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Comments and Replies

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

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The 15 January 2022 Hunga Tonga Hunga–Hai'apai (HTHH) eruptive sequence released a large amount of energy into Earth's atmosphere and hydrosphere, as well as the solid earth (Yuen *et al.*, 2022). It resulted in an extraordinarily high volcanic plume (Proud *et al.*, 2022), acoustic and acoustic-gravity waves recorded around the world (Matoza *et al.*, 2022), a source-region water displacement generated tsunami in the Pacific Ocean (Lynett *et al.*, 2022) and meteotsunamis in the Pacific and more distant water bodies (Kubota *et al.*, 2022), and globally recorded seismic waves (Matoza *et al.*, 2022; Poli and Shapiro, 2022; Garza-Giron *et al.*, 2023). Because of the eruptive nature of the sequence and the intense interaction with Earth's atmosphere and hydrosphere, it has been characterized as a phreatoplinean eruption (Sellitto *et al.*, 2022)—indeed one of the largest ever observed.

In the recent interpretation of seismic waves generated by the HTHH eruptive sequence, Thurin *et al.* (2022) proposed that the volcanic sources of seismic-wave energy can be characterized in the same manner as earthquakes buried well below the Earth's surface, that is, with seismic moment tensors. This is at odds with a conceptual model proposed for the previous large Plinian eruptions (e.g., 1980 Mount St. Helens) consisting of pulses of downward vertical forces representing a reaction force to a large upward momentum transfer to the atmosphere (Kanamori and Given, 1982; Kanamori *et al.*, 1984; Burger and Langston, 1985; Ohminato *et al.*, 2006). Thurin *et al.* (2022) briefly addressed this existing conceptual model with tests from which they infer that a vertical force model cannot explain observed seismic body-wave and surface-wave observations. In this comment, we point out an error in the tests of the reaction force model and argue that the vertical force model for the HTHH eruptive sequence is a more sensible physical representation of the source than the buried explosion model proposed by Thurin *et al.* (2022).

Past large Plinian events such as the HTHH eruption involved large transfer of momentum to Earth's atmosphere via the eruptive venting, as evidenced by observations of acoustic-gravity waves and Lamb waves through air pressure and satellite recordings, as well as observations of coupled atmosphere-solid earth seismic waves at global distances (Kanamori and Mori, 1992; Widmer and Zürn, 1992; Kanamori *et al.*, 1994). This momentum transfer must be matched by a similar downward momentum transfer to the solid earth at the volcano, which raises the issue of how large a role such forces play in the overall seismic source process. For the HTHH eruption, Poli and Shapiro (2022) calculated the integral of the downward force and estimated a volcanic explosive index of ~6. Garza-Giron *et al.* (2023) found that a data set of teleseismic *P* waves and regional Rayleigh waves could be explained with a reaction force model characterized with time-dependent downward forces being applied to the solid earth at the Earth's surface over a total duration of 4.5 hr with time-integrated cumulative force (moment transfer) of 3×10^{15} N · s. This seismically inferred force time series indicates net energy transfer (based on a simple relation between force time history and energy provided in Kanamori and Given (1983)) of $\sim 1 - 2 \times 10^{17}$ J in good agreement with an independent estimate of

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the pressure–volume work done in erupting material into the atmosphere (Yuen *et al.*, 2022). The corresponding reaction forces are sufficient to fully account for the seismic motions.

The moment tensors of the principal events inferred by Thurin *et al.* (2022), summarized in their article as four subevents occurring within the first 5 min of the eruptive sequence, have a dominant isotropic component of subterranean explosive expansion, with smaller deviatoric moment tensor components superimposed (Thurin *et al.*, 2022, their figs. 2–4 and table S1). Although the study's modeling demonstrates that moment tensor sources for seismic waves generated by the earliest subevents are mathematically plausible, it does not completely address significant trade-offs between permissible moment tensor and force representations. Garza-Giron *et al.* (2023) found that teleseismic *P* wave and regional surface-wave data are equally explainable with models of time-dependent downward vertical forcing and isotropic contraction, both of which have axisymmetry as does an isotropic expansion model. Allowing flexibility in the sign of the force–time history allows the data to be fit using Green's functions with opposite signs. This suggests that the similar far-field data considered in both the studies cannot discriminate among very different conceptual models for the eruptive process. Single-force representations play a role in other special situations of seismic wave excitation, for example, landslides (Dahlen, 1993) and spall (Day and McLaughlin, 1991), and the force components are indistinguishable from moment tensor components using far-field seismic data.

Our preferred predominant mechanisms contributing to seismic-wave energy during the early HTHH eruption are the near-vertical downward reaction force and simultaneous isotropic contraction representing pressure reduction and possibly collapse in the magma chamber at depth (Coppess *et al.*, 2022); some combination of these processes is likely. Apart from considering the physical mechanisms of the eruption, the regional seismograms provide guidance on the sources producing seismic-wave energy. Seismograms presented in Figure 1 illustrate Rayleigh-wave arrivals with repeating waveforms observed on the vertical and radial components that Garza-Giron *et al.* (2023) modeled with time-dependent downward vertical forcing. Relatively little energy is observed on the transverse components, which may consist of Love waves and off-azimuth Rayleigh waves. In either case, the pattern of repeating wavepackets that characterizes the Rayleigh waves is absent for possible Love waves. Hence, there is a little evidence for consistent nonaxisymmetric seismic sources; small 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).

Thurin *et al.* (2022) dismissed the reaction force model based partly on the consideration of teleseismic *P* waves. The study found that a moment tensor source model could successfully fit the observed *P* waveforms, which invariably consist of vertical and radial components that are in phase, that is, positive upward motion must correspond to positive away motion. In the study, the synthetic *P* waveforms for moment tensor sources replicate this basic pattern, but paradoxically the synthetic *P* waveforms for point-force sources have vertical and radial components that are of opposite polarity. Seismic source theory, for example, equation (4.57) of Aki and Richards (1980), dictates that the polarity of verical and radial components must match regardless of the source mechanism, which will only control the amplitude along a particular ray path. We believe that the explanation is that Thurin *et al.* (2022) extracted point-force impulse responses from the Incorporated Research Institutions for Seismology Synthetics Engine database without recognizing that the polarity of the radial components for the point-force calculations are erroneously reversed. Parallel with discussion of this issue on the instaseis GitHub repository (see Data and Resources), this error was recognized and corrected for by Garza-Giron *et al.* (2023). This invalidates the analysis of body waves produced by point forces presented by Thurin *et al.* (2022). The same issue applies to the analysis of surface waves produced by point forces. Observed Rayleigh waves clearly obey the expected retrograde particle motion, as do the synthetic Rayleigh waves from the moment tensor models (e.g., fig. 3 of Thurin *et al.*, 2022). However, the synthetic Rayleigh waves from the point-force model exhibit prograde particle motion (fig. S13 of Thurin *et al.*, 2022), again arising from the sign error in the radial components of the precomputed synthetic seismograms for point-force excitation.

Thus, the calculations presented to rule out a point-force representation are incorrect. It is logical that axisymmetric sources are very hard to distinguish in narrowband seismic data when the precise depth and moment rate function or force time history is not independently known.

Moment tensor analysis has played a key role in the interpretation of numerous past volcanotectonic events. For the HTHH eruptive sequence, it is physically sensible for noneruptive volcanotectonic events, which are not coupled to the atmosphere (Kintner *et al.*, 2022). However, the eruption

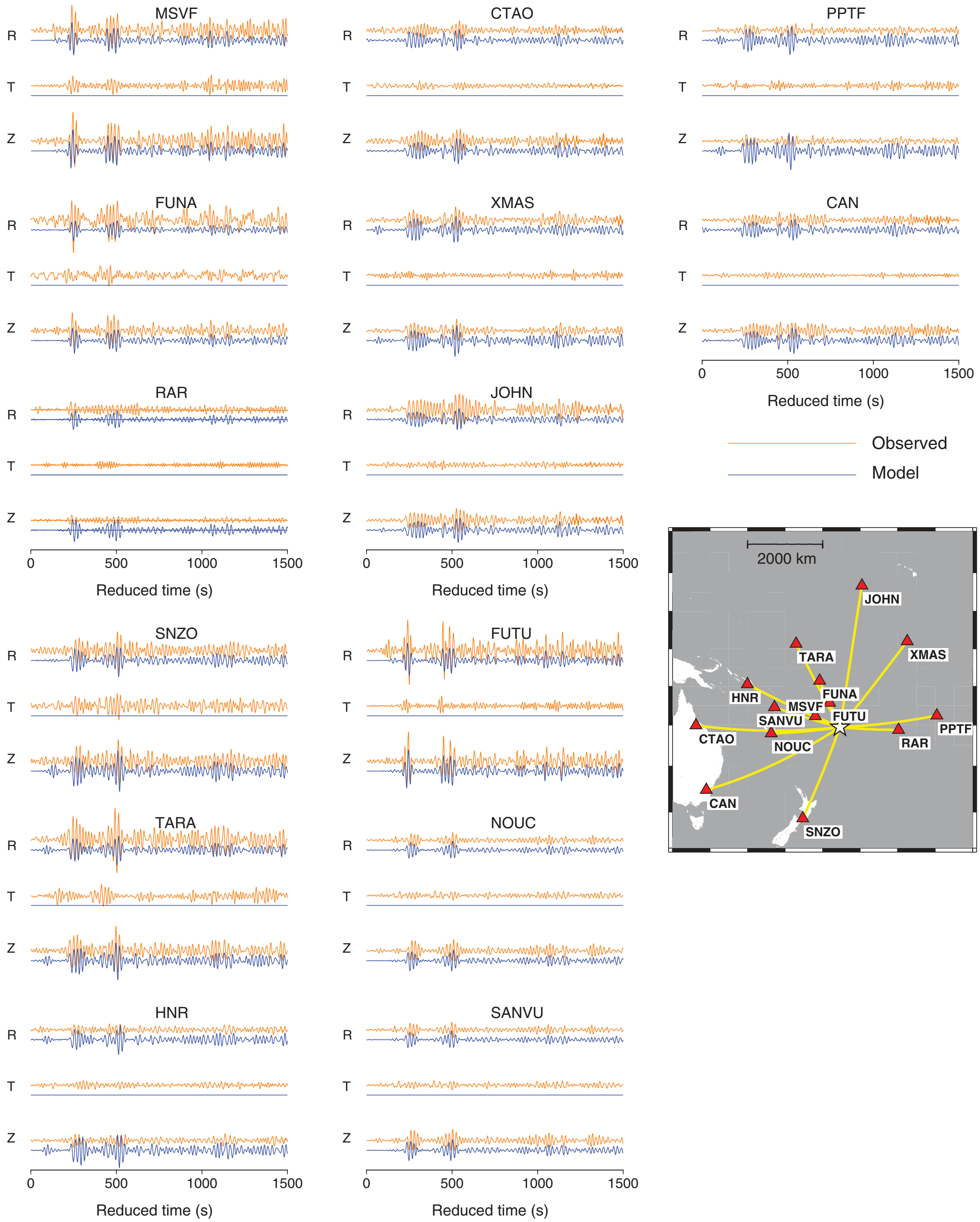

Figure 1. Three-component waveforms at broadband stations within 4500 km of the Hunga Tonga Hunga–Hai'apai (HTHH) epicenter (orange traces), together with the fit of synthetic waveforms generated by a time-dependent forcing model (blue traces). R, T, and Z denote radial, transverse, and radial components, respectively. For a given station, each component seismogram is plotted on the same scale. This figure is modified from figure 4 of Garza-Giron *et al.* (2023).

excavated 6.5–10 km^3 of rock from the caldera that was launched into the sea and/or air (O'Callaghan, 2022; Wei-Haas, 2022). That strong fragmentation and ballistic launching of the medium undermines the validity of a contained point-force representation (Dahlen, 1993) and leads us to favor the reaction force as a preferred force representation. Pressure reduction and possible collapse of the magma chamber at depth, as well as rock fragmentation, are also physically required and will further contribute to seismic radiation.

Data and Resources

Broadband seismic data were obtained from the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC). The IRIS syngine service (https://service.iris.edu/irisws/syngine/1/). The information about the issue on the instaseis GitHub repository is available at https://github.com/krischer/instaseis/issues/82 and https://github.com/krischer/instaseis/issues/77. All websites were last accessed in January 2023.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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