tomography choice. Relative to EP25, B25 and W25 reduce mean bias; W25 gives the largest reduction but the highest φ_{S2S}, consistent with regional cancellation around Wellington. B25 offers the best balance, while C22 changes amplitude predictions little (**Figure 5**).

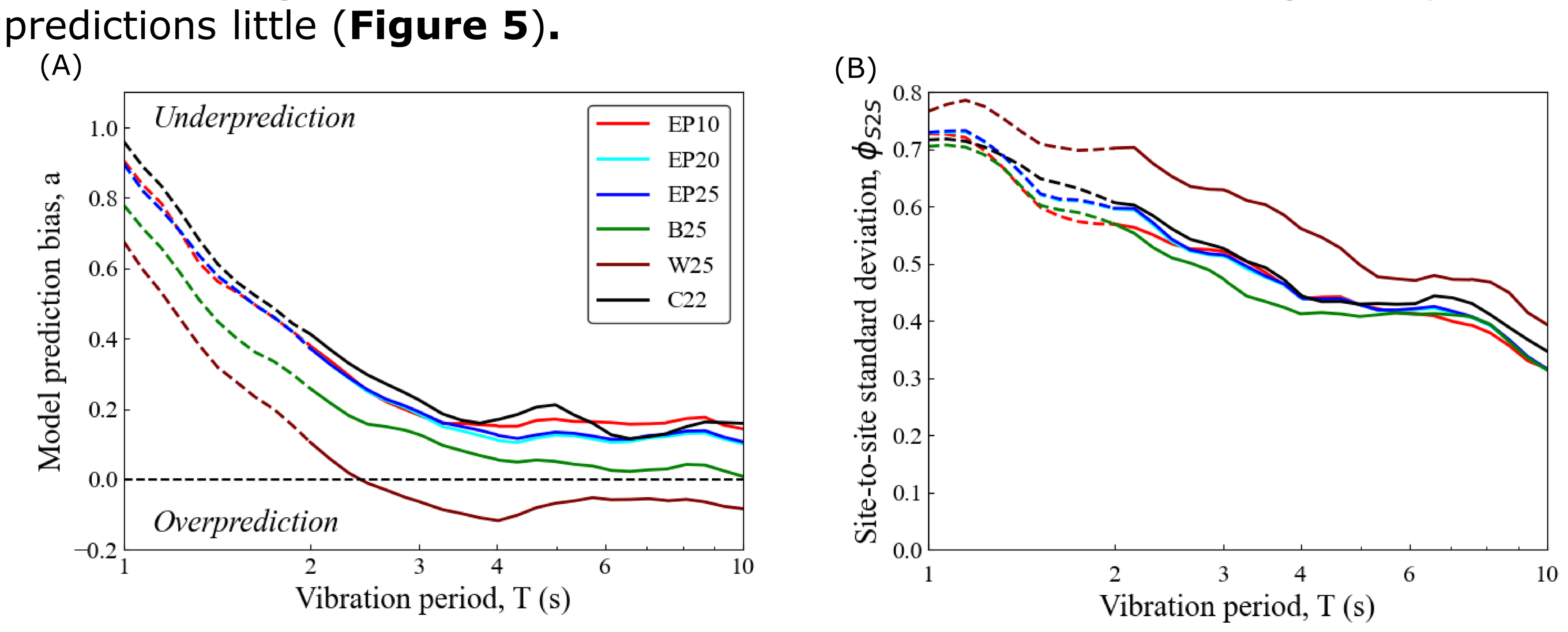


Figure 5. Prediction bias and φ_{S2S} across SA periods for six tomography models; dashed segments denote lower-confidence results at T< 2 s.

4. KEY CONCLUSIONS

1. **Systematic site effects:** Empirical adjustments reduced $\varphi_{S2S,cat}$ by *7–17%* at Hill sites, *12–29%* at Unmodeled Basin sites, and overall φ_{S2S} by *9–16%*.
2. **Sedimentary basin representation:** *37* new models and refinements to existing basins produced *45* explicit basin models in NZVM v2.09. Relative to the $V_{S,30}$-based GTL, explicit basins reduced bias by up to *11%* (SA) and *25%* (EAS), and φ_{S2S} by up to *18%* (SA) and *22%* (EAS).
3. **Crustal tomography:** Refinement does not guarantee better predictions; W25 *minimizes* bias but *increases* variability, whereas B25 provides the *best* bias-variability balance.