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Seismicity and Subterranean Sounds in the Northwest Deccan Volcanic Province of India

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Abstract The northwestern Deccan volcanic province in India is one of the most seismically active intraplate regions of the world. In addition, the region is associated with episodic swarm activity and reports of sounds, whose linkage hitherto remains elusive. During the month of January 2016, a swarm activity occurred in the Kachchh and Saurashtra regions and continued for about two months. Many of the events were accompanied by audible sounds, like blasting, that caused severe panic among local residents, prompting us to investigate the causative mechanism. The events were recorded by our seismic stations and an additional five stations that we were able to deploy at the onset of the swarm. The activity produced sounds with good energy in the audible frequency range of humans. Spectrogram analysis of the events with associated sounds revealed frequencies ≥20 Hz, in contrast to the lower frequencies for those that did not generate the sounds. In addition to the higher frequencies, we observed horizontal particle motion that was dominated by retrograde elliptical motion consistent with Rayleigh waves. These observations were not recorded from any of the events that did not generate sounds. Audible sounds generated by earthquakes are consistently reported from shallow earthquakes that generate high-frequency surface waves.

Introduction

Most sounds that people hear or experience are due to some type of anthropogenic noise, sonic boom, trains, airplanes, explosions, etc. However, there have been several reports of earthquake sounds that cannot be explained by man-made sources. These are heard similar to loud rumbling up to several kilometers around the epicentral area during or immediately before an event (e.g., Tosi *et al.*, 2000, 2012). Other subterranean sounds like blasting are heard within a few kilometers. The sound heard prior to shaking is mainly produced by *P* waves (Hill *et al.*, 1976), whereas noticeable shaking is often coupled with *S* waves.

Sometimes people have recorded these sounds on a tape recorder, providing evidence for energy at frequencies ≥20 Hz, because the tape-recorded response typically falls off rapidly below that value. The attenuation of audibility of the sound indicates that hearing is proportional to the logarithm of epicentral distance and linearly depends on earthquake magnitude, in accordance with the behavior of the ground displacement (Tosi *et al.*, 2000, 2012). The earthquake sound that is audible to humans is generated by the coupling of shallow seismic waves with the atmosphere (Hill *et al.*, 1976). In this process, the soil behaves as the moving diaphragm of a loudspeaker, transmitting sound directly to the observer (Hill *et al.*, 1976). As suggested by studies of infrasonic waves (Le Pichon *et al.*, 2002), the generation of sound near the epicenter is the result of propagation of air waves produced in the epicentral region (Mikumo, 1968), the radiation produced from secondary sources such as high mountains (Young and Greene, 1982), and the coupling of ground with air (Kanamori *et al.*, 1991). Sound propagation through the atmosphere is affected by several factors such as pressure fluctuations, temperature variations, and wind patterns (Ross, 2000; Sbarra *et al.*, 2010). Generally, earthquake sounds do not cause property damage and loss of life but can create fear and panic among local residents.

The mechanism of earthquake sound is not well understood, and is probably generated by shallow earthquakes that are too small to be recorded but large enough to generate a sound heard by people nearby. Instances of such sounds were reported by several researchers worldwide (e.g., Steinbrugge, 1974; Hill *et al.*, 1976; Stierman, 1980; Tosi *et al.*, 2000; Peng *et al.*, 2012). Some studies in different tectonic regimes show that earthquake sounds are caused by swarms containing events of magnitude −2 to 2.1 occurring at depths shallower than 2.4 km (e.g., Davison,

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1938; Ebel, 1982; Mallet and Mallet, 1985). A catalog of earthquake sounds generated by natural earthquakes, man-made structures, and human reactions to the shaking was compiled by Steinbrugge (1974).

In January 2016, swarm-type activities occurred near Chobari and Khopala villages of Kachchh and Saurashtra, respectively (Fig. 1), and continued for about two months. The swarm was localized in each of these regions and the earthquakes had magnitudes between 0.8 and 2.5. Many of the events were accompanied by audible sounds with or without shaking, which caused severe panic among the local residents (*The Times of India*, Ahmedabad, 29 May 2016). These swarms rekindled the fear of catastrophic damages like those caused by the 2001 Bhuj earthquake in the Kachchh district (Gupta *et al.*, 2001). Although there were no reports of damages or casualties, people were not willing to stay inside or sleep in their homes due to the sounds. The recent swarm activity is recorded at some of the stations that constitute a regional network of 54 broadband seismographs and 56 strong-motion accelerographs operated by the Institute of Seismological Research (ISR) since 2006, for near-real-time monitoring of seismicity in the northwestern Deccan volcanic province (NWDVP). Seismograms of swarm activities at stations Chobari (CHO) and Khopala (KOL) show several events within a short duration. The waveforms recorded at the nearby seismic stations consist of several high-frequency peaks (Fig. 1b). In the present study, we analyzed the waveforms recorded at local stations installed in and around both the villages to understand the mechanism of sounds generated by swarms.

Earthquakes and Swarm Activity in NWDVP

The NWDVP of India can be physiographically divided into three parts, namely Kachchh, Saurashtra, and mainland Gujarat (Fig. 1a). Despite being away from the active plate boundaries, each of these regions has experienced moderate-to-major (intraplate) earthquakes for more than two centuries (Oldham, 1926; Tandon, 1959; Gupta *et al.*, 2001). The prominent events in the region are the 1819 M_w 7.8 Allah Bund, the 1845 M_w 6.3 Lakhpat, the 1956 M_w 6.0 Anjar, and the 2001 M_w 7.7 Bhuj earthquakes. In the eastern part of Saurashtra, earthquakes of $M_w < 6$ have occurred near Bhavnagar, which lies in the proximity of the west Cambay fault. Although the Narmada rift zone has experienced shocks up to magnitude 5.4 (that occurred at Bharuch in 1970), earthquakes of magnitude more than 6.0 have occurred to the east of Gujarat (Bhattacharya *et al.*, 2004). Compared with Narmada and Kachchh, the Cambay rift has shown less seismicity, confined more to its southern part, with a maximum earthquake magnitude of 5.7.

Aftershocks of the devastating Bhuj earthquake are still continuing (Singh *et al.*, 2012, 2015; Mandal, 2013). More than 10,000 local earthquakes in the 2.0–5.1 magnitude range have been recorded by the Seismic Network of Gujarat (SeisNetG) during August 2006 to March 2016 (Fig. 1a).

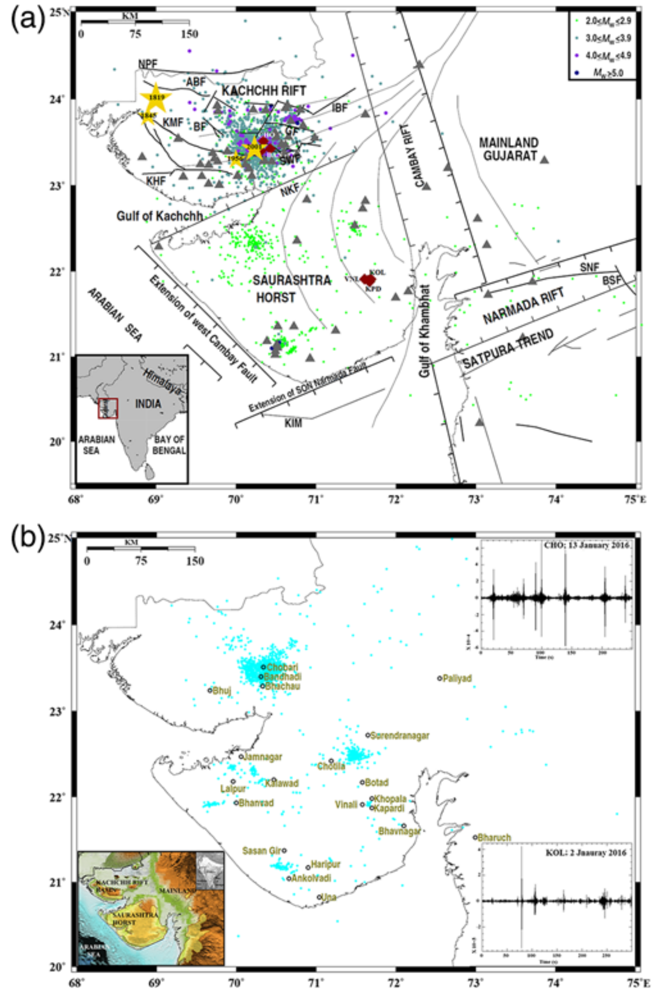

Figure 1. (a) Map of the major tectonic features in the Gujarat state. Thick and thin lines indicate the faults and lineaments, respectively. Stars indicate past earthquakes and dots indicate epicenters of earthquakes that occurred during the period August 2006 to September 2016. The triangles represent seismic stations operated by the Institute of Seismological Research. Diamonds represent the stations used in this study. (b) Map showing epicentral locations of earthquakes of magnitude ≤ 1.9 that occurred during the period August 2006 to September 2016. The regions with recent swarms at Chobari (Kachchh) and Khopala village, Botad (Saurashtra), which are about 10 and 140 km away from the 2001 Bhuj epicenter (M_w 7.7), respectively. (Inset) Lower left shows topographic map of the Gujarat regions and lower right is vertical-component seismogram of the swarm activities on 2 January 2016 at Khopala (KOL), whereas the right top shows the seismogram of the swarm activities recorded on 13 January 2016 at Chobari (CHO). The color version of this figure is available only in the electronic edition.

The Kachchh region accounts for ~70% of the total events in the NWDVP, where a total of 7000 shocks of M_w 2.0–5.0 are located. Although a total of 2700 shocks of M_w 2.0–5.1 (~27% of the total earthquakes events) are recorded from Saurashtra, the mainland Gujarat accounts for ~3% of the seismicity, with 300 shocks of M_w 2.0–3.2. Seismicity in the Kachchh region is mostly confined to depths of 15–35 km and is related to the rift basin (Mandal, 2013; Singh *et al.*, 2015). The Saurashtra region shows much shallower (3–6 km) seismicity, controlled by a horst-type structure bound by faults (Singh and Mishra, 2015). In mainland Gujarat, the seismicity is sparse and confined to the midcrust. Apart from these, a number of earthquakes of $M_w \leq 1.9$ have also been recorded, with large uncertainties in the epicentral parameters (Fig. 1b).

Historically, earthquake swarm activity occurred in and around Paliyad in Bhavnagar (Saurashtra) during July–August 1938 (Srivastava and Rao, 1997). This swarm contains four earthquakes of $M_w \geq 5.0$ with the maximum magnitude being 6.0 (Srivastava and Rao, 1997; Bhattacharya *et al.*, 2004). There were more than 190 shocks associated with blasting sound (Srivastava and Rao, 1997). The city of Bhavnagar has experienced swarm activity with a largest event of M_w 3.6, followed by 43 shocks during 9–25 August 2000. The same area again experienced swarm activity comprising earthquakes of $M_w \leq 4.2$ during August–October 2000. There were about 130 shocks associated with subterranean sounds (Bhattacharya *et al.*, 2004). In Una district, an event of M_w 4.6 occurred on 13 August 2000, followed by a few smaller events. During October–December 2001, the Sasan Gir area (Haripur village) experienced swarm activity with a largest event of M_w 3.2 recorded on 11 November 2001, followed by 1689 shocks of smaller magnitudes. Most of these shocks were accompanied by sounds and occasional shaking. Subsequently, during 2003–2004, the Sasan Gir area (Haripur) witnessed swarm activity with the events having magnitudes less than 3.1. The shocks were felt together with sound. Furthermore, during 2003, another swarm activity was reported from the Sasoi Dam near Lalpur area. The largest event in this swarm had a magnitude of 3.0, which was followed by numerous small shocks that were felt with blast-like sounds. After installation of the ISR seismic network in 2006, swarms have been reported at several places such as Lalpur, Kalawad, Chotila, Botad, Chobari, Surendranagar, and Ankolvadi (Saurashtra) in the NWDVP, Gujarat (Chopra *et al.*, 2008; ISR annual report, unpublished manuscript, 2013; see Data and Resources). The swarms were highly localized and subsided within a month. Earlier reports suggest that swarm activity in the Saurashtra region is generally observed after heavy rainfall during the Indian summer monsoon period (Chopra *et al.*, 2008, Singh and Mishra, 2015). Several hypotheses have been introduced to explain swarm activities; they include localized self-organized stress field, pore pressure, hydrothermal activity, and increase in pressure due to magma at shallower depth (Stuart and Johnston, 1975; Špičák and Horálek, 2001; Singh and Mishra, 2015).

The dense seismic network in the Kachchh region enables detection of earthquakes down to M_w 0.5. In Saurashtra, we installed a small network of five broadband seismic stations (Fig. 1a) and one strong-motion accelerometer within a radius of 8 km from the Khopala village in order to record smaller earthquakes. The data were recorded at 50 and 100 samples per second at stations CHO and KOL, respectively. Station spacing varies between 2 and 10 km for the studied events. The frequency range of earthquake signals recorded by SeisNetG lies between 0.008 and 50 Hz, which is at the lower end of the human audio spectrum, that is, 20 Hz to 20 kHz. At Chobari village, about 200 events of magnitude 0.8–2.5 were recorded during the period 1–22 January 2016. About 54 events with magnitudes between 0.8 and 1.8 were recorded near Khopala village during the period of 30 December 2015 to 27 February 2016 (Fig. 1b). These swarms were relocated using double-difference (hypoDD) algorithm (Waldhauser and Ellsworth, 2000). The hypoDD incorporates absolute travel-time measurements to determine high-resolution hypocenter locations. Residuals between the observed and theoretical travel-time differences are minimized for pairs of earthquakes at each station while linking together all the observed event–station pairs. A least-squares solution has been used for iterative adjustment of the vector difference between the hypocentral pairs. We used a total of five iterations for the conjugate gradient method with the hypoDD inversion scheme. The travel-time difference has been estimated for all event pairs with an interevent separation of less than 3 km for stations located in the range of 2–10 km radius from the clustered centroid. A maximum of 4–6 neighboring events linked to each other were considered for the relocation. The depths of the hypocenters vary between 1.2 and 3.7 km. The errors in depth and epicentral locations are found to be ±1.0 and ±0.20 km, respectively.

Spectrograms

We computed the spectrograms of records from stations KOL in Saurashtra and CHO in Kachchh, where sounds due to swarm events are reported. Additionally, we analyzed some more data recorded at stations Vinali (VNL) and Bandhadi (BAN) to understand the nature of signals that produced sounds and those that did not (Figs. 1 and 2). We present and discuss our spectrogram analysis for representative swarm (Figs. 2–5) and natural earthquake waveforms (Fig. 6). The general characteristics of the other waveforms are similar. The spectrograms reveal that the energy is mostly concentrated at frequencies around 20 Hz or more, closer to the audible range (Figs. 2b, 3b, 4b, 5b, and 7a–c). The background noise preceding the swarm signal could be related to microseisms. Also, the vertical components reveal two dominant frequencies between 2.5 and 5 Hz (Figs. 2b, 3b, 4b, 5b, 6b, and 7) reflecting local site effects. Similarly, the spectrograms at the SeisNetG stations, Kapardi (KPD), VNL, and BAN, slightly away from the source zones, reveal energy in the audio frequency range. However, the spectrograms of waveforms corresponding to natural earthquakes of similar magnitude that are not accompanied by sound and recorded at stations in similar distance ranges show that the maximum energy concentration is in the frequencies less than those in the audible range (Figs. 6b and 7d).

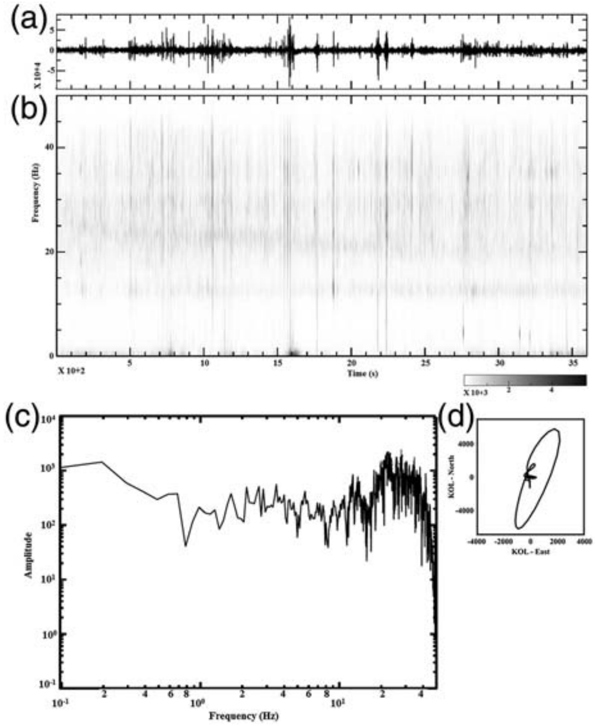

Figure 2. (a) Vertical-component seismogram recorded at 14:00 UTC on 5 January 2016 at KOL, Saurashtra, Gujarat, (b) corresponding spectrogram panel showing maximum energy at frequencies > 20 Hz, which are closer to the audible range, (c) amplitude spectrum, and (d) particle motion plots for the north–south and east–west horizontal components of the first few seconds of the swarm waveforms.

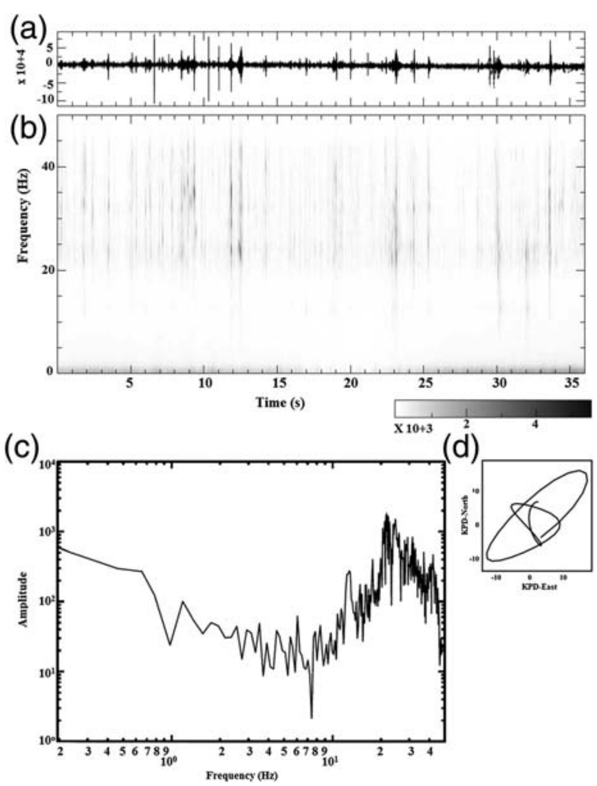

Figure 3. Same as Figure 2 but for waveform recorded at 06:19 UTC on 10 January 2016 at station Kapardi (KPD), Saurashtra, Gujarat.

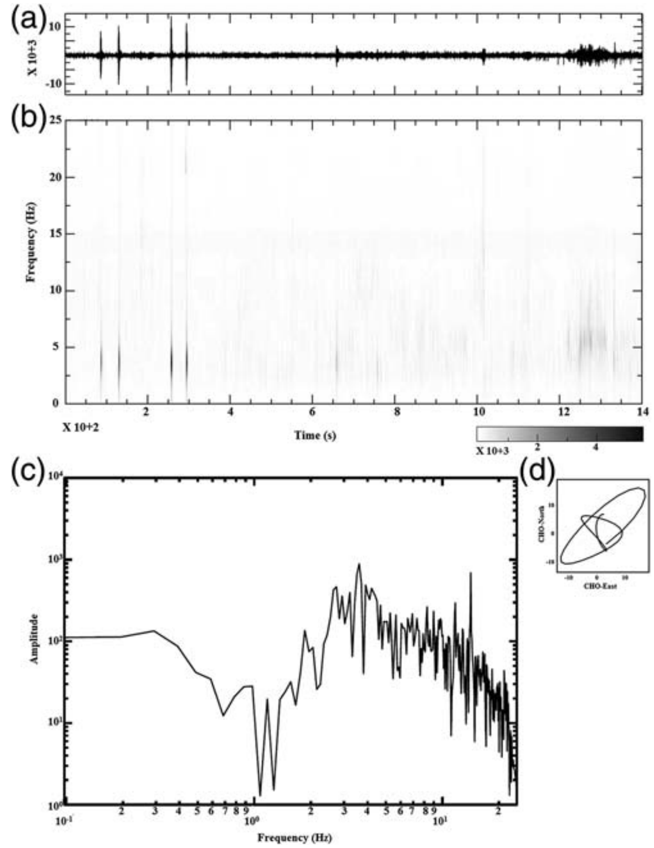

Figure 4. Same as Figure 2 but for seismic waveform recorded at 13:33 UTC on 11 January 2016, at station CHO, Kachchh, Gujarat.

Amplitude Spectra

In addition, the amplitude spectra of the waveforms of swarm earthquakes from both regions (Figs. 2c, 3c, 4c, and 5c) show predominance of energy in frequencies ≥ 10 Hz, which is probably due to the high-frequency ground motion generated by shallower hypocenters. The swarms recorded at CHO and BAN seismic stations in the Kachchh region during 10–15 January 2016 show energy in a different frequency range compared with the natural earthquake of similar magnitude recorded at CHO station at the same hypocentral distance (Figs. 4a, 5a, and 6a). The earthquake recorded at CHO did not generate any sound. The waveforms and the frequency content appear different compared with those that produced sounds (Figs. 2c, 3c, 4c, and 5c). In the case of a natural earthquake, we see energy in a lower frequency range compared with the swarm events, probably due to a different strain level at the source. The frequency of seismic energy radiated from the source is related to a particular dimension of the asperity on the fault. Large-dimension asperity radiates lower-frequency signals and vice versa. The large earthquakes have larger asperities, so they radiate lower-frequency signals compared with swarm events. Although it is not directly related to depth, the dimension of the asperity seems to decrease with depth, hence deeper events may radiate

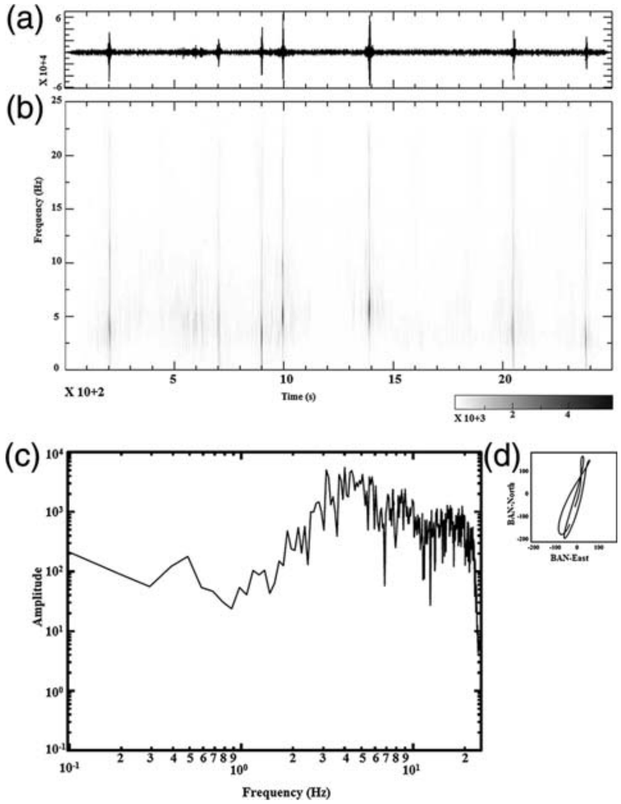

Figure 5. Same as Figure 2 but for seismic waveform recorded at 13:45 UTC on 14 January 2016, at station Bandhadi (BAN), Kachchh, Gujarat.

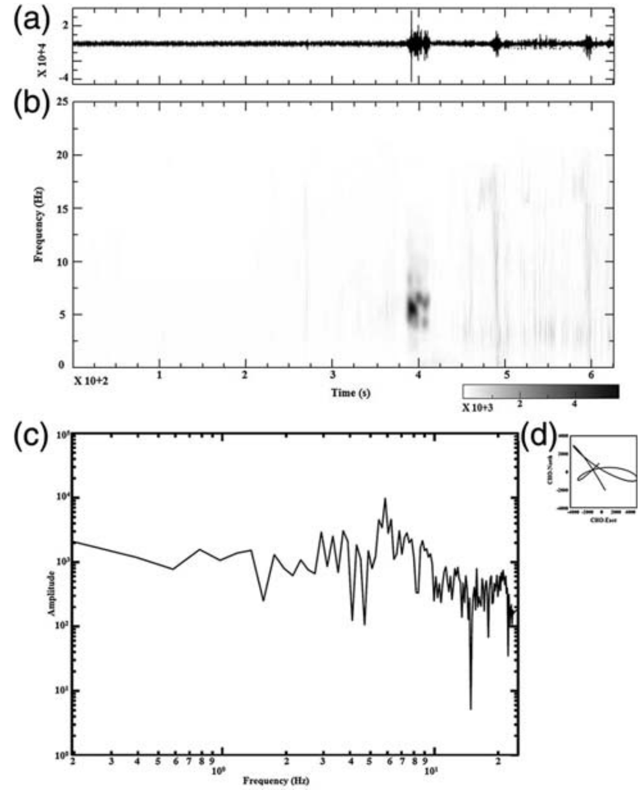

Figure 6. Same as Figure 2 but for a natural earthquake that occurred at 08:59 UTC on 15 January 2016 recorded at station CHO, Kachchh, Gujarat.

more higher-frequency signals than shallower events of the same magnitude.

The higher-frequency range seen in stations within Saurashtra compared with the Kachchh seismic stations is due to the higher sampling rate. The spectra of the recorded wave forms are akin to those of an acoustic signal, with frequencies between 20 and 50 Hz. The signal is similar to a surface wave which dies out in a very short duration. These observations are consistent with the reports of a low-rumbling sound frequently accompanied by earthquakes in the January 1975 swarm (Hill *et al.*, 1976).

Conclusions

The NWDVP is associated with swarm activity, in addition to being one of the most active intraplate earthquake regions in the world. We analyzed swarm activities recorded over a period of one month in Chobari and Botad areas in Gujarat to understand the mechanisms that cause sounds. These swarms occur at depths <4 km with magnitudes varying between 0.5 and 2.0. However, natural earthquakes in the study area are deeper (10–35 km). Spectrogram analysis seems to be a robust way of characterizing earthquakes and swarms that generate subterranean sounds, from those that do not. In the former case, the maximum spectral amplitudes are seen at frequencies ≥ 20 Hz, in the audible range perceived by humans. The elliptical shape of the particle motions suggests that they are Rayleigh waves generated by small shallow earthquakes.

Data and Resources

We used the waveform data recorded by the Seismic Network of Gujarat (SeisNetG) during August 2006 to April 2016 and we installed five temporary stations at the onset of the swarm. The SeisNetG is operated by the Institute of Seismological Research (ISR), Gandhinagar, Gujarat, India (www.isr.gujarat.gov.in, last accessed September 2016). The unpublished annual report 2013 by ISR was also referred to in this article. The catalog of the events is compiled at ISR. We used the Seismic Analysis Code for seismic-waveform data analysis. Many of the figures are produced using the Generic Mapping Tools software (Wessel and Smith, 1995).

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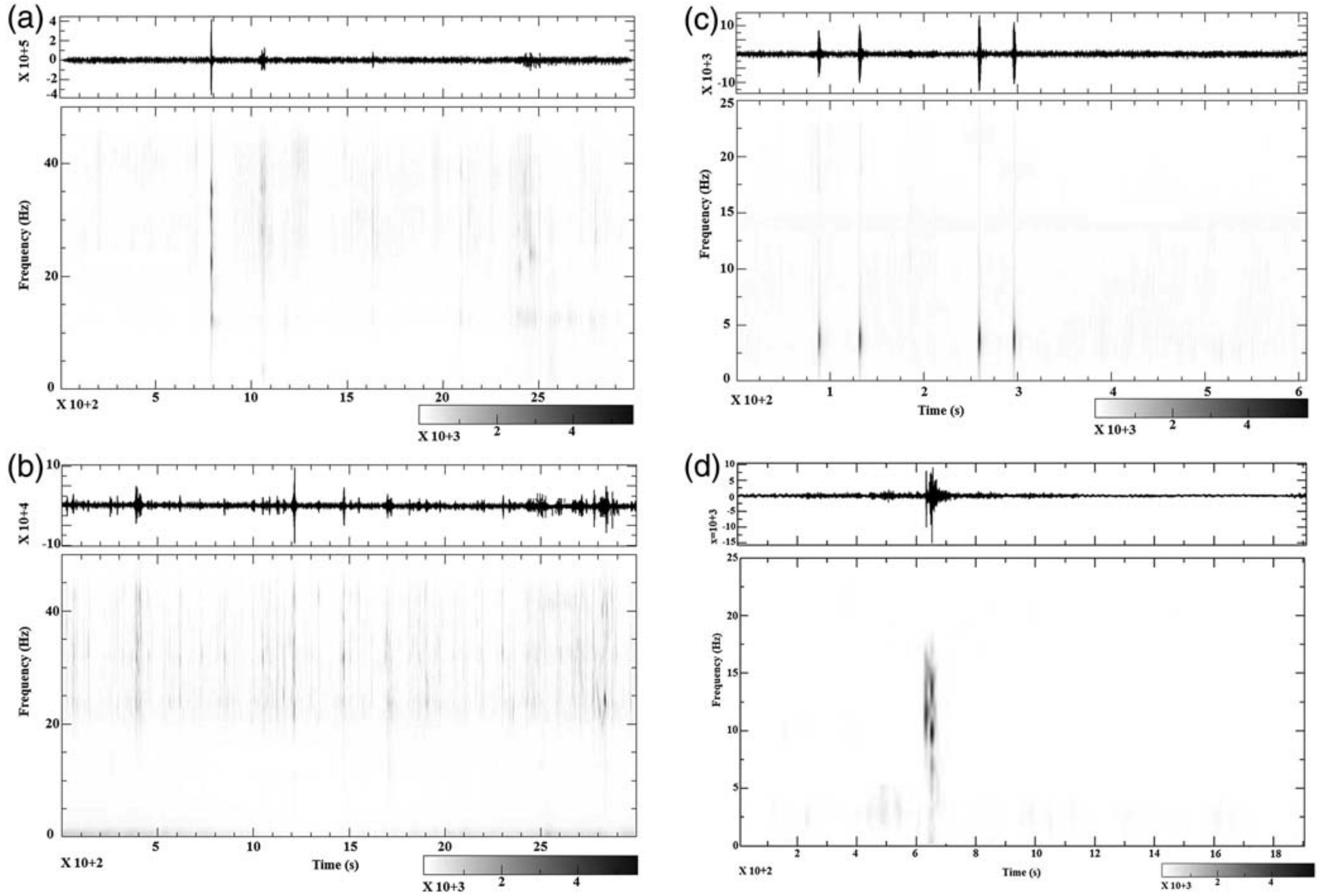

Figure 7. Spectrogram of (a) swarm event that occurred at 06:33 UTC on 2 January 2016 at KOL, Saurashtra, Gujarat, (b) swarm event that occurred at 06:59 UTC on 10 January 2016 at VNL, Saurashtra, Gujarat, (c) swarm event that occurred at 07:09 UTC on 11 January 2016 at CHO, Kachchh, Gujarat, and (d) natural earthquake that occurred at 13:07 UTC on 16 January 2016 at BAN, Kachchh, Gujarat.

References

Bhattacharya, S. N., K. V. Karanth, R. S. Dattatrayam, and P. S. Sohoni (2004). Earthquake sequence in and around Bhavnagar, Saurashtra, western India during August–December 2000 and associated tectonic features, *Curr. Sci.* **86,** no. 8, 1165–1170.

Chopra, S., K. M. Rao, B. Sairam, S. Kumar, A. K. Gupta, H. Patel, M. S. Gadhavi, and B. K. Rastogi (2008). Earthquake swarm activities after rains in Peninsular India and a case study from Jamnagar, *J. Geol. Soc. India* **72,** 245–252.

Davison, C. (1938). Earthquake sounds, *Bull. Seismol. Soc. Am.* **28,** no. 3, 147–161.

Ebel, J. E. (1982). The 1981 micro earthquake swarm near Moodus, Connecticut, *Geophys. Res. Lett.* **9,** no. 4, 397–400.

Gupta, H. K., T. Harinarayana, M. Kousalya, D. C. Mishra, I. Mohan, N. P. Rao, B. K. Rastogi, P. R. Reddy, and D. Sarkar (2001). Bhuj earthquake of 26 January 2001, *J. Geol. Soc. India* **57,** 275–278.

Hill, D. P., F. G. Fischer, K. M. Lahr, and J. M. Coakley (1976). Earthquake sounds generated by body-wave ground motion, *Bull. Seismol. Soc. Am.* **66,** no. 4, 1159–1172.

Kanamori, H., D. Mori, D. L. Anderson, and T. H. Heaton (1991). Seismic excitation by space shuttle, *Nature* **349,** 781–782.

Le Pichon, A., J. Guilbert, A. Vega, M. Garces, and N. Brachet (2002). Ground-coupled air waves and diffracted infrasound from the Arequipa earthquake of June 23, 2001, *Geophys. Res. Lett.* **29,** no. 18, 1886.

Mallet, C. E., and J. W. Mallet (1985). *The Earthquake Catalogue of the British Association with the Discussion, Curves, and Maps, Etc*, British Association for the Advancement of Science, London, 768 pp.

Mandal, P. (2013). Seismogenesis of the uninterrupted occurrence of the aftershock activity in the 2001 Bhuj earthquake zone, Gujarat, India, during 2001–2010, *Nat. Hazards* **65,** 1063–1083.

Mikumo, T. (1968). Atmospheric pressure waves and tectonic deformation associated with the Alaskan earthquake of March 28, 1964, *J. Geophys. Res.* **73,** no. 6, 2009–2025.

Oldham, R. D. (1926). The Cutch (Kachh) earthquake of 16th June, 1819 with a revision of the great earthquake of 12th June, 1897, *Memoir Geol. Surv. India* **46,** 71–146.

Peng, Z., C. Aiken, D. Klib, D. R. Shelly, and B. Enescu (2012). Listening to the 2011 Magnitude 9.0 Tohoku-Oki, Japan, earthquake, *Seismol. Res. Lett.* **83,** 287–293.

Ross, C. D. (2000). Outdoor sound propagation in the US Civil War, *Appl. Acoust.* **59,** 137–147.

Sbarra, P., P. Tosi, and V. De Rubies (2010). Web-based macroseismic survey in Italy: Method validation and results, *Nat. Hazards* **54,** no. 2, 563–581.

Singh, A. P., and O. P. Mishra (2015). Seismological evidence for monsoon induced micro to moderate earthquake sequence beneath the 2011 Talala, Saurashtra earthquake, Gujarat, India, *Tectonophysics* **661,** 38–48.

Singh, A. P., O. P. Mishra, D. Kumar, S. Kumar, and R. B. S. Yadav (2012). Spatial variation of aftershocks activity across the Kachchh rift Basin and its seismotectonic implications, *J. Earth Syst. Sci.* **121,** no. 2, 439–451.

Singh, A. P., I. G. Roy, S. Kumar, and J. R. Kayal (2015). Seismic source characteristics in Kachchh and Saurashtra regions of western India: b-value and fractal dimension mapping of aftershock sequences, *Nat. Hazards* **77,** no. 1, 33–49.

Špičák, A., and J. Horálek (2001). Possible role of fluids in the process of earthquake swarm generation in the West Bohemia/Vogtland seismoactive region, *Tectonophysics* **336,** nos. 1/4, 151–161.

Srivastava, S., and D. T. Rao (1997). Present status of seismicity of Gujarat, *Vayu Mandal* Jan–Jun, **27,** 32–39.

Steinbrugge, K. V. (1974). A catalog of earthquake related sounds, *Bull. Seismol. Soc. Am.* **64,** no. 5, 1409–1418.

Stierman, D. J. (1980). Earthquake sounds and animals cues; some field observations, *Bull. Seismol. Soc. Am.* **70,** no. 2, 639–643.

Stuart, W. D., and M. J. S. Johnston (1975). Intrusive origin of the Matsushiro earthquake swarm, *Geology* **3,** no. 2, 63–67.

Tandon, A. N. (1959). The Rann of Katch earthquake 21 July 1956, India, *J. Met. Geophys.* **10,** 137–146.

Tosi, P., V. D. Rubeis, A. Tertulliani, and C. Gasparini (2000). Spatial patterns of earthquake sounds and seismic source geometry, *Geophys. Res. Lett.* **27,** no. 17, 2749–2752.

Tosi, P., P. Sbarra, and V. D. Rubeis (2012). Earthquake sound perception, *Geophys. Res. Lett.* **39,** no. 24, L24301, doi: 10.1029/2012GL054382.

Waldhauser, F., and W. Ellsworth (2000). A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.* **90,** no. 6, 1353–1368.

Wessel, P., and W. Smith (1995). New version of the Generic Mapping tools (GMT) version 3.0 released, *Eos Trans. AGU* **76,** 329.

Young, J. M., and G. E. Greene (1982). Anomalous infrasound generated by the Alaskan earthquake of 28 March 1964, *J. Acoust. Soc. Am.* **71,** 334–339.

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