Distinguishing natural sources from anthropogenic noise in seismic data

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Main Text

As seismic data are increasingly used to investigate a diverse range of subsurface phenomena beyond regular fast-rupturing earthquakes (Peng and Gomberg, 2010; Beroza and Ide, 2011), it is important to acknowledge that human-generated ground vibrations may be mistaken for naturally-generated subsurface processes (Larose et al., 2015; Li et al., 2018). Correct discrimination of natural processes from anthropogenic noise is especially pressing given the trend in seismic detection research toward automated algorithms and machine learning methods (Yoon et al., 2015; Kong et al., 2019; Mousavi and Beroza, 2022) and the growth in seismic data collection in new environments such as urban and industry settings (e.g., Díaz et al., 2017).

Studies that consider human-generated seismic noises are rare compared to earthquake studies, creating an observation bias that may lead to erroneous categorization of human-generated signals as natural earthquakes. For example, vibrations from freight trains have been mistaken for tectonic tremor, resulting in discussion among researchers in that community (Hutchison and Ghosh, 2017; Inbal et al., 2018, 2023; Li et al., 2018; Hutchison et al., 2023). In a more extraordinary case, seismic signals caused by moving trucks (Fernando et al., 2024) were misinterpreted as the signature of a meteoroid entry in the atmosphere (Siraj and Loeb, 2023) and were used to locate fragments of a supposedly interstellar object (Loeb et al., 2023). Such man-made sources of seismic energy at the surface may continue to cause confusion in other contexts such as the oil, gas, CO_2 sequestration, and geothermal industries (Das and Zoback, 2013a, 2013b; Hu et al., 2017; Chen et al., 2018), or in academic fields such as volcanology (Eibl et al., 2015).

The misidentification of human-generated noise as earthquakes, and especially long period events, not only results in misinterpretation of subsurface processes but can also mislead hazard assessment. As an instructive example, we examine a recent study of seismic signals interpreted as related to CO_2 injection near Wellington, Kansas (Niyogi et al., 2023) and show the signals could be simply explained by nearby train movements. The misinterpretation of these human-generated signals as natural demonstrates the need for ground-truth verification.

In their study, Niyogi et al. (2023) examined seismic signals with long duration (minutes), low frequency (<20 Hz), and gliding harmonics that were first noted by Kumar et al. (2019). Niyogi et al. (2023) attribute the signals to periodic shear failure on a fault in response to elevated pore pressures after CO_2 injection into a depleted oil reservoir at an enhanced oil recovery site in Wellington, Kansas. They support their interpretation with beamforming results that indicate low slowness values corresponding to seismic velocities at depth, as well as source locations near the injection site.

It is worth noting that Li et al. (2018) performed a similar analysis using a much larger dense nodal array at the neighboring state of Oklahoma. With essentially the same beamforming array analysis indicating low slowness values and amplitude decaying away from the nearby Union Pacific railway, that study argued that their observations are more consistent with train-generated noises, rather than naturally-occurring fast-moving masses such as volcanoes or glaciers (Hotovec et al., 2013; Lipovsky and Dunham, 2016).

Given the similarity between the signals observed at Wellington Field (Niyogi et al., 2023) and train noise (Fuchs et al., 2018; Li et al., 2018), we examine publicly-available data from seismometers both within the dense array analyzed by Niyogi et al. (2023) (ZA.WK*) and located along a nearby railroad (GS.KS21, GS.KAN06, and GS.KAN12) (Figure 1a). For an exemplary event documented by Niyogi et al. (2023) we observe similar gliding spectral lines as far as 50 km from the Wellington Field (Figure 1b). Arrival times of the signal on available seismometers are too slow (<0.05 km/s) for seismic wave propagation but are consistent with westbound travel of a train at approximately 50 miles per hour.

Niyogi et al. (2023) also state that the tremor-like signals occur only during the period of active injection at the Wellington Field. However, we find that these signals are common before the start of fluid injection (e.g., Figure 1c). Note that because the frequency characteristics of train signals are primarily controlled by the train's speed near the receiver (Lavoue et al., 2021), the spectrograms may look different at separate locations (Figure 1b,c). On December 19, 2015 alone, we observe at least 30 separate tremor-like events during visual inspection of the spectrogram for station ZA.WK08, accounting for more than 12 hours of signal on that day (Figure 2). Similar activity is observed on other days. The existence of signals that share many of the same features (gliding harmonics over several minutes) as those reported in Niyogi et al. (2023) prior to the start of fluid injection clearly demonstrates that the tremor-like signals are unrelated to the fluid injection.

Array beamforming can be a powerful tool for discriminating between surface and subsurface seismic signals based on slowness values (e.g., Glasgow et al., 2018). However, care must be taken to ensure that the source-receiver geometry validates the plane wave assumption inherent to the method (Rost and Thomas, 2002). The distance of the array from the seismic source must be sufficiently large compared to the array diameter so that the arriving wavefront is effectively planar; otherwise, non-planar wavefront propagation between receivers will degrade estimates of slowness and back azimuth. In the case of Wellington Field, the plane wave approximation is not valid because the array's diameter is similar to its distance from the estimated tremor sources and from the nearest railroads (Figure 1a). Further, when locating the events using beam back projection, Niyogi et al. (2023) assume the tremor occurs at the depth of injection (~1.2 km depth). They locate most of the tremor-like signals to the south and east of the array, in the direction of the closest rail lines (Figure 1a).

While Niyogi et al. (2023) state that the signals' variable timing and duration are inconsistent with passenger train schedules, freight trains operate at irregular times that are not reported to the public. Freight trains also vary considerably in length and weight, resulting in seismic signatures with different durations and spectral properties (Lavoue et al., 2021). Train noises have been detected as far as 90 km from railroads (Inbal et al., 2018), and freight lines traverse much of North America (Pinzon-Rincon et al., 2021), so caution must be taken in interpreting tremor signals in many different contexts and study areas. Wellington Field lies within 5 km of railroads to the east and south (Figure 1a), so detectable train signals can be expected at the ZA array.

Niyogi et al. (2023) use typical criteria to evaluate the seismic signals recorded on a dense array to assess whether the signals were natural, but those tests were insufficient to rule out anthropogenic discrete noise sources. For any unusual seismic signals, analyzing available local and regional stations will aid in the identification of the source of the signals. In particular, it is important to consider known potential noise sources, such as railroads (e.g., Figure 1b,c), wind farms (Schippkus et al., 2020), aircraft (Eibl et al., 2015; Meng and Ben-Zion, 2018), roads (Riahi and Gerstoft, 2015), and even military bases (Cochran and Shearer, 2006; Carmichael et al., 2021). Surface sources can be identified through slow moveout times between stations. If an array is available, moveout rates can be further constrained through beamforming slowness results, as long as plane wave propagation can be assumed, as previously discussed. Additionally, the event timing may reflect human-made sources; for example, signals that recur every 12 hours, 24 hours, 7 days, or during special holidays may be anthropogenic (e.g., Díaz et al., 2017; Zhai et al., 2021; Maher et al., 2024; Chu et al., 2024). However, we cannot definitively use the fact that potential signals do not occur at particular time or recur at a fixed time interval as the argument that they are not anthropogenic. As noted before, certain anthropogenic sources, such as aircraft or freight trains, do not follow a fixed schedule.

Misidentification of train signals has broad implications for the physical source process of seismic tremor. Niyogi et al. (2023) claim that repetitive shear-failure earthquakes can explain tremor observations across a range of environments including hydrocarbon reservoirs, volcanoes, and glaciers. However, alternative source models have been proposed in each of these settings; for example, some tremor could represent fluid flow through deformable channels (e.g., Julian, 1994; Ozaki et al., 2023) or resonance of fluid-filled cavities (e.g., Chouet, 1988, Roeoesli et al., 2014; Tary et al., 2014; Gräff et al., 2019; Sicking and Malin, 2019). The shear-failure model remains one of several plausible hypotheses, but accurate identification of subsurface tremor is required to evaluate it.

The challenges described in this letter and in recent work (Inbal et al., 2018; Hutchison and Ghosh, 2023; Li et al., 2018; Fernando et al., 2024) illustrate the need for broader awareness of seismic noise characteristics and better discrimination of surface noise from subsurface signals. Seismic literature is biased toward examination of shear-failure earthquake signals, but the vast majority of raw seismic data is dominated by a wide variety of surficial and anthropogenic signals. Further, as earthquake detection research increasingly relies on automated algorithms, surface noises may be increasingly miscategorized as subsurface signals. Deep-learning approaches may particularly suffer from the biases present in human-labeled datasets that under-represent noise sources. Timestamps of human activity such as from schedules or field observations are valuable information that can be used to ground truth the seismic data for a known source. Ultra-dense observations such as fiber-optic sensing along major railways or highways can also help identify moving trains or cars (Wang et al., 2020; Zhang et al., 2022). In general, more routine labeling, monitoring, and publishing of noise data would greatly benefit the seismology community. Seismologists should therefore collectively determine best practices for discriminating surface noise from subsurface signals, and increased attention should be paid to ground-truth identification and labeling of surface noise (e.g., Schippkus et al., 2020, Dean and Al Hasani, 2020).

Figures

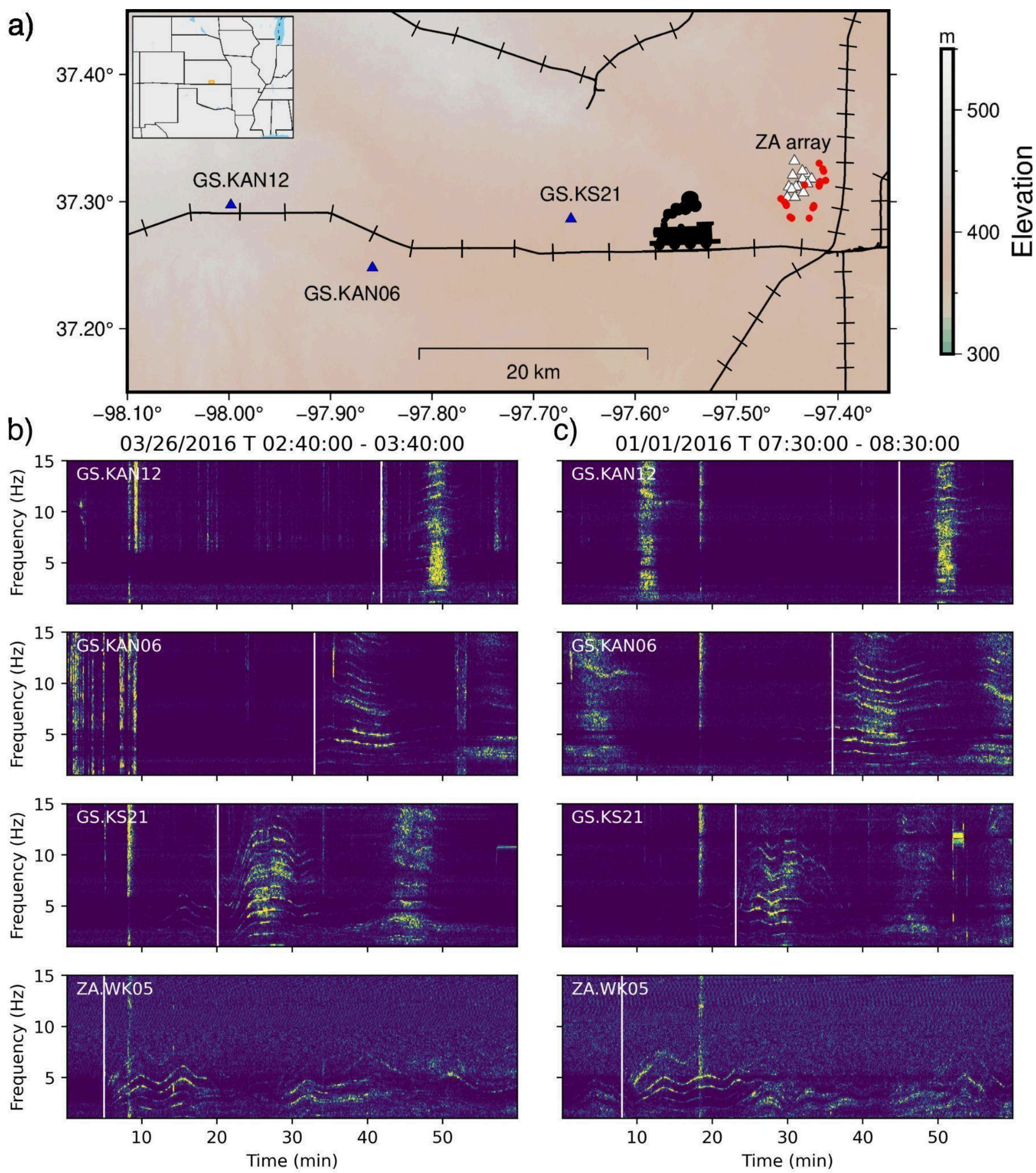

Figure 1. a) Map of study area including stations of the ZA array at Wellington Field (white triangles), tremor location results from Niyogi et al (2023) (red dots), nearby permanent seismic stations (blue triangles) and railroads according to the USGS National Transportation Dataset (black lines) (U.S. Geological Survey, 2024). Inset shows the map area as an orange rectangle. b) Spectrograms at four seismic stations during March 26, 2016 02:40 – 03:40 (UTC),

corresponding to the event shown in Figure 2C of Niyogi et al (2023). Vertical white lines show the tentative timing for a westbound train traveling at 50 miles per hour relative to manually-picked start time at ZA.WK05. c) Spectrograms at four seismic stations during January 1, 2016 07:30 – 08:30 (UTC), before fluid injection. Array and station names are in the top right of each plot. Station ZA.WK05 is station WK05 from the ZA array (Watney, 2014) used by Niyogi et al. (2023).

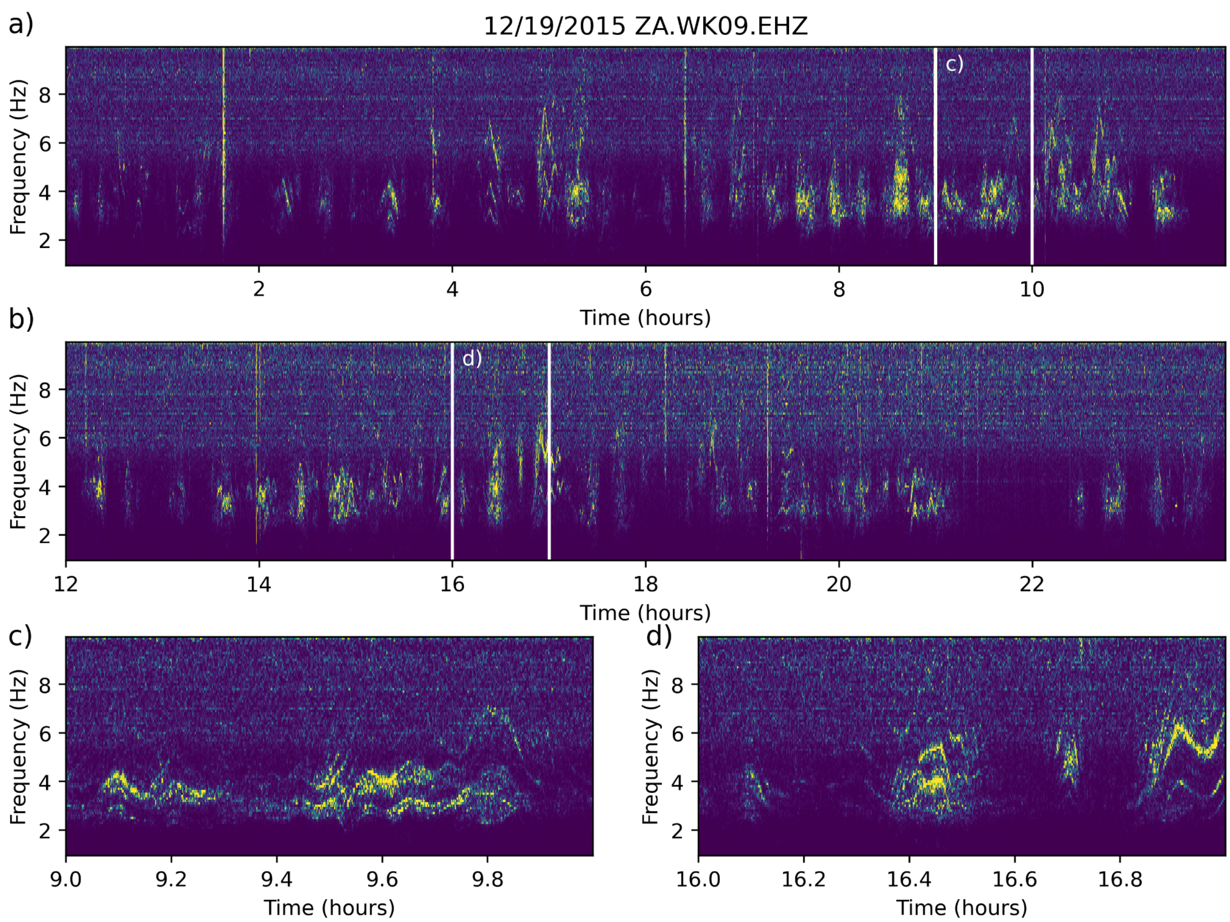

Figure 2. Example of spectrograms for one day of data at one ZA station (Watney, 2014) before the start of fluid injection. Panels a) and b) show the first and second 12 hours of the day on December 19, 2015 (UTC), respectively. Vertical white lines indicate the times used to show one-hour zooms in c) and d).

Data and Resources

Waveform data from the temporary array at Wellington Field are available through the EarthScope Consortium with network code ZA (Watney, 2014). Waveform data from temporary stations KS21, KAN06, and KAN12 are available through the EarthScope Consortium with network code GS (Albuquerque Seismological Laboratory, 1980).

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