Hunga-Tonga Games: Unravelling the Timing and Size of the Biggest Volcanic Explosion in 30 Years

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Abstract

We attempt to construct a timeline of The Hunga Tonga – Hunga Ha'apai eruption on 15 January 2022 through analyses of seismic, barometric, infrasonic, lightning, and satellite data. Satellite imagery at 04:00 UTC showed no ash in the air, but by 04:10 UTC, a plume had risen to 18 km. Over the next 20 minutes, the plume rose to 58 km. USGS determined that Mw5.8 volcanic earthquake of unknown mechanism had occurred at 04:14:45. Gravity waves were observed in satellite imagery, and barometric and infrasound stations around the world recorded ultra-low frequency pressure variations of more than 100 Pa, inducing ground-coupled airwaves around the globe, and meteo-tsunamis in the Caribbean Sea and Mediterranean Sea. Tsunami waves were recorded in coastal areas around the Pacific Ocean. From record sections, we determined speeds of 3.9 km/s and 299 m/s for the initial seismic and infrasound signals respectively, converging to an eruption onset time of ˜0402 UTC ± 1 minute. The global pressure pulse has a speed of ˜314 ± 3 m/s, consistent with theoretical models for Lamb waves (Bretherton, 1969), suggesting an origin time of ˜0415 ± 2 minutes (consistent with the Mw5.8 volcanic earthquake, and sharp increases in lightning flash rates), and peaking around ˜0429 ± 2 minutes. We suggest that Surtseyan volcanic activity commenced at ˜04:02, building to a sub-Plinian eruption ˜7 minutes later, before a phreato-Plinian eruption commenced at ˜04:14. The peak Lamb wave amplitude at the closest station (757 km from HTHH) was 780 Pa. Assuming geometrical spreading like 1/[?]r (where r is the source-receiver distance), we estimate a lower bound of ˜23 kPa for reduced pressure by extrapolation back to 1 km. Adding a near field term that decays like 1/r, we estimate an upper bound of 170 kPa for reduced pressure. Comparison of these values with those from other eruptions (McNutt et al. in this session) suggests the 15 January HTHH eruption was in the VEI 5-6 range.

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1. Introduction: The 2022-01-15 eruption

USGS located a Ms5.8 volcanic non-double-couple earthquake at Hunga Tonga – Hunga Ha'apai (HT-HH) with an origin time of 04:14:45, and a depth of 0-6 km beneath the sea floor. A Lamb wave (Fig. 1), presumably from a very powerful explosive eruption, propagated around the globe several times, and was recorded on barometric and infrasound stations, and induced ground-coupled airwaves and meteo-tsunamis. But a crucial question is which came first, the earthquake, or the explosion?

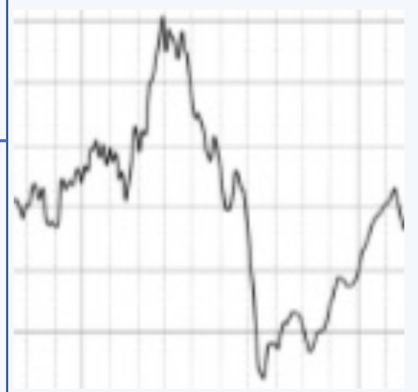

Fig. 1: This N-shaped waveform is an atmospheric Lamb wave that propagated around the world many times. Onset is emergent, duration 30-40 minutes. (Vertical lines are 3 minutes apart)

A first step towards understanding the eruption is to determine the relative timing and size of different phases from the geophysical signals recorded. But the closest station is MSVF on Fiji, 757 km NNW. We have to correct for travel time (including supersonic travel), and geometrical spreading on curved Earth.

Related papers: Yuen et al. (2022) found that there were 4 similar earthquakes within ~300 s of the USGS origin time labelled E-1, E-2, E-3, and E-4. Zheng et al. (9 am talk in this session) model these as sets of vertical forces, and link these to 'magma hammer'. McNutt et al. (4:30 pm talk in this session) uses results from this poster to estimate instrumental VEI.

2. What came first? The earthquake or the explosion?

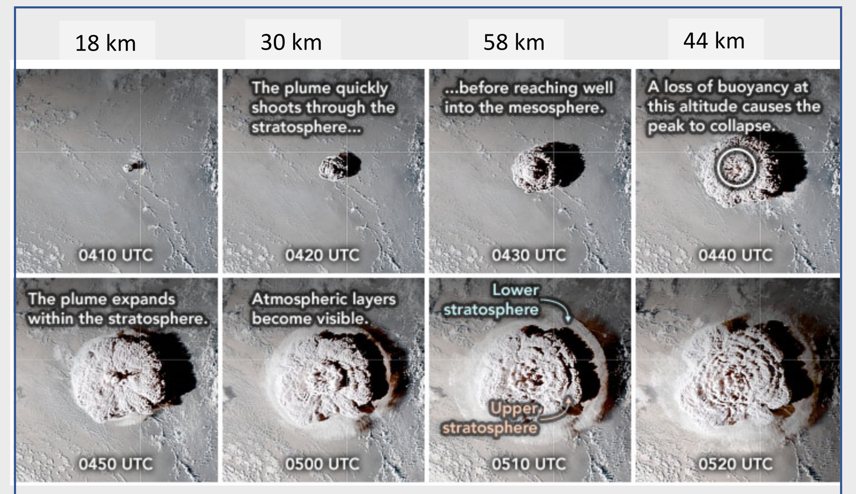

Fig. 2: GOES-17 satellite imagery from 0410-0520 UTC. The ash column reached 18 km by 0410, and peaked at 58 km at 0430, before collapsing.

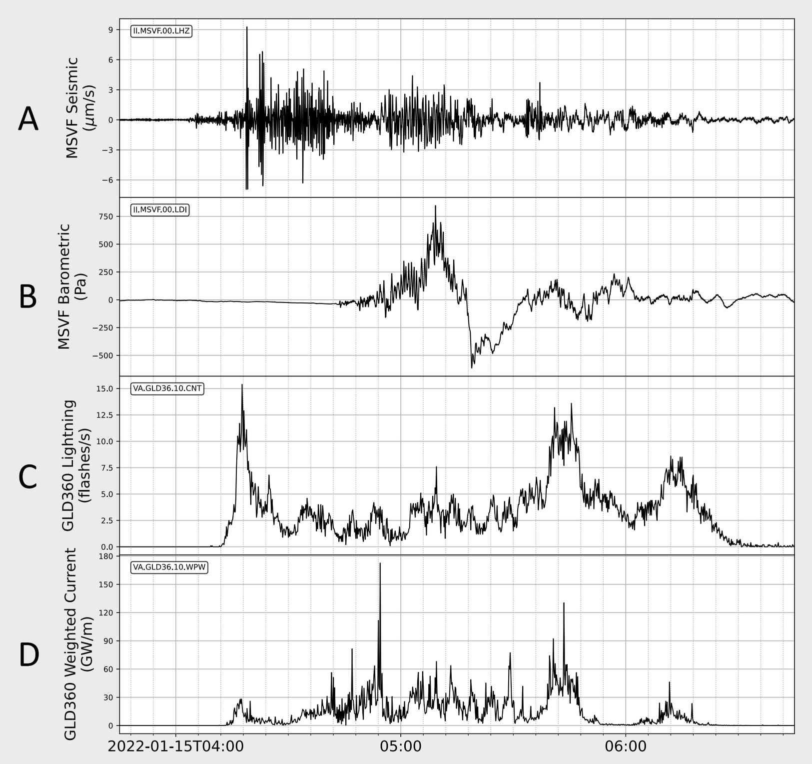

Fig. 3: Seismic (A) and barometric (B) data from GSN station MSVF on Fiji, 757 km from HT-HH, compared with GLD360 lightning network data from Vaisala, Inc. (C) shows detected flashes per second within 15 km of the volcano. (D) is related to electrical power in the center of the ash column.

A crucial question is which came first, the earthquake, or the explosion? This is not easy to answer, because of the lack of local stations; the emergent, ultra-low-period (30-40 minute) Lamb wave dominating the barometric and infrasonic recordings; and the uncertainty in infrasound wave travel times.

Independent evidence for explosive eruption timing comes from satellite imagery and lightning data.

Satellite imagery (Fig. 2) provides unambiguous evidence of ash column height and radius, but only at 10-minute sample intervals. Lightning data have a very high sample rate, but previous work suggests there is a delay of 4-12 minutes between explosion and detectable lightning by the Vaisala GLD360 network.

We combine seismic and barometric data from MSVF with global lightning data (Fig. 3). But we need to remove travel time, to unravel signal times at the source. Record sections (Fig. 4) show speeds determined from least-squares fit to picked seismic and infrasound arrival times. EM radiation travel times (for lightning data) are < 0.1 s.

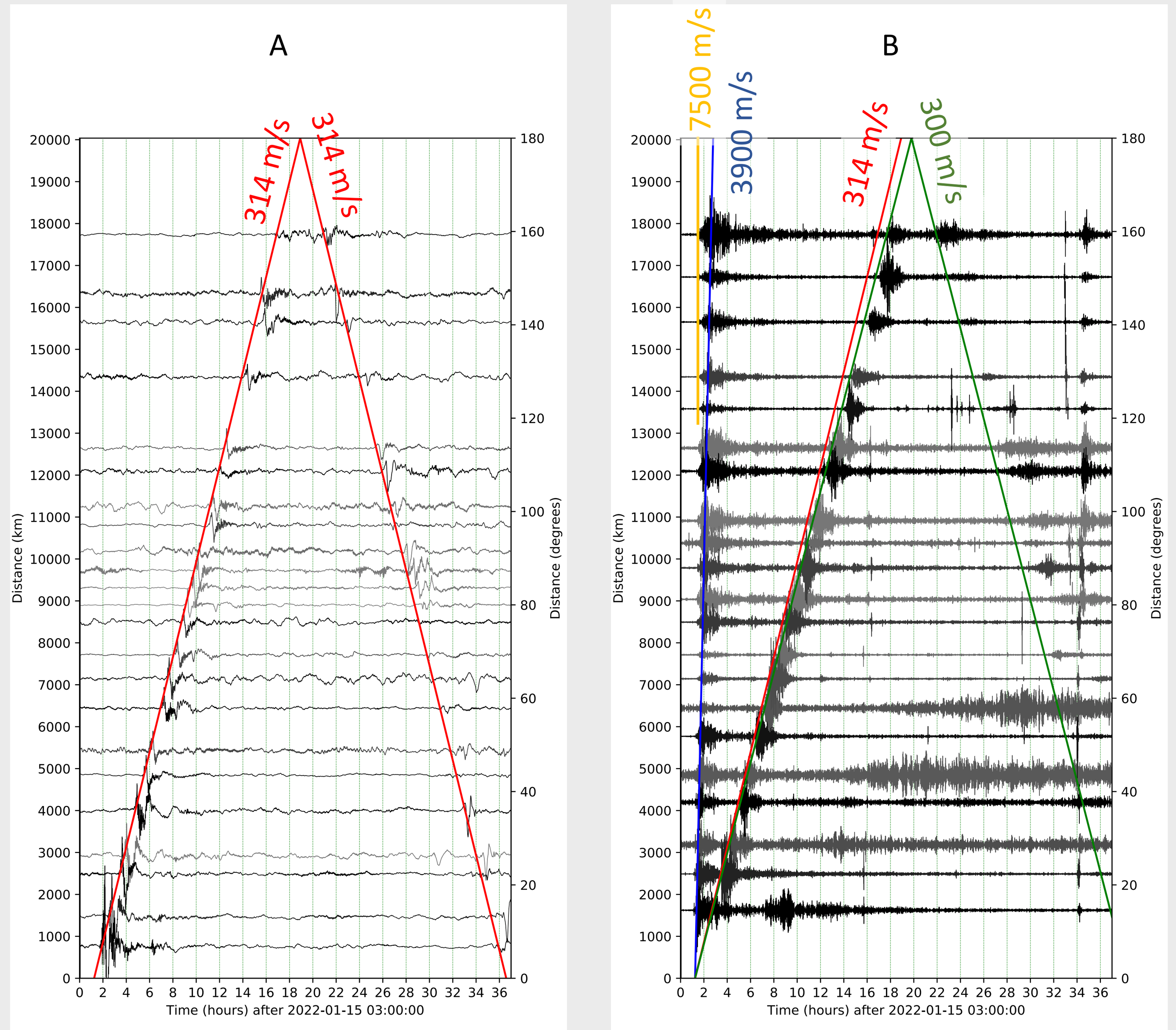

Fig. 4: Record sections of selected barograms (A), and seismograms (B). Barograms, filtered from 0.1 mHz to 0.1 Hz, show infrasound waves with a characteristic N-shaped-waveform (a Lamb wave), propagating around the globe at a speed of ~314 m/s (red line). Seismograms are filtered from 1 mHz – 0.1 Hz, show P waves (gold line, 7.5 km/s), surface waves (blue line, 3.9 km/s), and ground-coupled airwaves (green line, 300 m/s) induced by the infrasound waves. Barometric and seismic data are from IRIS DMC.

3. What about supersonic shockwaves?

Near the source, atmospheric waves would have been non-linear, supersonic shock waves. So how much does reduce travel times?

We can compute shock wave travel times using equation 4-26 from Kinney & Graham (1985):

$$M = \sqrt{1 + \frac{(k+1)\Delta P}{2k\,P}} \qquad (1)$$

where k = specific heat ratio (1.4 for air), ΔP = overpressure, P = ambient pressure, and M = Mach number.

First we have to estimate the overpressure, ΔP, as a function of distance. This is difficult to constrain, given that the nearest station is 757 km. We use a model like:

$$\Delta P(r) = \left[\frac{a}{r} + \frac{b}{\sqrt{r * r_c}}\right] \qquad (2)$$

In brackets are near and far field terms, which model spherical waveforms locally and cylindrical waveforms at global distances. Here, r is the radius of the wavefronts, which on a spherical earth ranges from 0 to 6378 km, and back to 0 km at the antipode. It is always less than distance measured along the Earth's curved surface.

A metric commonly estimated by the volcano infrasound community is reduced pressure, the overpressure estimated 1 km from the source. Fig. 5 shows two lines extrapolated back to 1 km, which we consider to be limiting cases.

1. Setting a=b=1 in Eqn. 2, r_c is then a cross-over distance beyond which the cylindrical wave term dominates. The solid line in Fig. 5 corresponds to r_c = 100 km, approximately the maximum altitude that infrasound energy propagates to. Upper limit for reduced pressure = 170 kPa.
2. The dashed line corresponds to a=0 (near field term ignored). We estimate a reduced pressure range of 23 – 170 kPa. Lower limit for reduced pressure = 23 kPa.

Using the upper limit (Fig. 5, solid line), we then use Eqn. 1 to estimate Lamb wave speed as a function of distance (Fig. 6). We estimate shock wave speeds of up to 500 m/s. However, this falls asymptotically to the distal Lamb wave speed of 314 m/s, and we calculate that the shock wave only arrives 26.6 s early as MSVF.

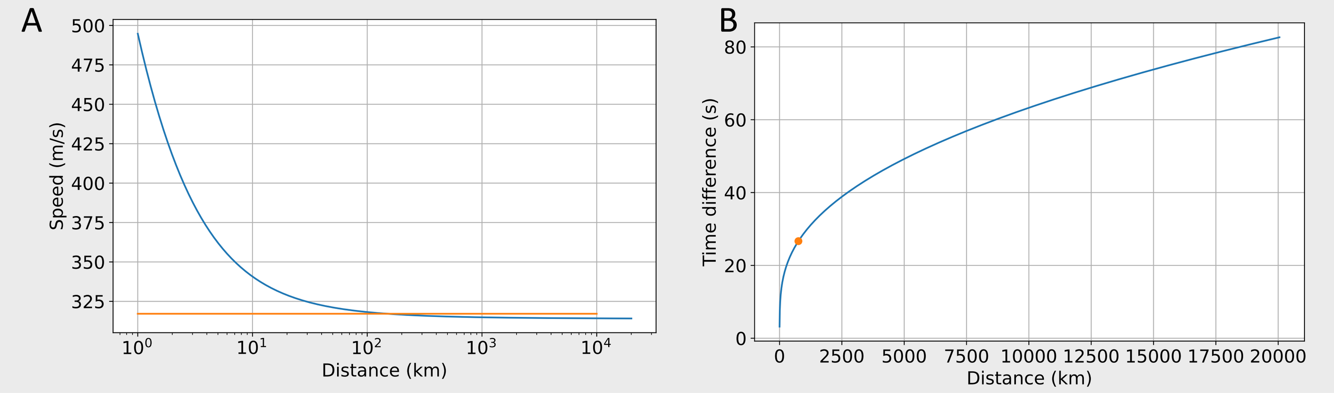

Fig. 6: (A) Lamb wave speed versus distance. Beyond 100 km, non-linear effects can be ignored. (B) How many seconds early does the shock wave arrive? Answer:26.6 s at 757 km

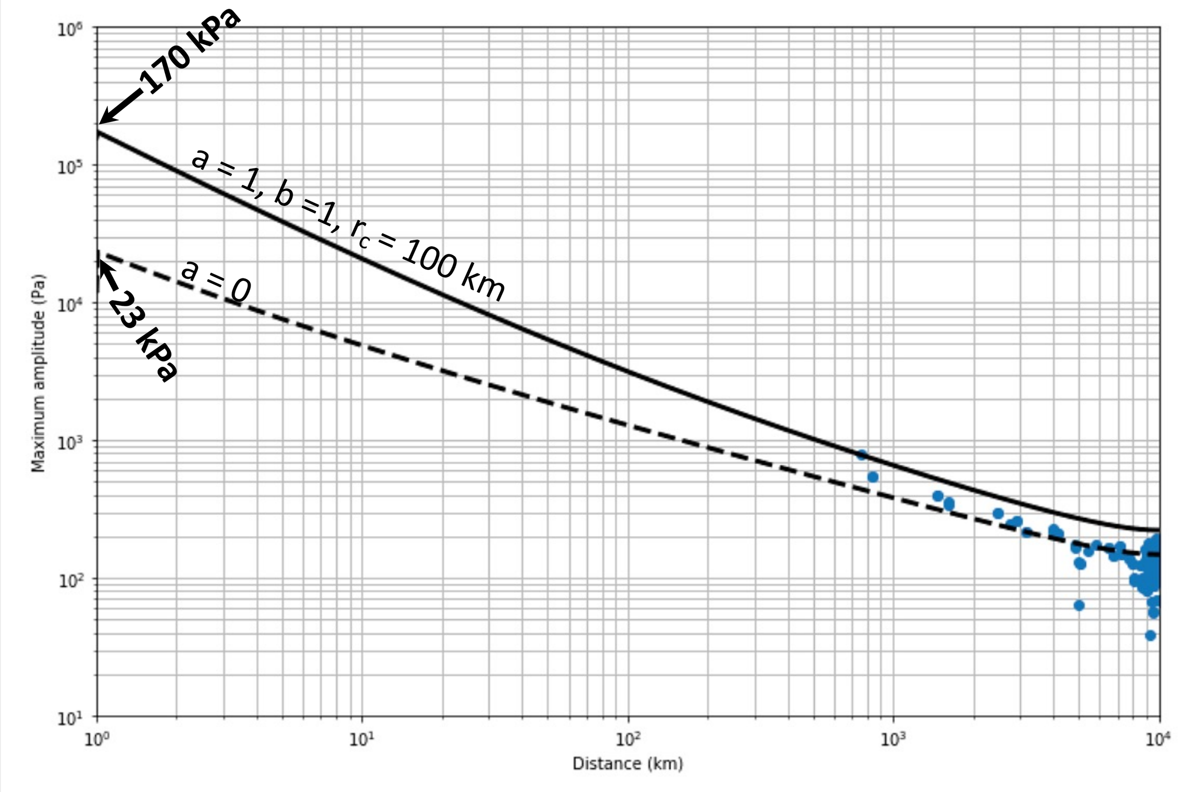

Fig. 5: Peak overpressure amplitude of the Lamb wave vs. distance, modelled with equation 2. Blue dots show zero-to-peak overpressure amplitude measured on waveforms from 156 barometric stations available from the IRIS DMC.

4. Results: signals migrated back source

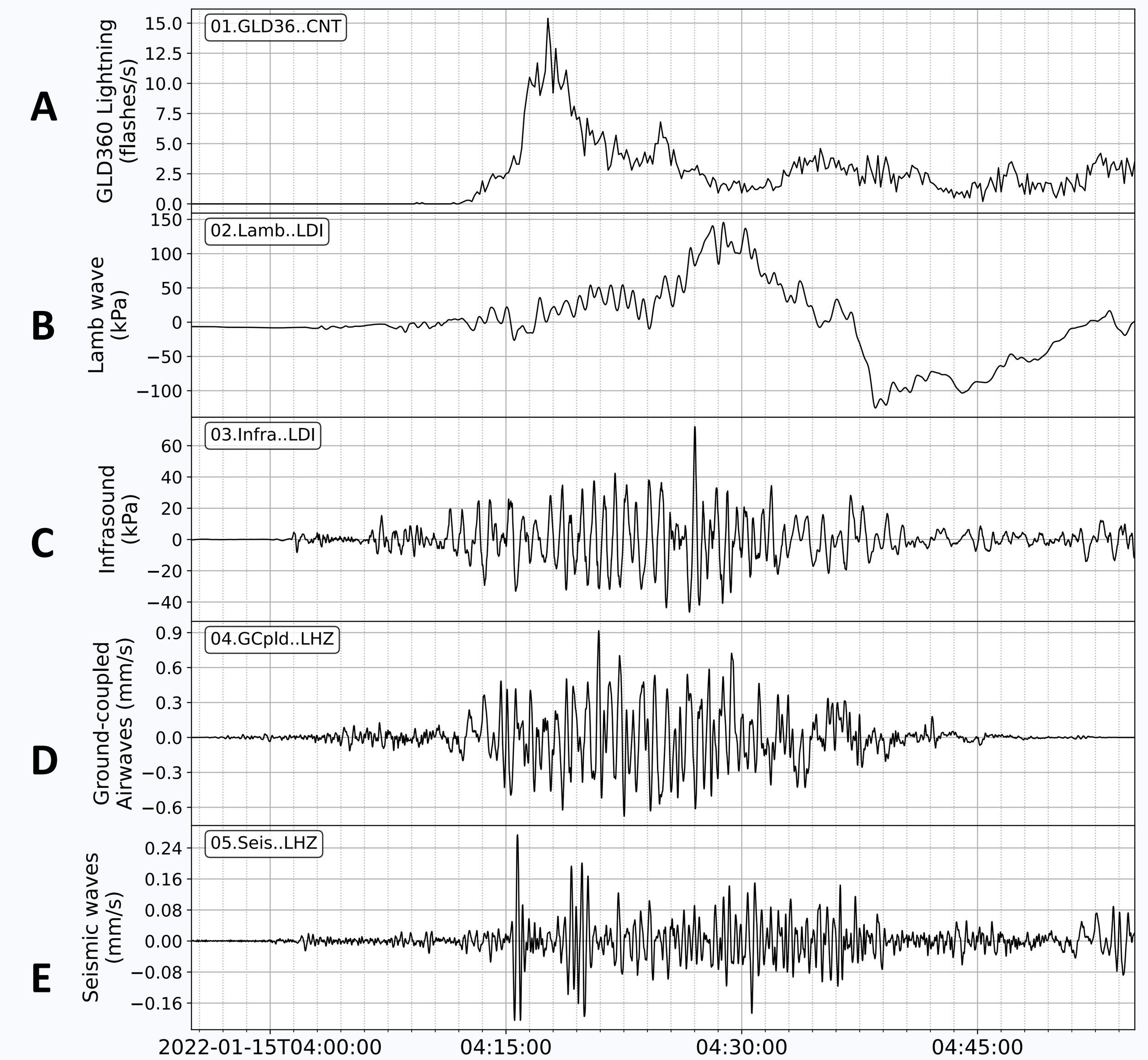

Fig. 7: Signals time migrated back to 1 km from source & corrected for geometrical spreading. Source dimension was likely greater than 1 km, but this distance as it is widely used for in volcanic infrasound community. .

Lightning flash rate (within 15 km) began to climb at 04:12 and shot up at 04:16, peaking just before 04:18 at 16 flashes per second. Thereafter it gradually diminished (possibly obscured by lightning from rapidly expanding umbrella cloud).

Lamb wave (0.0001 – 0.01 Hz bandwidth) began at 04:17, peaking around 04:28 at ~145 kPa. The positive phase lasted until 04:35 (18 minutes total), before reaching a negative peak at -120 kPa, then slowly recovering back to equilibrium by 04:52 (17 minutes total for negative phase). The positive Lamb wave phase likely coincided with the rise of an ash cloud from 0 to 55 km in 11 minutes, an average ascent rate of ~80 m/s.

Infrasound energy (0.01 – 1 Hz bandwidth) began at 04:01:30. Thus there was likely more than 13 minutes of eruptive activity before the earthquake. Further escalations in infrasound happened at 04:07 and 04:11, peaking at 04:27 at 70 kPa, then gradually becoming lower frequency and waning out at 04:39.

Ground-coupled airwaves were induced by infrasound waves from about 04:05 but particularly from 04:12 to 04:39. Amplitude almost 1 mm/s, suggesting a coupling ratio of 1.3 x 10^{-8} m/s per Pa.

Seismicity began at 04:01:30, increased at 04:12, but the main events are observed from 04:15-04:16 and 04:18-04:20, consistent with Zheng et al (2022). Peak amplitude is about 0.3 mm/s, but if body wave rather than surface wave spreading used, would peak at 8 mm/s.

5. Conclusions

Table 1: Proposed eruption timeline

Time (UTC)	Description
04:00	No ash cloud, no evidence of eruption.
04:01:30	Surtseyean activity began, as evidenced by simultaneous seismic and infrasound activity.
04:07	Escalation in infrasound. Vulcanian?
04:10	Ash cloud reached 18 km, radius 5 km.
04:11	Escalation in infrasound. Sub-Plinian?
04:12	Ground-coupled airwaves began (infrasound generating seismic Rayleigh waves). Lightning detection rate started to climb, likely in response to 04:07+ ash cloud.
04:14:45-04:16	**Main earthquake activity (E-1 sub event) and onset of Plinian eruption / cataclysmic explosion.**
04:16	Lightning flash rate shot up, either in response to 04:11+ ash cloud, or Plinian eruption at 04:15+.
04:17	Lamb wave signal began to emerge.
04:18	Lightning flash rates (within 15 km of volcano) peaked, and slowly began to decline. Possibly because ash cloud is also spreading laterally and flashes near center are being masked by those at expanding edge?
04:18-04:20	More earthquake activity (E2-E4 sub events).
04:20	Ash cloud reached 30 km, but this was likely the event at 04:15+, so it rose at average speed of 100 m/s.
04:28	Lamb wave peaked. This likely coincided with ash cloud peaking at 55 km. So since 04:20 it rose at average speed of 52 m/s.
04:30	Narrow ash column seen at 55 km, with umbrella at 38-40 km.
04:37	Sharp negative phase of Lamb wave might suggest ash column at 55 km began cascading downwards rapidly for next 2-3 minutes.
04:40	Ash column seen at 44 km. Infrasound and ground-coupled airwave energy, and seismicity were waning rapidly, suggesting eruption de-escalating.
04:50	Ash column had risen slightly – perhaps oscillating?
04:52	Lamb wave ends. Perhaps just ongoing low level eruption at this time.

The main earthquake and cataclysmic explosion likely occurred within tens of seconds of each other. We cannot be certain which happened first, given the resolution of the data.

Reduced pressure estimate of 23 – 170 kPa suggests a VEI 5-6 eruption (McNutt et al., this session). Ash cloud ascended at average speed of 100 m/s to 30 km from 04:15-04:20, likely supersonic initially.

References:
- GF Kinney and KJ Graham, "Explosives Shocks in Air," 2nd Edition, Springer-Verlag, Berlin, 1985.
- DA Yuen et al. Earthquake Research Advances, 100134, 2022. https://doi.org/10.1016/j.eqrea.2022.100134.
- Y Zheng et al. "Early Episodic Eruption Characteristics…". (9am talk in this session today).
- SR McNutt et al. "Using infrasound and umbrella cloud radius…(to estimate VEI)". 4.30 pm talk in this session .

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