A first report on meteor-generated seismic signals as detected by the SANSN

AUTHORS:
Frederick Roelofse[1]
Ian Saunders[2]

AFFILIATIONS:
[1]Department of Geology, University of the Free State, Bloemfontein, South Africa
[2]Seismology Unit, Council for Geoscience, Pretoria, South Africa

CORRESPONDENCE TO:
Frederick Roelofse

EMAIL:
roelofsef@ufs.ac.za

POSTAL ADDRESS:
Department of Geology, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

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A bright meteor with an apparent magnitude of -18 was seen over large parts of southern Africa at ~23:00 South African Standard Time on 21 November 2009. Here we discuss the eye-witness accounts related to the meteor as well as the seismic signals generated by the meteor's passage through the atmosphere as detected by the Mussina seismograph station forming part of the South African National Seismograph Network. Two signals were identified on the seismogram; the first arrival is interpreted as a precursor coupled seismic wave and the second, which arrived ~138 s after the first, as a directly coupled airwave. The meteor is thought to have entered the atmosphere close to Mussina shortly before 22:55.06 local time, from where it proceeded in a westerly to northwesterly direction with an elevation angle not exceeding 43°. Our results presented here dispel the beliefs of many observers who thought that the meteor must have made landfall very close to their localities. In addition, this contribution documents the first instance of meteor-related seismic signals recorded by the South African National Seismograph Network.

Introduction

A bright meteor with an apparent magnitude estimated at -18 was seen over large parts of southern Africa on 21 November 2009 at approximately 23:00 South African Standard Time (SAST) or 21:00 Universal Time (UT). Sighting reports were received from locations as far south as Durban in the KwaZulu-Natal Province (South Africa), as far east as Ezulwini (Swaziland), as far west as Rustenburg (North West Province, South Africa) and as far north as Gweru (Zimbabwe) (Figure 1). Most sighting reports did not make mention of noise or tremors accompanying the meteor, except for reports received from the northern part of South Africa, specifically the Alldays region. At the time of writing this paper, a trajectory had not yet been defined for the meteor and no meteorites related to the event had been recovered. In this short paper we will discuss the eye-witness accounts of the meteor sighting and the seismic signal generated by the meteor as recorded by the Mussina seismograph station, which forms part of the South African National Seismograph Network (SANSN) operated by the Council for Geoscience.[1] These data, in conjunction with the eye-witness accounts, are used to provide estimates on the meteor's trajectory. In addition, this contribution documents the first instance of meteor-related seismic signals recorded by the SANSN.

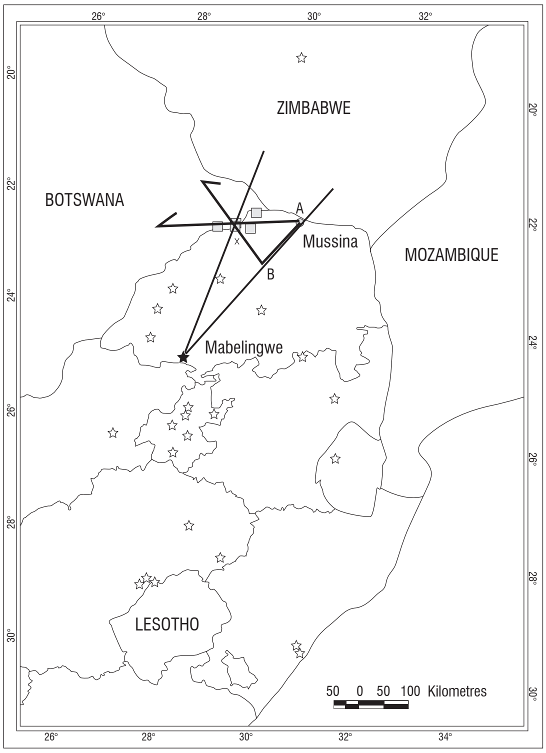


Figure 1: Map showing the locations at which the meteor was observed. Stars indicate locations at which the meteor was observed visually whereas squares indicate locations at which the meteor was seen as well as heard or felt. The two lines radiating from Mabelingwe show the limits over which the meteor was observed visually from this location. Point A shows the point where the meteor would have entered the atmosphere assuming it became visible at an altitude of 120 km and Point B shows the corresponding point for an altitude of 80 km. Two possible trajectories are indicated which pass through the locus of points with the highest number of audible or felt reports.

Eye-witness accounts

Eye-witness accounts were collated by Mr Auke Slotegraaf, the director of the Deep-sky Section of the Astronomical Society of Southern Africa and published on his website www.psychohistorian.org. Additional eye-witness accounts, mostly from the Alldays region in northern South Africa, were published in February 2010 in the Monthly Notes of the Astronomical Society of Southern Africa.[2] Most reports give the time of the sighting at ~23:00 SAST. There was a (mis)conception by many observers that the meteor must have made landfall very close to their locations at the time of sighting:

> *My husband and I were driving on the N3 passing the London Bridge offramp [in Johannesburg]. The time was 22:57 according to our car clock. It was relatively cloudy and from where we were it was very confusing because it seemed the big, bright, green light which was white in the centre became brighter as it got closer to the Earth's surface. It was strange because it seemed really close and low. My husband was convinced that it had landed on the next offramp.*

> *My husband and I also witnessed this frightening and fascinating sight in Ezulwini, Swaziland. We first thought it was fireworks, but then it turned green and seemed to get bigger and bigger. We assumed it hit the next town (Mbabane) but didn't notice an explosion of any sort.*

> *We live in Mokopane and we saw the light as well. I saw the big ball, it was then bright blue / white light and then when it got closer to the ground / earth it went bright orange! We heard nothing but it was scary. Some people say it fell here in our town.*

> *It was moving from east to west with an angle probably between 30° and 45°. It was exactly north of my location (N1 North just before New Road) and I estimate it landed in the Wierda Park [Centurion] area, but it was very difficult to judge the location because it was large and moving very fast.*

Only in the region of Alldays were the sightings accompanied by sound and/or tremors. The following eye-witness account (from Alldays, 22°30'S, 29°07'E) is shared by Streicher[2]:

> *We decided to turn in shortly before 23:00. I hardly got to the bedroom when I suddenly saw a bright glow through the curtains of the Bushveld outside lighting up, as if with a huge flashlight. The next moment a loud double impact sound, like a bomb-blast hit us – it sounded as if something massive struck the ground. This was followed by an after-sound in the form of a rumble, lasting about three seconds, causing the windows to rattle. Then suddenly … dead silence.*

The contemporaneity in the visual and auditory observations at this location implies that the meteor must have passed fairly close by, certainly within a couple of kilometres. Streicher[2] also makes mention of farmworkers who were to the north of the above locality and claimed to have seen the meteor passing overhead in the direction of Pontdrif, further north. This report is, however, questionable.

A particularly illuminating sighting of the 21 November 2009 fireball was made by an Australian amateur astronomer based at the Mabelingwe caravan park (24°50.774'S, 28°2.797'E) in the Limpopo Province, who placed the start of the fireball track at approximately halfway between β-Taurus and θ-Auriga at 22:55 SAST, corresponding to a bearing of ~37° and an altitude of ~19° (Figure 2). The meteor then sped towards the horizon, leaving the observer's view at the horizon directly below the Pleiades (NGC 1432 / M45). Ignoring the effects of the curvature of the Earth and complicating factors related to local topography and assuming the fireball became visible at an altitude of between 80 km and 120 km,[3] it can be shown that the fireball must have been overhead at a distance of about 230–350 km from the observer, which places the fireball overhead approximately 110 km southwest of Mussina to virtually directly over Mussina. This finding suggests that the meteor moved in a westerly to northwesterly direction from the vicinity of Mussina to a position fairly close to the ground in the vicinity north of Alldays. Such an interpretation is also consistent with video footage (collected by an east facing security camera in Burgersfort, approximately 250 km south of Mussina) of the flashes of light generated by the meteor's passage through the atmosphere, which shows the landscape being illuminated from the north.

Figure 2: View of the night sky, as observed by the amateur astronomer at Mabelingwe Caravan Park, showing the approximate path of the fireball track.

Seismic observations

An enigmatic seismic signal was recorded at the Mussina seismograph station (22°26.92'S,30°01.42'E) at the approximate time the meteor was sighted. The signal was not recorded at other stations of the SANSN or seismograph stations of the International Monitoring System located in southern Africa.[4] The recorded signals are shown in Figure 3 which demonstrates its dissimilar nature to that of a terrestrial signal originating from an earthquake in Mozambique. It is evident that the signal consists of two distinct parts: a signal originating at 20:55:37.59 (UT) with a duration of approximately 77 s (Figure 4), which will be referred to as S1, and a second signal (S2) commencing almost 138 s after the first at 20:58:11.08 (UT) (Figure 5). The second signal's duration is approximately 193.14 s (measured from the signal onset to a point visually determined where the signal decays and merges with the background noise). Spectral analysis of S1 indicates a good signal-to-noise ratio on the vertical channel in the frequency range ~0.5–3 Hz with the highest energy around 1 Hz (Figure 4). The dispersed pulse shape is typical of signals originating from the fragmentation or terminal airbursts of meteors.[5] Additionally, Figure 4 indicates that the particle motion seen over a 5-s window indicates retrograde elliptical motion as is expected for air-coupled Rayleigh waves.[5]

The second signal (S2) indicates a W-shaped impulsive onset with downward first motion which is expected for a signal from a ballistic shock (Figure 5). Beyer[6] attributes the W-shaped pulse to the velocity

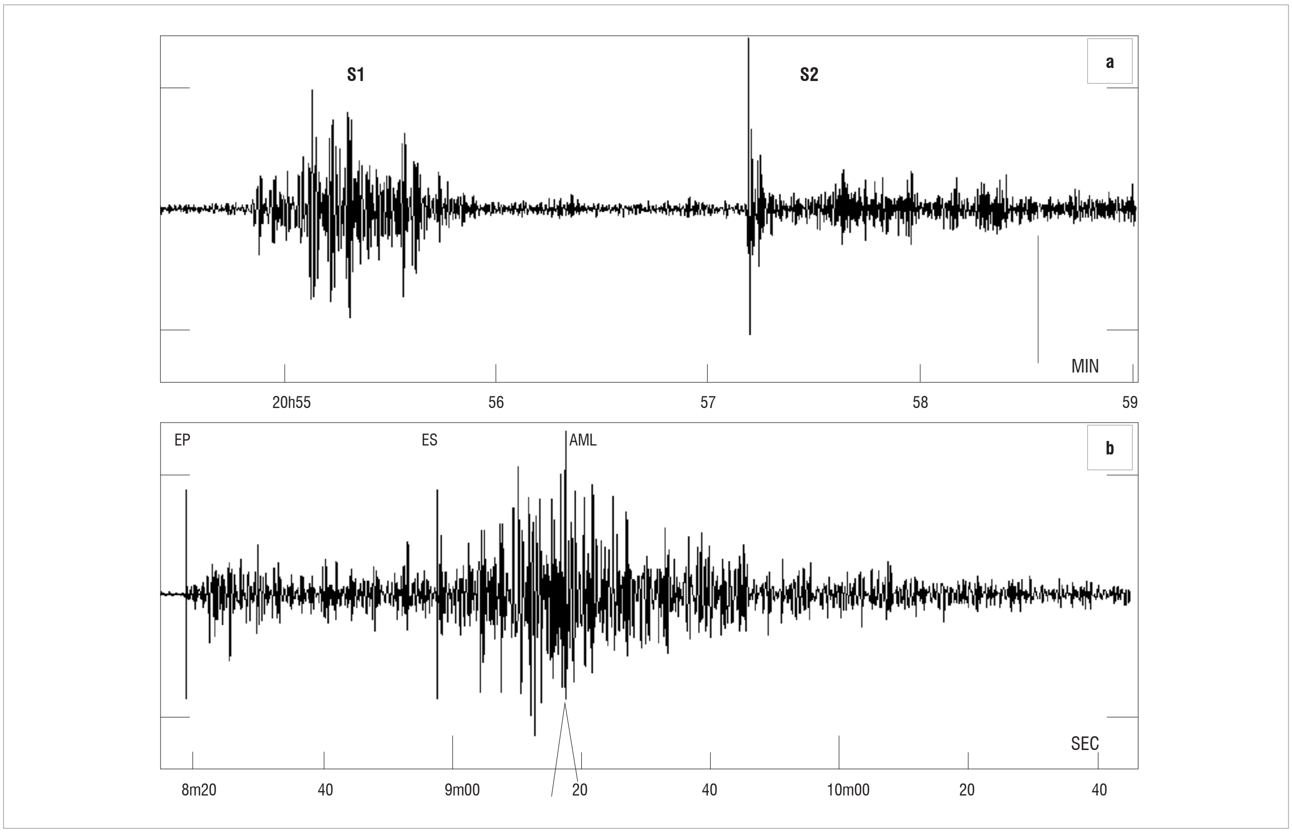


Figure 3: (a) Signal recorded at the Mussina station during the passage of a meteor on 21 November 2009. (b) Signal of a magnitude 3.2 earthquake originating in Mozambique recorded on 04 March 2009 at 17:08 (UT).

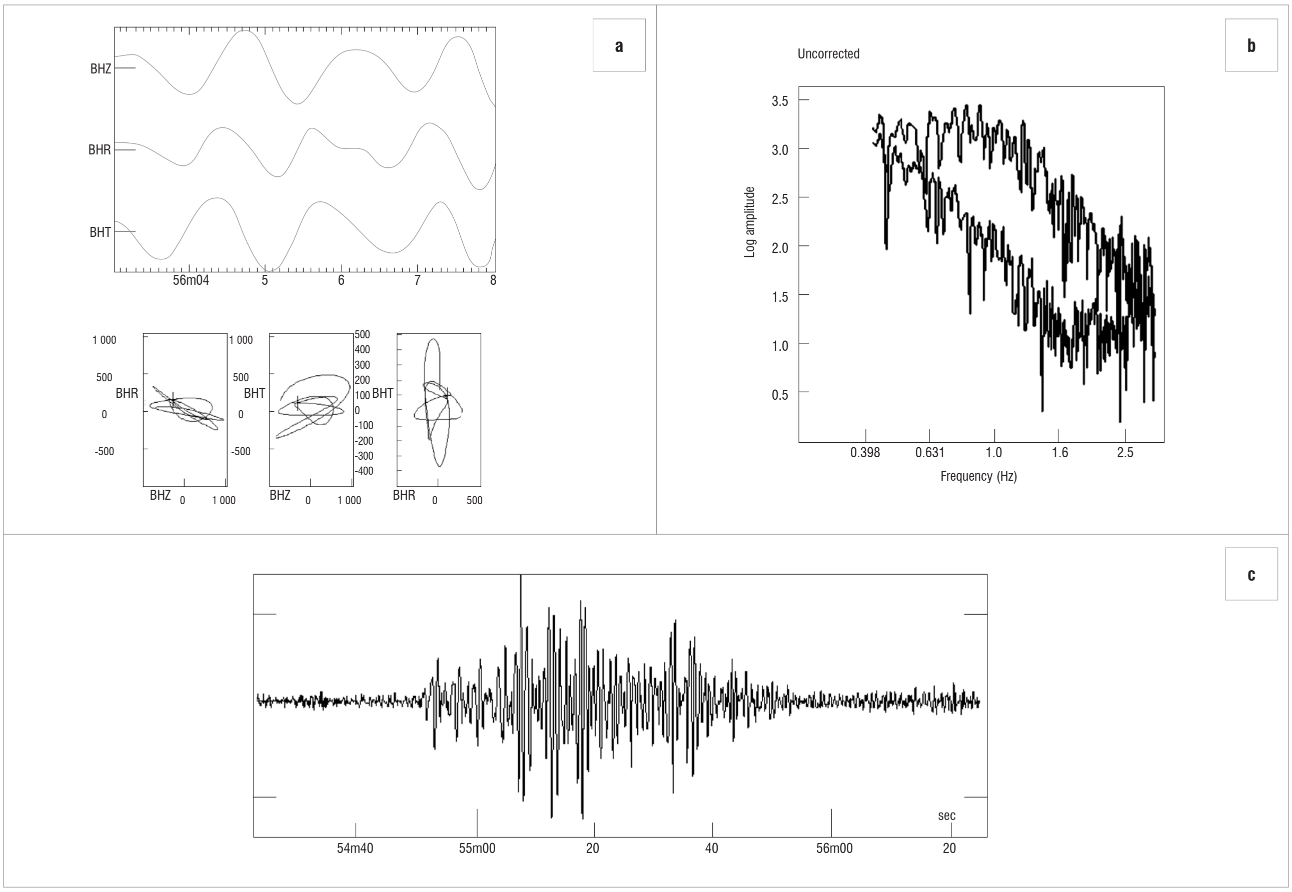


Figure 4: Detailed view of signal S1 showing (a) the particle motion, (b) the spectra of the signal and (c) the time series.

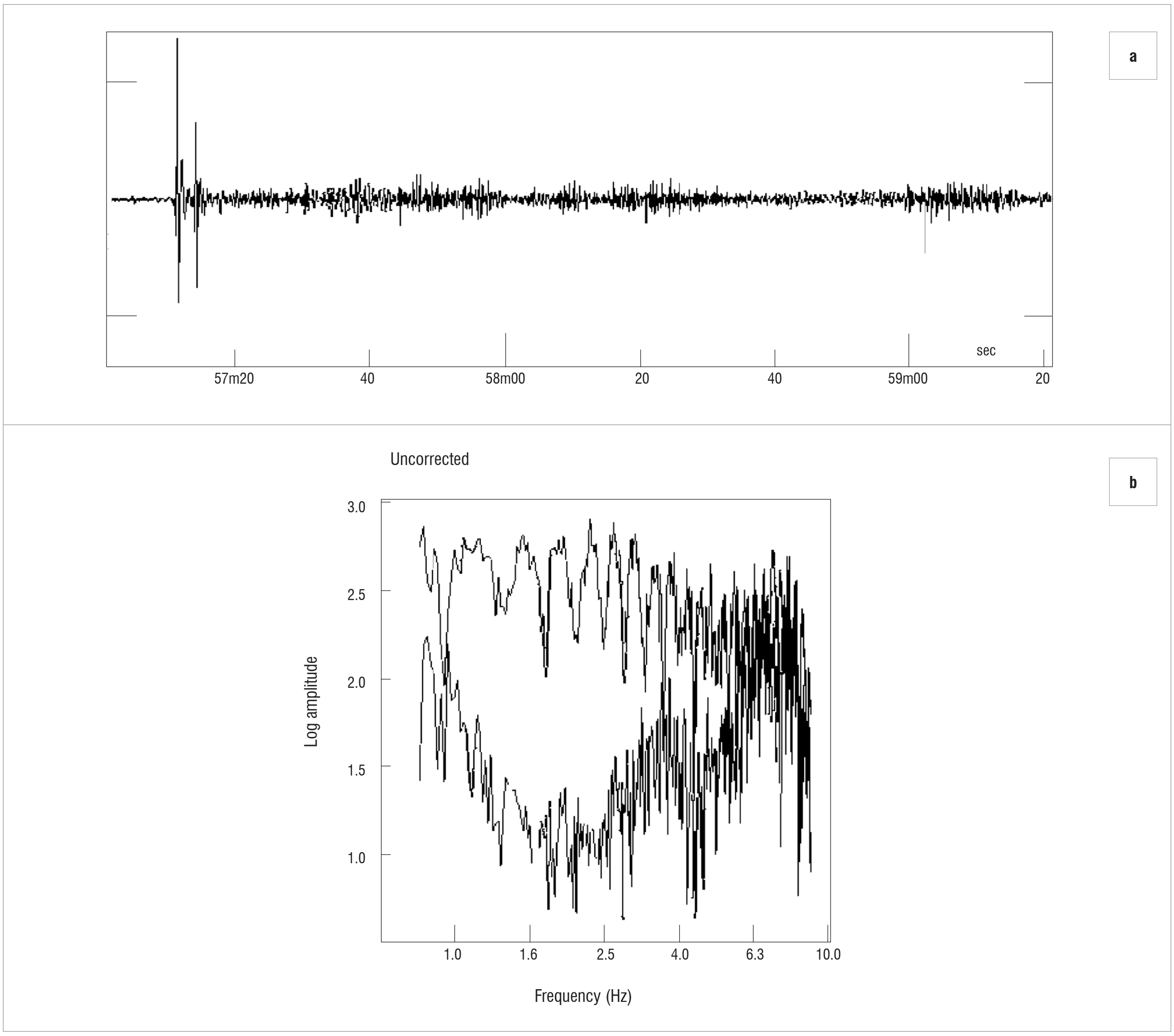


Figure 5: Detailed view of signal S2 showing (a) the time series and (b) the spectra of the signal.

response of seismometers that is more or less proportional to the time derivative of the N-shaped acoustic pulse. A plot of the frequency content for S2 indicates a higher spectral frequency (~0.5–6.5 Hz), with the highest energy occurring around 4 Hz; this finding agrees well with observations by Edwards et al.[5] that the spectral content of directly coupled airwaves typically peaks at frequencies of 0.1–10 Hz.

It is known that the origin of a single point seismic source, of terrestrial origin, can be calculated through the polarisation of the *P*-wave in the vertical and radial directions.[7] The azimuth from the recording station to the epicentre can be inferred by calculating the three-component vector *P*-wave ground motion, whereas the amplitude ratio of the *P*-wave recorded on the horizontal components (A_E/A_N) of the seismogram can be used to calculate the back azimuth (Φ) through the relationship:

$$\Phi = \tan^{-1} A_E / A_N \quad \text{Equation 1}$$

The distance (*D*) to the seismic source for local seismic disturbances, assuming a Poisson solid, can be determined by the difference between the arrival times of the *P*-wave and *S*-wave using Equation 2:

$$D = \frac{t_s - t_p}{\sqrt{3} - 1} \quad \text{Equation 2}$$

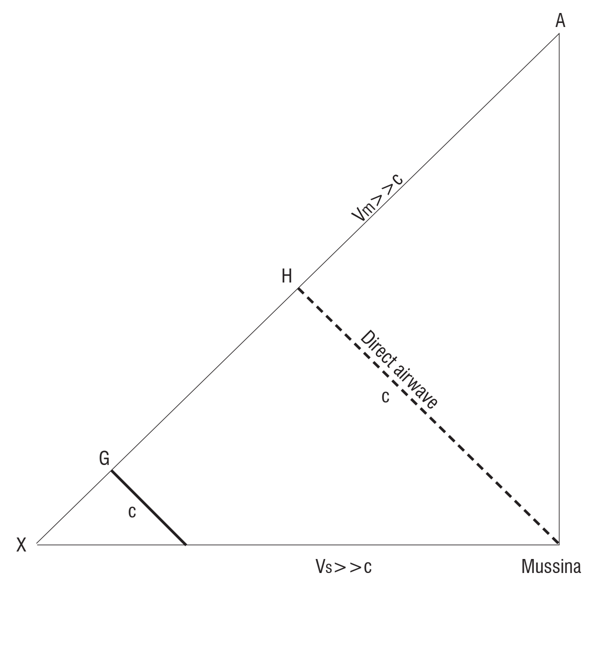
where t_s and t_p are the arrival times of the *S*-wave and *P*-wave, respectively. However, because the signal generated by the meteor's passage through the atmosphere (S2) induced vibrations over a large terrestrial area, the origin of the signal as a point source could not be determined. Additionally, the atmospheric conditions during the evening may have complicated the observed seismic signal to the extent where a simple interpretation of the waveform is not possible as multiple reverberations from the base of clouds could have led to interference.

Discussion

The peculiar features of the seismic waveforms recorded at the Mussina seismograph station are unlike those normally seen for earthquakes. This finding, taken in conjunction with the close association in space and time between the seismic signals and the visual observations of the meteor, undoubtedly suggests that the seismic waveforms were generated by the meteor's passage through the atmosphere. According to Edwards et al.[5], a number of different mechanisms may be responsible for generating seismic signals associated with the passage of meteors through the Earth's atmosphere. These mechanisms include (1) direct coupling of atmospheric pressure waves with the surface at the seismic recording site, (2) the generation of seismic waves as a result of the meteor impacting the Earth's surface and (3) precursor coupling, in which the shock waves generated by the meteor couple with the Earth's surface and propagate away from the point(s) at which coupling takes place to be recorded by the seismic recording site, which in this case is located further away.[8-10]

The W-shaped pulse of the second signal recorded at the Mussina seismograph station suggests that this signal was caused by the arrival of the directly coupled airwave.[5,8,11,12] The directly coupled airwave is caused by the production of a conical shock front (Mach cone) that has a very small Mach angle because of the very high speed at which meteors are known to travel.[5] As a result of the very small Mach angle associated with meteors entering the atmosphere, the path followed by the shock wave towards a particular recording station can be approximated by a line running perpendicular between the recording station and the meteor's trajectory.[5,13,14]

Figure 6 shows a schematic diagram that can be used to explain the origin of the first signal recorded by the Mussina seismograph station. As mentioned previously, the dispersed pulse shape of the first signal is typical of the fragmentation or terminal airburst of meteors.[5] However, inspection of Figure 6 shows that it is impossible for air-coupled seismic signals produced by fragmentation of the meteor to reach the Earth's surface at a particular recording station before the arrival of the directly coupled airwave. Taking this observation into account, we suggest that the first signal is the result of precursor coupling of the incident acoustic waves with the Earth's surface towards the end of the meteor's trajectory. As is seen from Figure 6, shock waves generated at point G will reach the Earth's surface much in advance of the shock waves generated at point H. Once the shock waves generated at point G reach the Earth's surface, they may cause seismic waves that will be transmitted to the recording station faster than the shock waves generated at H. In support of the recognition of the first signal recorded at the Mussina seismograph station representing a precursor coupled seismic wave is the dispersed pulse shape of the waveform recorded by seismometers for a fireball in Norway on 07 June 2006[15] – the waveforms in the Norwegian case were also interpreted as precursor coupled seismic waves.



V_m, velocity of the meteor; V_s, velocity of the seismic waves generated by ground coupling; c, speed of sound.

Figure 6: Schematic diagram showing one of the possible trajectories of the meteor in profile, specifically that along line A-X in Figure 1. Note that the directly coupled airwave will arrive later than the precursor coupled seismic signal at the observation station.

Conclusions

It is unfortunate that a rigorous treatment of the seismic data could not be performed because the signals generated by the meteor were recorded by only one station, which nevertheless appears to have been fortuitously located. From the eye-witness accounts and the seismic recordings of the meteor, the following generalised statements may be made:

1. The meteor entered the atmosphere approximately directly overhead of Mussina or up to ~110 km southwest of Mussina, shortly before 22:55.6 SAST and proceeded in a westerly to northwesterly direction.
2. Based on the observations of the amateur astronomer, the meteor should still have been airborne as it crossed the border between South Africa and Botswana. A geometric analysis, taking into account the meteor's starting altitude and the position at which the meteor was last seen by the amateur astronomer, suggests that the elevation angle of the meteor was not more than 43°.
3. The meteor's passage through the atmosphere caused a shock wave that coupled with the ground, causing the signal recorded at 22:55.6 SAST at the Mussina seismograph station. The directly coupled airwave caused by the meteor arrived significantly later at 22:58.2.

The above account dispels the beliefs of the many witnesses who suggested that the meteor made landfall very close to their locations. Furthermore, any attempts at recovery of the meteor should be focused not in South Africa, but rather in the eastern part of Botswana. Importantly, this study represents the first documented instance of meteor-related seismic signals recorded by the SANSN.

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Authors' contributions

I.S. evaluated the seismic signals and F.R. collated the eye-witness reports and assessed their significance. Both authors contributed to the writing of the manuscript and the final interpretation.

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