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A repeating secondary source of infrasound from the Wells, Nevada, earthquake sequence

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[1] The Wells, Nevada, earthquake of February 21, 2008, generated a complex seismo-acoustic wavefield. Epicentral infrasound was recorded at 5 seismo-acoustic arrays in Nevada, Utah, and Wyoming. In addition to epicentral infrasound, the earthquake triggered a secondary source of infrasound at the BGU array in Utah, which was also triggered by subsequent aftershocks. By applying simple constraints on the propagation of seismic and infrasound waves, we show that the secondary source is an isolated peak ('Floating Island') that appears to efficiently generate infrasound through the interaction with seismic surface waves. This hypothesized source location is broadly consistent with crosswind directions extracted from the Ground-to-Space (G2S) atmospheric model (for the appropriate time and source/receiver locations), although modeling the propagation of infrasound predicts this source location to be within the so-called 'zone-of-silence'. In contrast to epicentral infrasound, secondary infrasound associated with the Wells, Nevada, earthquake sequence appears to be local to each array (i.e., not observed at multiple arrays). Secondary infrasonic arrivals observed at BGU are much higher in amplitude than epicentral arrivals, highlighting the importance of being able to clearly identify and separate epicentral and secondary arrivals for infrasonic event discrimination. **Citation:** Arrowsmith, S. J., R. Burlacu, R. Whitaker, and G. Randall (2009), A repeating secondary source of infrasound from the Wells, Nevada, earthquake sequence, *Geophys. Res. Lett.*, *36*, L11817, doi:10.1029/2009GL038363.

1. Introduction

[2] Earthquakes can generate complex seismo-acoustic wavefields, consisting of seismic waves, epicenter-coupled infrasound, and remote-coupled (secondary) infrasound. With regard to the latter type of wave, which is the focus of this paper, the interaction of seismic surface waves with the atmosphere is known to generate infrasound in regions that can be remote from the epicenter, due to the amplification of ground displacement by topography. Here, we refer to regions where infrasound is generated by such mechanisms as 'secondary sources', to distinguish them from infrasound generated at the earthquake epicenter. Previous studies of secondary sources from earthquakes have primarily been limited to single array observations of individual large events [*Le Pichon et al.*, 2002, 2003, 2005]. *Le Pichon et al.* [2006] attempt to reconstruct the secondary source regions for the magnitude 7.8 Chilean earthquake of June 13, 2005 using three separate arrays. However, since secondary sources are thought to be largely directional [*Le Pichon et al.*, 2003], and due to variations in propagation to each array, the authors reconstruct large distributed secondary source regions for each array separately.

[3] In this study, we present the first detailed observation of a repeating secondary source from an earthquake and aftershock sequence. Our study extends previous studies in several ways: (1) the association is more robust (i.e., multiple observations of the same source provide statistical confidence in our interpretation); (2) we focus on understanding an isolated secondary source rather than a large distributed region, reducing the complexity of the problem; and (3) we are able to study variations in the source relative to event magnitude.

[4] As reported by the USGS, the Wells earthquake occurred at 14:16:02 UTC on February 21, 2008. The earthquake had a reported magnitude (M_W) of 6.0, depth of 6.7 km, and epicenter located at (41.153°N, 114.867°W). The earthquake moment tensor was consistent with a northeast striking normal fault dipping northwest or southeast. The mainshock caused an extensive aftershock sequence, lasting for approximately 2 months. The first 3 aftershocks, which are the focus of this paper, were closely located spatially (they are associated with a lateral spread of 11.7 km (E–W) by 17.8 km (N–S), and a vertical spread of ~3 km) and temporally (they occur within ~30 minutes of the mainshock). Here, we focus on understanding a repeating signal at the BGU infrasound array in Utah, which we show below to be associated with an isolated secondary source.

2. Observations

[5] The Wells, Nevada, earthquake mainshock was observed infrasonically at 5 arrays in Nevada, Utah, and Wyoming (Figure 1). Epicentral infrasound is detected at all arrays (highlighted by the red lines in Figure 1), however there are additional signals observed at BGU, such as the high-amplitude signal arriving between the seismic arrivals and epicentral infrasound labeled 'Ground-air coupled infrasound', that are not associated with corresponding signals at the other arrays. Similarly, there are unique signals observed at EPU, NVIAR, and PDIAR, which arrive between seismic and epicentral infrasound arrivals (Figure 1).

[6] The BGU infrasound array comprises 4 Chaparral-2 sensors, fitted with porous hoses for wind noise reduction, with an array aperture of ~100 m and sampling rate of 100 Hz. The array was deployed as part of a collaboration between the University of Utah, Southern Methodist

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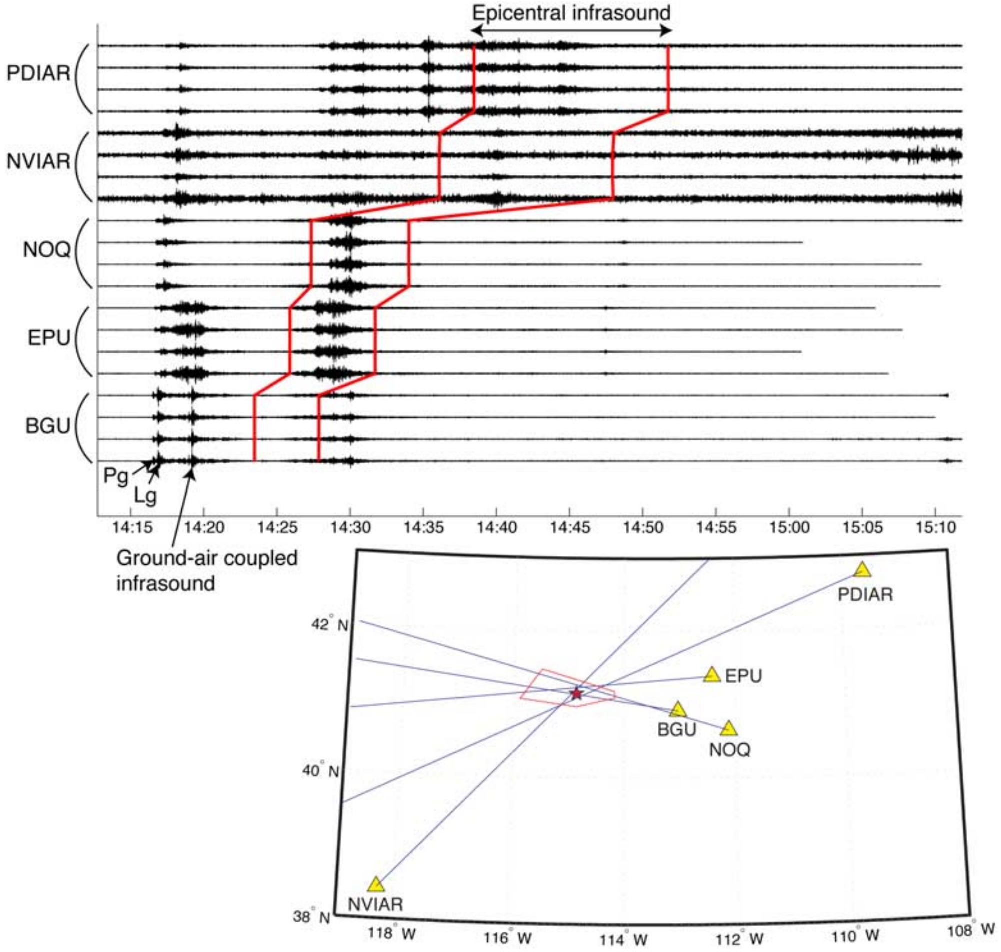

Figure 1. Summary of all infrasonic observations of the Wells, Nevada, earthquake mainshock. (top) Epicentral infrasound, observed at all 5 arrays (within the red lines), is located using the technique outlined by *Arrowsmith et al.* [2008]. (bottom) The location polygon is shown (red polygon), with the corresponding seismic location (red star) shown for reference.

University, Weston Geophysical, and ENSCO Inc. [*Stump et al.*, 2007]. The infrasonic observations of the mainshock and first three aftershocks of the Wells, Nevada, earthquake sequence at BGU are detailed in Table 1. Figure 2 shows the detailed observations of all four events at the BGU infrasound array. Only two of the events (Events 1 and 3) generated epicentral infrasound (i.e., infrasound generated at the epicenter and propagating through the atmosphere to the receiver as a pure acoustic wave). However, three events (Events 1, 2, and 3) generate a unique signal, which is observed at a backazimuth of 264° (16° off the great-circle backazimuth of 280° connecting the epicenter of the main event and the BGU array). The unique signals (Figure 2) are associated with identical phase velocities (0.37 km/s), and apparent group velocities that range from 0.82–0.91 km/s (indicating a hybrid seismic to acoustic wave).

3. Location

[7] We can constrain the location of the secondary source by applying simple physical constraints on the seismic and infrasonic group velocities, and on the backazimuth. The

Table 1. Summary of Infrasonic Observations at BGU for the Wells, Nevada, Mainshock and First Three Aftershocks

	Event 1	Event 2	Event 3	Event 4
Origin Time	14:16:02	14:20:51	14:34:43	14:46:31
Location	41.15, −114.87	41.11, −114.9	41.00, −114.79	41.16, −114.93
Magnitude	6.0	4.7	5.1	3.6
Phase ID	I (S), I (E)	I (S)	I (S), I (E)	
Max. amplitude (Pa)	2.18, 0.34	0.24	0.15, 0.05	
Period at max. amplitude (s)	0.54, 0.79	0.45	0.48, 1.53	
Backazimuth (°)	264.1, 284.5	264.1	264.1, 279.8	
Phase velocity (km/s)	0.372, 0.389	0.372	0.372, 0.368	
Apparent group velocity (km/s)	0.91, 0.27	0.91	0.82, 0.32	

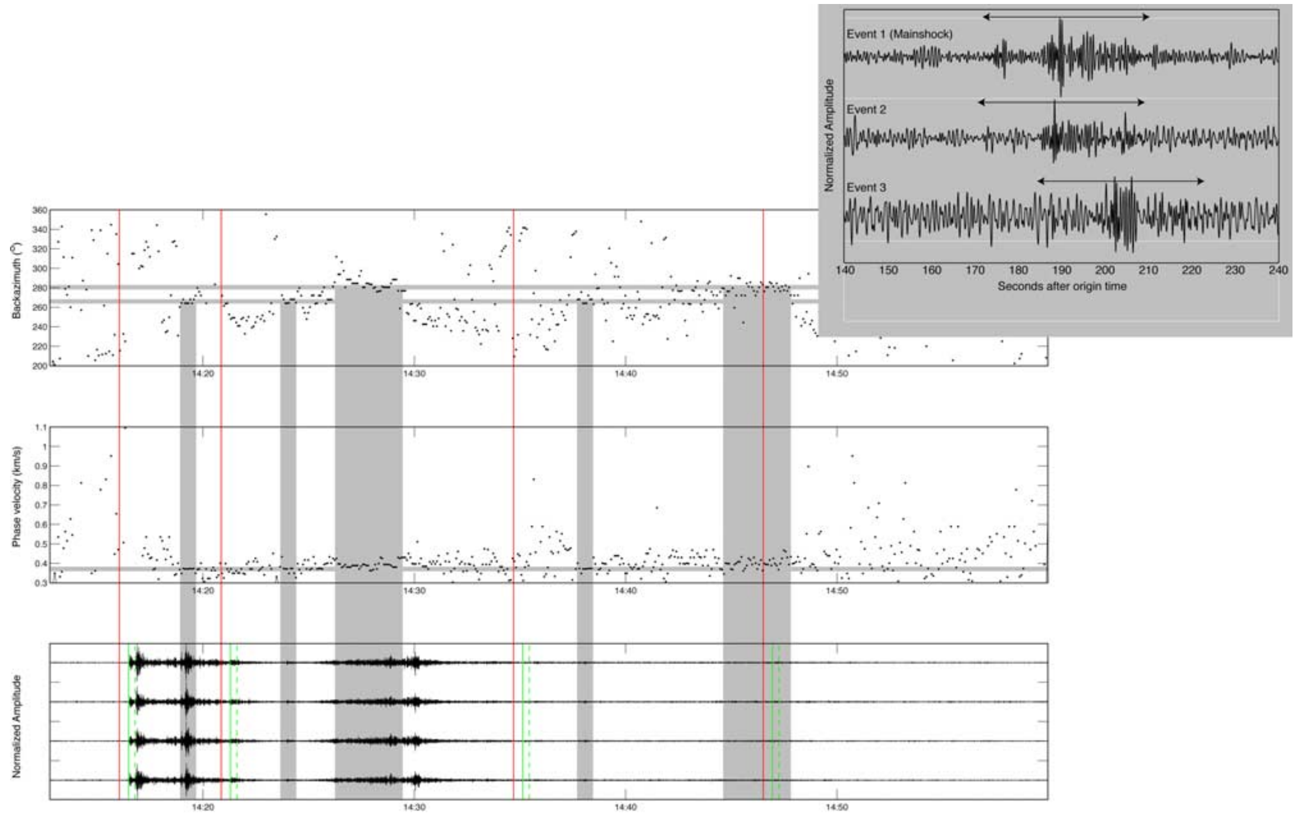

Figure 2. Acoustic observations at BGU. Acoustic traces at each array element are bandpass filtered from 1 to 5 Hz. Red lines denote the origin times of Events 1–4 (Table 1); green lines denote corresponding predicted arrival times for seismic waves (Pg, solid; Lg, dashed) using group velocities of Pg = 6.0 km/s and Lg = 3.5 km/s from *Kennett* [2002]. Vertical grey shaded regions highlight epicentral (shorter-duration) and secondary (longer-duration) arrivals. Inset figure shows a zoom on the secondary arrivals.

constraints are as follows: (1) the seismic surface wave must propagate with a group velocity of between 3.0 and 3.5 km/s [*Kennett*, 2002], (2) the infrasonic wave must propagate with a group velocity of between 0.28 and 0.35 km/s (this spans the full range of possible group velocities at this range) [*Ceplecha et al.*, 1998], and (3) the deviation in backazimuth between the observed backazimuth and the actual backazimuth to the source must be less than 5° (accounting for measurement error and wind bias), based on empirical observations by *Mutschlecner and Whitaker* [2005]. Although the surface wave velocity could be better constrained using seismic data, it is far outweighed by the effect of uncertainty in the infrasound group velocity on the size of the location polygon. To locate the source we simply discretize a pie-shaped region with grid nodes (Figure 3), and for each grid node apply the constraint that $t_s + t_i = t_{obs}$ (where t_s is the seismic travel time, t_i is the acoustic travel time, and t_{obs} is the observed travel time, respectively). If this criterion can be satisfied for any grid node given the three constraints listed above, the grid node is a possible event location. The final location (including uncertainty) is a polygon that encloses all the possible locations.

[8] As shown in Figure 4, the location polygon encloses an area known as the Bonneville Salt Flats, but does include the edge of an isolated peak called Floating Island (reaching an elevation of 1000 ft above the surrounding salt flats). Given that there is a wide distributed region of salt flats near BGU, the only plausible source with a unique local site response is Floating Island. This hypothesis would imply a wind bias of ~5° (such a backazimuth deviation cannot be explained from measurement error alone and must be predominantly due to wind bias) [*Szuberla and Olson*, 2004], and a relatively slow surface wave velocity. Given the three constraints used in the location algorithm, the computed seismic and acoustic group velocities corresponding to a source location centered on Floating Island are $v_S = 3.0$ km/s and $v_I = 0.28$ km/s (i.e., the slowest values allowed in the location algorithm).

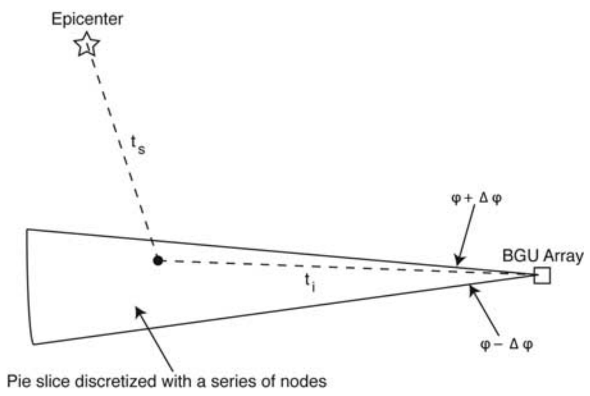

Figure 3. Schematic diagram illustrating the method used to locate the secondary source.

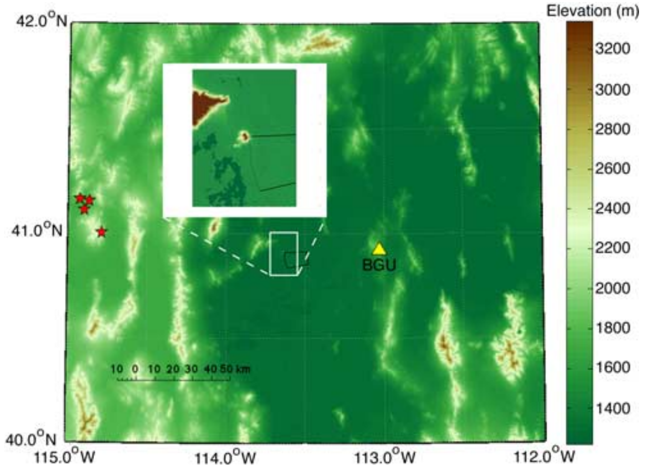

Figure 4. Map showing location of the secondary sources recorded at BGU (open black polygon). Red stars denote earthquake locations; the BGU array is denoted by a yellow triangle. The inset map is a zoom centered on the location of Floating Island. Note that the distance from the epicenter location to BGU is 156 km, and the distance from Floating Island to BGU is 51 km.

[9] The fidelity of models for infrasound propagation and associated specifications of relevant atmospheric parameters (temperature and winds) varies on a case-by-case basis. Recent studies have suggested that the combined use of state of the art 4D atmospheric specifications and simple ray-tracing algorithms may provide a statistical improvement for event location over simple bounding constraints. However, such a strategy does not reliably predict observed phases for any given event, due to either limitations in the propagation physics or limitations in the spatial and/or temporal resolution of 4D atmospheric specifications. By modeling the propagation of infrasound using a 3D range-independent ray-tracing code (based on the Tau-P method of *Garces et al.* [1998]) and state of the art G2S atmospheric specifications [*Drob*, 2004], we do not predict the observed arrivals from the Wells earthquake at BGU. Our results indicate that the secondary source is located in the so-called 'zone-of-silence'; highlighting the need for further research into infrasound propagation in this zone, beyond the scope of this paper. However, despite this limitation, stratospheric winds in the G2S model for this location and time are consistent with both the direction and magnitude of the observed backazimuth deviation at BGU (for a hypothesized source centered on Floating Island). The meridional wind component from the G2S model for this location and time (i.e., crosswind component for essentially E−W propagation) is strongly negative in the stratosphere between $\sim$21 and 54 km elevation (the maximum stratospheric meridional wind, v_{max} is equal to -27.5 km/s at an elevation of 44 km).

[10] As discussed above, the Wells earthquake was recorded at five infrasound arrays, including two additional arrays in Utah (EPU and NOQ) shown in Figure 1. Although secondary arrivals are observed at EPU (no clear secondary arrivals at NOQ), they do not correspond with this source location, implying that secondary sources associated with the Wells earthquake are dominated by local topography near the arrays.

4. A Brief Comment on Amplitude and Event Discrimination

[11] *Mutschlecner and Whitaker* [2005] developed scaling relationships for earthquake magnitude and duration (from $\sim$ magnitude 4–7), which were corroborated for larger magnitudes by *Le Pichon et al.* [2006]. They developed simple linear relationships for the duration and amplitude of epicentral infrasound as functions of magnitude. *Anderson et al.* [2009] propose using the *Mutschlecner and Whitaker* [2005] relationships as the basis for an event discriminant, since observational studies suggest that the corresponding infrasonic amplitudes of underground explosions are greater at constant magnitude.

[12] For the case of the Wells, Nevada, earthquake sequence, duration is difficult to measure due to the emergent onset of the acoustic arrivals, and relatively high ambient noise levels (which is typical of infrasound data). However, maximum peak-to-peak amplitudes (Table 1) are simpler to measure for epicentral and secondary arrivals since they are less susceptible to being corrupted by background noise and are therefore more robust. As shown in Table 1, amplitudes of secondary arrivals recorded at BGU are significantly larger than the corresponding amplitudes of epicentral arrivals. This observation highlights that it is critical that epicentral arrivals be separated from secondary arrivals, since incorrect identification could result in incorrect event identification. This is especially important in instances where the origin time is unknown, or where the source of secondary signals is close to the epicenter, since it would not be possible to identify secondary signals based on group velocity, as we have done in this paper.

[13] A full understanding of the generation of infrasound from earthquakes remains to be achieved. Empirical observations by *Mutschlecner and Whitaker* [2005] and *Le Pichon et al.* [2006] have pointed towards a simple linear relationship between wind-corrected amplitude and earthquake magnitude for stratospheric returns. However, the generation of infrasound by secondary sources must be further understood for such a relationship to be of practical use as part of an infrasonic event discriminant. Furthermore, the effects of earthquake depth and source mechanism are not considered by *Mutschlecner and Whitaker* [2005] or *Le Pichon et al.* [2006]. These effects could provide significant scatter in such scaling relations. Aftershock sequences could provide an invaluable mechanism for improving our understanding of these issues since, as is the case of the sequence of four events considered in this paper, the depths and source mechanisms are very similar, allowing us to isolate the effect of earthquake magnitude.

5. Conclusions

[14] Previous studies of secondary infrasound from earthquakes have found broad correlations between topographic highs and source generating regions for major – great earthquakes. Our observations and analyses extend such studies in 3 primary ways: (1) we focus on much smaller events ($M < 6.0$), (2) we observe a repeating source,

providing robust association, (3) our observations highlight an isolated source, rather than a broad-scale region. Our findings highlight the need to improve our understanding of the physical generation of infrasound from secondary sources, since the ability to discriminate between earthquakes and explosions infrasonically hinges on our ability to separate epicentral and secondary source signals. We show that aftershock sequences provide a unique opportunity to improve our understanding of earthquake-generated infrasound, by allowing us to separate effects of earthquake magnitude, depth, and source mechanism on infrasonic amplitudes. This work also highlights the need for further research into the propagation of infrasound at local and near-regional distances in order to address the 'zone-of-silence' issue (the observations of secondary infrasound at BGU are a classic example of observations in the zone-of-silence). Further work is required to investigate these issues in more detail, using an extensive dataset of robust associations of earthquake-generated infrasound.

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