Comments and Replies

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Reply to "Comment on 'Multievent Explosive Seismic Source for the 2022 M_w 6.3 Hunga Tonga Submarine Volcanic Eruption' by Julien Thurin, Carl Tape, and Ryan Modrak" by Fred F. Pollitz, Ricardo Garza-Giron, and Thorne Lay

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The comment by Pollitz *et al.* (2023) points out the previously (July 2020) documented error in the Green's functions available from the Incorporated Research Institutions for Seismology Data Management Center and which are provided via Syngine (Krischer *et al.*, 2017), assembled by Instaseis (van Driel *et al.*, 2015), and computed within AxiSEM simulations. The error is that the radial-component synthetic seismograms generated by a point-force source are erroneously flipped in sign. This error was brought to our attention shortly after the publication of Thurin *et al.* (2022), and we have published a correction in Thurin *et al.* (2023), including revisions to the two figures in the supplemental material of Thurin *et al.* (2022, their figs. S12, S13) that were impacted.

Pollitz *et al.* (2023) reiterates and reinforces the results of Garza-Girón *et al.* (2023), who demonstrated the viability of a downward force source to model the seismic waveforms of the 2022 Hunga Tonga–Hunga Ha'apai (HTHH) eruption. Invoking the two-part force plus implosion model of Kanamori *et al.* (1984, their appendix A), they also considered an implosion moment tensor source at 5 km depth (fig. S5). Their main results (figs. 3–6) were only based on the downward force.

In Thurin and Tape (2023), we performed a set of 17 inversions to estimate the best-fitting force or moment tensor for the main subevent of the HTHH seismic signal, considering different source models (force or moment tensor), wave types (P waves, surface waves), seismogram components (vertical, radial, and transverse), and depth. We also examined forward models for eight chosen sources. The results show that the best-fitting force is in the downward direction and provides comparable waveform fits to the best-fitting moment tensor of Thurin *et al.* (2022).

The approaches of Garza-Girón *et al.* (2023) and Thurin *et al.* (2022) have illuminating similarities and differences that we attempt to convey here within the context of a parameter estimation problem. Both studies examine similar waveforms—regional surface waves and teleseismic P waves—and assume a layered Earth model for synthetic seismograms. At this stage, the studies diverge in their approaches. Garza-Girón *et al.* (2023) reason that the volcanic eruption is evident, and that a downward reaction force—acting on the surface—is a natural model to assume for the source of the seismic signal. Meanwhile, Thurin *et al.* (2022) consider a force or moment tensor as the source model, establishes a waveform-based misfit function, and then pursues an exploration of model parameter space to find the best-fitting source model.

Garza-Girón *et al.* (2023) assumes a downward force and fixed depth, inferring that the observed transverse components plotted in figure 1 of Pollitz *et al.* (2023) were most likely not Love waves: "The Love wave observations can be accounted for by up to 30° deflection of the point force from vertical, directed toward the WNW; but the dominant period range of the observations is from 10 to 50 s, so deflections from the great circle path and similarity of the group velocities for these periods may cause contamination of the putative transverse components." Pollitz *et al.* (2023) emphasize the overall axisymmetric nature of the recorded wavefield, pointing out that "small

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deviations from perfect axisymmetry such as a nonvertical point force or a tilted ellipsoidal pressure reduction can include horizontal forcing, as in the moment tensor solution of Thurin *et al.* (2022).”

The proper approach to document the source effect on the transverse component is to perform a parameter estimation problem that thoroughly explores model parameter space for an assumed representation of a source model (e.g., force or moment tensor) and Earth structure (e.g., layered Earth or 3D Earth). In the case of the force source for a fixed depth, only three model parameters are needed to specify the force’s amplitude and direction. A direct grid search can be used to examine how the waveform misfit function varies in model parameter space (e.g., Run SF8 of Thurin and Tape, 2023). And, at that point, one might be cautious about overfitting the data in light of known approximations in the forward model (i.e., layered Earth structure) and then choose a vertical force based on eruption considerations, with only the amplitude as a free parameter. In the case of the moment tensor and variable depth, seven parameters can still be thoroughly explored using a grid search (e.g., fig. 4 of Thurin *et al.*, 2022).

Garza-Girón *et al.* (2023) and Pollitz *et al.* (2023) are guided by careful data exploration and awareness of wave propagation and source effects, and they take a holistic approach by considering physical processes and products of the eruption. Our approach emphasizes parameter estimation and allows for a broader range of possibilities, notably every force direction, every moment tensor, and greater depths.

In light of the seismic results and interpretations (Thurin *et al.*, 2022; Garza-Girón *et al.*, 2023; Thurin and Tape, 2023; Pollitz *et al.*, 2023), we pose one question for consideration: which of these HTHH seismic signals originated from the events that formed the plume or crater? There remains ambiguity on the timing of events and links among different data sets (Purkis *et al.*, 2023). For example, the plume already had a radius of 38 km and height of at least 20 km at 04:15:17 (Carr *et al.*, 2022; Proud *et al.*, 2022)—the origin time of the main seismic subevent (S1 in Thurin *et al.*, 2022).

Our approach is admittedly narrow in its focus on parameter estimation. But even within that realm, there are major opportunities. Tomographic models of the Earth’s subsurface will constantly improve with time, as data coverage improves. Our source estimation code enables 3D Green’s functions (e.g., Liu *et al.*, 2004), which would reduce the impact of cycle skipping between observed and synthetic waveforms. Effects such as topography, bathymetry, and near-source heterogeneities can generate *S* waves and Love waves even for an explosion (or vertical force) source (Takemura *et al.*, 2015; Burgos *et al.*, 2016; Gualtieri *et al.*, 2020), and these effects may be more pronounced for shallow sources. A key remaining question is what portion of the HTHH Love waves was generated by the source versus structural heterogeneities. Measurement uncertainties could be improved by accounting for station-specific noise (Mustać and Tkalčić, 2017). Both body waves and surface waves could be considered simultaneously. Both the source models (force and moment tensor) could be considered simultaneously, as in the model of Kanamori *et al.* (1984) and the work of Chouet *et al.* (2003). Finally, the point-source models we consider are extremely simplified representations and could be expanded to accommodate more realistic physics, chemistry, and thermodynamics of volcanic eruptions.

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