Source of unusual monochromatic wave packets recorded globally in the seismograms of 11 November 2018

S. N. Bhattacharya¹, V. K. Gahalaut¹,²,*, Narendra Pandey¹, Shankar Pal¹, Rajeev Manhas¹ and G. Suresh¹

¹National Center for Seismology, New Delhi 110 003, India
²Present address: CSIR-National Geophysical Research Institute, Hyderabad 500 007, India

On 11 November 2018, all global seismic stations recorded unusual long-period wave packets without any discernible body waves. Our analyses show that the wave packets are monochromatic with period 15.6 sec and are fundamental-mode non-dispersive Rayleigh waves. Using the arrival times of wave packets, the source is approximately located at the northeastern edge of the recent earthquake swarm zone, off the east coast of Mayotte, a volcanic island between North Madagascar and East Africa. Synthetic seismograms for an isotropic source at 15 km depth with a transient oscillation of the same period as that observed in the wave packets, are consistent with the recorded seismograms. We estimate an equivalent magnitude (M_w) of ~4.8 for this source and suggest that a volcanic fluid sphere of radius ~5 km might have generated such radial oscillations. Interestingly, similar monochromatic waves with lesser amplitude were also recorded on many occasions from the same source during 21 June 2018 to 10 September 2019. The period of waves increased from 15.2 sec in June to 15.6 sec in October–November 2018 and then decreased to 15.0 sec in September 2019, which implies an increase and then decrease in radius of the fluid sphere at the source.

Keywords: Monochromatic wave packets, seismograms, seismic stations, source characterization.

On 11 November 2018, all global seismic stations recorded unusual long-period wave packets without any discernible body waves. Our analyses show that the wave packets are monochromatic with period 15.6 sec and are fundamental-mode non-dispersive Rayleigh waves. Using the arrival times of wave packets, the source is approximately located at the northeastern edge of the recent earthquake swarm zone, off the east coast of Mayotte, a volcanic island between North Madagascar and East Africa. Synthetic seismograms for an isotropic source at 15 km depth with a transient oscillation of the same period as that observed in the wave packets, are consistent with the recorded seismograms. We estimate an equivalent magnitude (M_w) of ~4.8 for this source and suggest that a volcanic fluid sphere of radius ~5 km might have generated such radial oscillations. Interestingly, similar monochromatic waves with lesser amplitude were also recorded on many occasions from the same source during 21 June 2018 to 10 September 2019. The period of waves increased from 15.2 sec in June to 15.6 sec in October–November 2018 and then decreased to 15.0 sec in September 2019, which implies an increase and then decrease in radius of the fluid sphere at the source.
The absence of body waves prior to the surface wave-like wave packets of 11 November 2018 implies that either the source of the event has small magnitude or it is a slow, non-double couple event. Yet, it is surprising that the wave packets were recorded worldwide; the waves were well-recorded at far-off stations, like Sierra La Laguna (SLBS), Baja California, Mexico at a distance of 154° from the source and at Pohakuloa (POHA), Hawaii, USA at a distance of 159°. Here we analyse the records of 11 November 2018 at seismic stations around Comoros archipelago (Figure 1c) and also at other global stations to obtain some fundamental characteristics of the wave packets and their possible source.

Data

We analysed broadband seismic data (flat velocity response at least up to 120 sec) pertaining to the 11 November 2018 event from seismic stations in the Indian region, acquired by the National Centre for Seismology, New Delhi along with data from Incorporated Research Institutions for Seismology (IRIS) at other global stations (Figure 1c). We considered the data with 1 sample/sec, containing waves above period 2 sec. Figure 2 shows an example of three-component (V, N–S, E–W) unfiltered record at station KOD. To improve clarity in the signal, a bandpass filter 0.02–0.2 Hz was used. However, at some stations close to the Mayotte Island, noise was large in the frequency band 0.1–0.2 Hz, and so a band pass filter 0.02–0.1 Hz was required for clarity. In Figure 3 we display the filtered vertical-component seismograms at stations with varying azimuths and distances, where distance (Δ) is computed from the assumed source location as mentioned in the previous section.

Wave characteristics

Amplitude spectra

The period of waves in the seismograms did not change with time (Figures 2 and 3). We obtained amplitude spectra, which showed that the event at all 24 stations (Figure 3) had a dominant peak at period 15.63 sec, except at distant stations like POO, COCO and DHRM, where the peak was at 15.52, 15.75 and 15.75 sec respectively (Figures 4 and 5). Thus on average, the peak was at 15.6 sec. Other secondary peaks had spectral amplitudes less than one-tenth of the amplitude at 15.6 sec. Such sharp peaks,
present at all stations, suggest that the recorded waves of 11 November 2018 are monochromatic with period of 15.6 sec and thus are non-dispersive.

Variation of amplitude with distance and azimuth

The maximum in the amplitude envelopes of the wave packets, in general, decreased with distance in all directions from the assumed source (Figure 3). Further, amplitudes at nearly same distances were approximately same, irrespective of the direction, implying an isotropic nature of the source. At short-distance stations ($\Delta < 30^\circ$, Figure 3a) only one wave packet was recorded, whereas at many distant stations ($\Delta > 30^\circ$, Figure 3b and c), two or three wave packets were recorded, which may be due to the arrival of waves from different wave paths$^{5,6}$.

Particle motion

The three-component record showed that the wave packet arrived at the same time at all components and no other wave prior to this was seen in the horizontal component
(Figure 2). This indicates the presence of Rayleigh waves and absence of Love waves in the records. To confirm this further, we estimated the radial and transverse components at each station by rotating the N–S and E–W components for different back azimuths. We considered the back azimuth of a station as one which showed maximum amplitude in the radial component and minimum in the transverse component (Figure 6). The amplitudes in the transverse components at all stations were found to be significantly smaller than those in the vertical and radial components. This again confirms the absence of Love waves in the records. The estimated back azimuths were close to the direction of the assumed source.

Using the radial and vertical components, particle motion was drawn on a vertical plane through the wave path (Figure 7). The particle motion exhibited retrograde elliptic motion and further confirmed that wave packets are actually the Rayleigh waves. However, at a few stations the major axis of the ellipse was slightly tilted from the vertical, which may be due to some lateral heterogeneity around the stations.

Source characterization

Origin time

For the near-source stations ($\Delta < 30^\circ$), we could mark the arrival times of the wave packets quite unambiguously (Figure 3a). However, at stations beyond $30^\circ$ distance, unambiguous identification of arrival times of the wave packets was generally not possible, except at a station KOD (Figure 3b). Azimuths from the source to stations MSEY and KOD were nearly the same (Figure 1b). We observed that the arrival time at KUBO was 21 sec after FOMA, which is nearly in accordance with $\Delta$ value of the two stations. However, arrival time at MSEY was 28 sec earlier than that at FOMA, although $\Delta$ value was 0.45° more for the former. The difference in arrival times may be due to the difference in the Rayleigh wave speed along the two wave paths. However, to accommodate a part of the arrival time difference, the actual source location may be about 0.2° towards northeast of the assumed location. With such a shift, the source was estimated to be located at the northeastern edge of the swarm zone (Figure 1b), which corresponds to a location between the Mayotte island and Geiser bank.

Mechanism

In the recorded seismograms of the event, the $P$- and $S$-waves were not visible but Rayleigh waves were clear and non-dispersive. To explore this theoretically, synthetic seismograms were generated using the PREM earth model. In this model, the ocean thickness is assumed as 3 km. Synthetic seismograms were obtained at the bottom of ocean following Bhattacharya. We assumed an isotropic source at 15 km depth with a monochromatic time-derivative source–time–function of period 16 sec (Figure 8a). The assumption of isotropic source was based on observations that the seismograms had no Love waves but only Rayleigh waves, whose amplitude was nearly the same at the same distances in all azimuths.

Figures 8b and c shows the vertical and radial components of synthetic seismograms at epicentral distances 20° and 50°. We do not show the transverse components whose amplitudes are zero in these synthetics, consistent with the relatively smaller amplitude observed in the transverse component (Figure 6) at all stations. Synthetic seismograms show that not only are $P$- and $S$-waves weak, but also the Rayleigh wave amplitudes are relatively
Figure 5.  a, Amplitude spectra of velocity of the vertical components of stations in Figure 3a.  b, Same as (a), but for stations in Figure 3b.  c, Same as (a), but for stations in Figure 3c.

Figure 6. Vertical (V), radial (R) and transverse (T) components at station CRZF. Scale is the same for all the three-components. The amplitude in the T-component is significantly small compared to the V- and R-components.

large. However, with increase in focal depth, the amplitudes of P- and S-waves increase relative to those of Rayleigh waves. Thus instead of keeping the focal depth too shallow, an optimum focal depth is obtained so that body wave amplitudes remain relatively smaller. The amplitude spectra of synthetics show sharp peak at 16.0 sec. Thus the waves in synthetic seismograms at stations are monochromatic of similar period as that of the source–time–function. The synthetics in Figure 8b and c show similarity with the observed seismograms (Figure 3).

As seen in the waveforms at stations LSZ (Δ = 17.06°) and FURI (Δ = 22.59°) in Figure 3a, the average observed maximum amplitude at Δ = ~20° is about 3000 nm/s. Further, using the waveforms of JHNI (Δ = 49.75°), BLSP (Δ = 49.88°), COCO (Δ = 49.98°) and BWNR (Δ = 51.40°) in Figure 3b and c, the average observed maximum amplitude at Δ = ~50° is about 800 nm/s. To achieve nearly the same amplitude in synthetics at these distances, we have considered seismic moment (M0) as 1.50 × 1023 dyn cm for the source and this corresponds to Mw = 4.8. However, this is an approximate estimate as we are not using an exact earth structure along the wave path.

The time-derivative of source–time–function in Figure 8a implies that we have considered a transient oscillation at the isotropic source. This is similar to the radial oscillation of a fluid-filled sphere considered by Fujita et al.10 for the source mechanism of a harmonic volcanic tremor. They considered a fluid-filled sphere of radius r0 with density ρ1 and P-wave velocity α1, embedded in an infinite Poisson solid medium with density ρ2 and P-wave velocity α2. Using the equation of motion and boundary conditions they derived an equation to evaluate eigen frequencies in terms of Ω = ω(r0/α1), where ω is the angular frequency. Thus the radius of the sphere is

\[ r_0 = \alpha_1 \Omega / \omega, \]  

Model 2 of Fujita et al.10 gives the average parameters of the sphere of the volcanic fluid. In this model, \( \alpha_2/\alpha_1 = 5.49, \rho_2/\rho_1 = 2.0 \) and \( \alpha_1 = 0.4552 \) km/s, which gives the eigen frequency as \( \text{Re}(\Omega) \approx 4.3 \) for the fundamental mode (which has higher amplitude than other higher modes) of oscillation. In the present case, \( \omega = 2\pi 15.6 \) s\(^{-1}\) and considering the model 2 for our source region, eq. (1) gives \( r_0 = 4.9 \) km, which suggests that radial oscillations of the fluid-filled sphere of ~5 km radius generated the wave packets.

Discussion

Low-frequency or long-period (LP) seismic events are recorded from volcanic regions in many parts of the world11 and their frequency normally varies between 0.5 and 5 Hz (ref. 12), with their duration less than 1 min.
Figure 7. Particle motion on the vertical plane through the wave path: for stations (a) FOMA (plotted from 09:35:08 to 09:36:10 UTC), (b) CRZF (plotted from 09:47:01 to 09:48:16 UTC) (c) KOD (plotted from 09:48:11 to 09:49:27 UTC) and (d) BLSP (plotted from 09:56:50 to 09:58:18 UTC) showing retrograde elliptic motion. For clarity, particle motion is drawn for limited part of the wave when the amplitudes are increasing.

Figure 8. a, Time derivative of source–time–function, which is an amplitude-varying sine wave of period 16 sec and duration 256 sec. Source is at 15 km depth with $M_0 = 1.5 \times 10^{23}$ dyn cm. b and c, Vertical (V) and radial (R) synthetic seismograms using PREM at epicentral distance of (b) 20$^\circ$ and (c) 50$^\circ$. Rayleigh waves (wave packets) in synthetics are of the same period as that of the source–time–function and are of much larger amplitude compared to the P- and S-waves. The transverse components have zero amplitude for the source considered here and hence are not shown.
Further, such waves have rarely been recorded beyond 100 km. The difference between the earlier observations and the present one is in the frequency content, the duration of waveform and the distance at which they are observed. However, Talandier et al.\textsuperscript{13} analysed two seismic events of May 2011 and April 2013 generating monochromatic Rayleigh waves of period 17 sec and duration of about 40 min, which were recorded only at regional distances. These events probably originated from a hot spot of Rocard submarine volcano in southern Pacific, about 100 km east of Tahiti. The present case is anomalous in the sense that waveforms are recorded worldwide and such monochromatic Rayleigh waves have been recorded on many occasions at large distances since June 2018 from the same source with slight increase and decrease in periods (Figure 9\textit{a}).

These LP harmonic waveforms are interpreted as oscillations of a fluid-filled resonator. As a possible origin of the 17 sec period Rayleigh waves, Talandier et al.\textsuperscript{13} proposed that the entire volcanic conduit might have vibrated during the ejection of lava and resonated to generate the monochromatic Rayleigh waves. Although many geometries are possible for a source resonator\textsuperscript{11,12}, we considered a fluid-filled sphere as the resonator because a sphere is one of the simplest shapes in nature and radial oscillations of a sphere act as an isotropic source which, in this case, is required to fit the observations. Gudmundsson\textsuperscript{14} noted that some magma chambers become spherical due to isotropic and close-to-isotropic stress. Such geometry may also occur directly from cooling of a differently shaped chamber\textsuperscript{14,15}. With a radial oscillation of such a spherical source, we have generated synthetic seismograms which consist of wave packets with non-dispersive Rayleigh waves and relatively negligible body wave amplitude, consistent with the observations. The size of the fluid sphere is estimated to be large compared to the previous findings\textsuperscript{16}; but a large size is needed to have ultra-LP oscillations of period 15.6 sec. We assumed a point source while generating synthetic seismograms, because the diameter of the fluid sphere is negligible compared to the epicentral distances considered here.

It is interesting to note here that since 21 June 2018, similar monochromatic waves from the same source have been recorded at nearby stations such as FOMA, MSEY, KMBO and LSZ; however, amplitudes of these waves are smaller than those of 11 November 2018. Such
occurrences are more during October and early November 2018 (Figure 9a). As before, the period of the monochromatic waves is derived from the sharp peak of amplitude spectra and it increased from 15.24 sec on 21 June 2018 to 15.63 during October and early November 2018. However, the period started decreasing from 20 November 2018 and reached 15.0 sec on 10 September 2019 (Figure 9a). Using eq. (1) and considering no change of material within the fluid sphere, this increase and decrease in period indicate that the radius of the fluid sphere increased from 4.7 to 4.9 km and again decreased to 4.7 km. It appears that the decrease in period or shrinking of the fluid sphere occurs along with decrease of swarm activity (Figure 9b).

Conclusion

(1) The particle motion and the wave speed show that the observed wave packets are fundamental mode Rayleigh waves. Further, the amplitude spectra showed that the waves are monochromatic and non-dispersive. Transverse components of the wave packet show the absence of Love waves.

(2) At nearby stations, single wave packet was recorded, whereas at some distant stations multiple packets were recorded which were possibly caused by multi-pathing.

(3) The source of the event is located at the northeastern edge of Mayotte earthquake swarm zone, which started in May 2018.

(4) The recorded monochromatic wave packets with a period of 15.6 sec are consistent with the synthetic seismograms for an isotropic source at ~15 km depth with a transient oscillation of the same period. Comparison of amplitudes between the observed and synthetic seismograms implies an $M_c$ of ~4.8 for the source.

(5) Considering source of the event as a volcanic fluid-filled sphere oscillating radially with a period of 15.6 sec, the radius of the sphere is estimated to be ~5 km.

(5) Similar monochromatic Rayleigh waves with lesser amplitudes have been recorded on several occasions from 21 June 2018 to 10 September 2019. The period of the waves increased till October and early November 2018 and then decreased from 20 November 2018, which implies an increase and then decrease in the radius of the fluid sphere.


ACKNOWLEDGEMENTS. We thank the two anonymous reviewers for their constructive comments. This is NGRI publication number NGRI/Lib/2019/Pub-80.