



An investigation of the 27 July 2018 bolide and meteorite fall over Benenitra, southwestern Madagascar

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Several dozen stones of an ordinary chondrite meteorite fell in and around the town of Benenitra in southwestern Madagascar during the early evening of 27 July 2018, minutes after a widely observed meteor fireball (bolide) transit and detonation. The event was confirmed by low-frequency infrasound recordings received at ~17h15 UTC (Coordinated Universal Time; 19h15 local time) at the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) infrasound station I33MG near Antananarivo, 542 km north-northeast of Benenitra. An energy release equivalent to 2.038 kt of TNT was calculated from the infrasound signals. Seismograph readings at the SKRH station 77 km north-northwest of Benenitra recorded a two-stage signal consistent with the arrivals of an initial air-coupled ground wave at 16h48:08 UTC and a stronger pulse at 16h49:22 UTC linked directly to the atmospheric pressure wave. The infrasound and seismic signal arrival times suggest that the bolide entry and detonation occurred at approximately 18h46 local time (16h46 UTC), entry was from the northwest, and the detonation hypocentre was located within ~20 km of Benenitra. Despite meteorite debris being found among buildings within Benenitra, there was no damage to structures or injuries reported. Eyewitness accounts and photographic records indicate that approximately 75 mostly intact stones were collected; however, the remoteness of the area, the rugged nature of the terrain and sales of fragments to meteorite collectors have limited scientific analysis of the fall and the extent of the strewn field. The total mass of recovered stones is estimated at between 20 kg and 30 kg, with one fragment of 11.2 kg and several of ~1 kg. Petrographic and mineral chemical analyses indicate that the stones belong to the L6 class of ordinary chondrites. Cosmogenic radionuclide analysis confirms that the fall is linked to the bolide event. The name *Benenitra* has been officially accepted by the Meteoritical Bulletin Database.

Significance:

- Eyewitness reports, CTBTO infrasound records, seismograph records and cosmogenic radionuclide analysis confirm a meteorite fall over Benenitra on 27 July 2018.
- Petrographic and geochemical analyses confirm that the meteorite is an L6 ordinary chondrite.
- Recovery of meteorite falls is rare; this is Madagascar's second known meteorite fall and the first that can be linked to a bolide.
- Regional and global science monitoring networks can be interrogated to improve the understanding of bolide events.
- Interaction of scientists with local communities is important to dispel misunderstandings around scientific phenomena, and can improve collection of data.

Introduction

Although the widespread availability of both static and mobile digital camera equipment for surveillance and social media purposes in the past two decades has substantially increased the documentation of meteor fireball events and the consequent chances of retrieval of debris (stones), meteorite falls still constitute fewer than 5% of recovered meteorites.^{1,2} In addition, the chances of recovering stones from a fall in remote areas away from surveillance technology remain exceedingly low. In this article, we document a meteorite fall that fortuitously deposited stones with characteristic fused crusts in and around Benenitra in the Atsimo-Andrefana District of the Toliara Province of southwestern Madagascar (Figure 1). The fall can be linked via cosmogenic radionuclides, infrasound and seismograph recordings and eyewitness accounts to a bright meteor fireball (bolide) event that occurred at approximately 18h46 (local time) on 27 July 2018. This is Madagascar's second known meteorite fall, and the first that can be linked to a bolide.

Background of the area

The small town of Benenitra lies in the east of the Toliara Province, in one of the most sparsely populated parts of Madagascar (fewer than five people per square kilometre). The nearest significant town (commune population >20 000) is Bezaha, approximately 110 km by gravel road to the west (Figure 1). Topographically, Benenitra is located at 220 masl (metres above sea level) on the west bank of a large meander of the Onilahy River. Rounded hills dissected by perennial streams rise to 250–270 masl in the vicinity of the Onilahy River, but a deeply dissected plateau escarpment rises to 700–750 masl north of the town. The area is underlain by predominantly horizontal to shallowly west-dipping siliciclastic Palaeozoic sediments of Karoo Supergroup equivalence, which unconformably overlie older deformed and more steeply dipping strata that crop out to the east. The town lies on the southern edge of a broader area of artisanal alluvial sapphire mining that exploits the local rivers and ancient river palaeochannels.

The area receives an annual average rainfall of 730 mm, mostly in the summer months. Vegetation comprises mostly semi-arid grassland with isolated trees; however, dense forest is found along watercourses and the escarpment slopes. Most homestead settlements are located close to the river and its tributaries where crop fields (cassava, maize) and rice paddies occur; subsistence farming also involves cattle and goats.

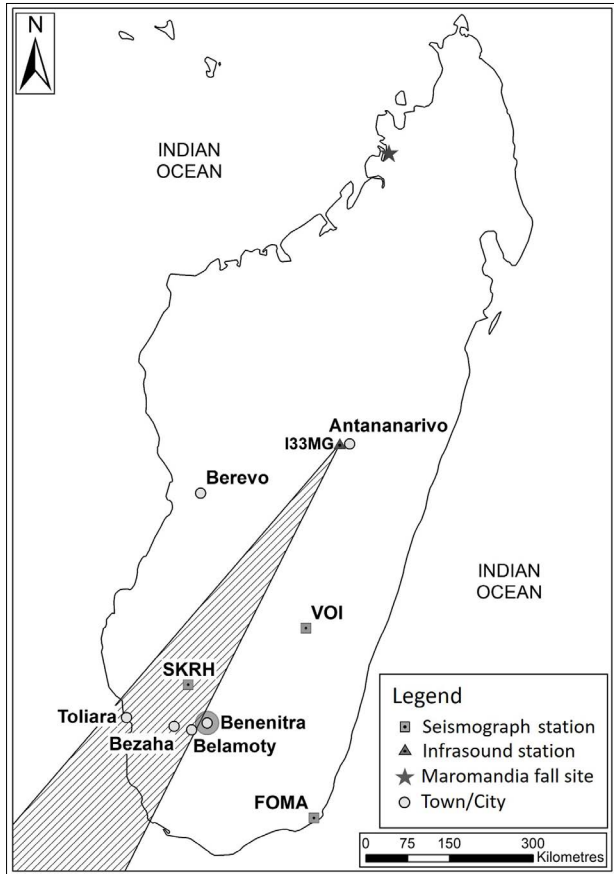


Figure 1: Map of Madagascar showing the locations of Benenitra, the Comprehensive Nuclear Test Ban Treaty Organization station I33MG and the SKRH, VOI and FOMA seismograph stations. The star indicates the location of the Maromandia fall of 5 July 2002. The hatched region indicates the vector range of the infrasound sources detected at I33MG (Figure 3b) and the dark grey circle marks the 20-km radius from Benenitra as used in the model in Figure 5.

History of the Benenitra Event and its investigation

During the early evening of 27 July 2018, residents in various towns and farming settlements in southwestern Madagascar observed a rapidly moving bright light in the sky for a few seconds before it exploded into multiple smaller glowing fragments with smoke trails that descended more steeply before extinguishing. In the vicinity of Benenitra, a few residents standing or sitting outside saw a rapidly approaching fireball, too bright to look at directly, that exploded in a bright flash. Other residents who were indoors reported a brief bright flash of light from outside. Many residents reported hearing a loud noise like rolling thunder a few minutes later, while a few mentioned feeling a ground tremor and/or slight wind accompanying the noise. A small group reported seeing rocks falling between the buildings in town and bouncing across the ground until they came to rest.

Some Benenitra residents who witnessed both phenomena were concerned that these were somehow linked to the imminent total lunar eclipse, which was due to commence at 20h15 local time. Consequently, they immediately contacted the local authorities. Furthermore, 3 days later, they also described the events to a geophysical team from the Antananarivo Institute and Geophysical Observatory (IOGA) of the

University of Antananarivo, who were shown several of the collected fragments. A short article with an accompanying photograph of an ~1 kg stone with a smooth black surface was published in the *Triatra Gazette* in the provincial capital Toliara on 4 August 2018. The article reported that stones had been collected from locations up to 3 km apart in and east of the town. It quoted an unnamed IOGA geophysicist as saying that ‘stones falling from the sky’, whilst potentially dangerous for anyone unfortunate enough to be struck, were a well-known, albeit relatively rare, natural phenomenon. The article ended by speculating on whether the falling rocks were indeed parts of a meteorite or were related to a secret military exercise or failed rocket test, or some sort of prank; however, it made no mention of the fireball phenomenon.

Although it is likely that some of the Benenitra stones would have eventually found their way to meteorite dealers and private collectors, the reporting of the events of 27 July would probably have ended with the single *Triatra Gazette* article (no further follow-up was conducted) were it not for the fortuitous timing of a visit to the area by one of our number (Marais). Marais was overnighting with his driver-interpreter, Rene Robinson, in Benenitra on 29 July on his way to a geological project in the area east of the town and heard rumours of stones having fallen from the sky. He was shown a fragment with a black crust enclosing a greyish-white interior that was exposed on fractured surfaces (Figure 2). Although clearly not an iron meteorite, he noted millimetre-sized metallic grains that proved to be magnetic. Prior to departure the following day, Marais and Robinson were able to speak to several eyewitnesses who showed them photographs of multiple fragments collected after the event as well as locations in the town of where two of the larger stones, reputed to each weigh >0.5 kg, landed. The coordinates of these two fall sites were recorded, one of which had narrowly missed the town’s electricity power station. He also noted that there were rumours of a larger stone having fallen ‘east of the river’. At least three main fall sites in the town were reported by locals: the aforementioned site next to the power station (at 23°26.786’S, 45°4.692’E), another ~250 m west of the power station alongside the District Office, and a third ~400 m south of the power station next to the Catholic Church. At least one stone generated a 40-cm wide crater in the soil (Figure 2a), which was filled in after the stone was removed.

Whilst purchasing supplies in the town market in preparation for departure, Marais noticed several broken fragments lying on a chair behind the store counter and managed to successfully negotiate their purchase. These were delivered to the School of Geosciences at the University of the Witwatersrand for analysis upon his return to Johannesburg on 3 August, where hand specimen and petrographic analysis confirmed a chondrite meteorite type (see next section).

Prior to leaving Madagascar, Marais had already contacted the International Meteor Organisation (IMO) to enquire if any recent meteor events had been recorded over southern Africa, but was informed that no reports had been received in the previous month. In view of this, a three-pronged approach to collect more information was immediately adopted: first, in the absence of any audiovisual records, eyewitness accounts needed to be more thoroughly documented via a standardised questionnaire; second, any hard scientific data relating to the timing and nature of the bolide needed to be found; and third, scientific confirmation was needed to tie the meteorite unequivocally to the bolide.

The primary objective of the questionnaire was to obtain unbiased data to help constrain the bolide trajectory and the extent and size of the fall, such as was possible after the 2002 Thuete fall in Lesotho.^{3,4} Without the option of scientists on the ground, this task was assumed by R. Robinson, who used an adapted version of a questionnaire developed for the 6 June 2018 bolide in Botswana⁵ to conduct face-to-face interviews with witnesses not only from Benenitra but also from the nearby towns of Belamoty, Bezaha and Berevo (Figure 1). These provided first- and second-hand accounts of the event, as well as a range of perspectives of the sequence of events. One of the interviewees reported that a ‘15 or 20 kg’ stone had landed 3 km east of the town, but that this had disappeared, possibly to a dealer; residents also reported that a similar-sized stone was collected 8 km west of the town and was apparently etched with the number ‘144’ that could not be erased, despite repeated rubbing (Robinson R 2018, personal communication).

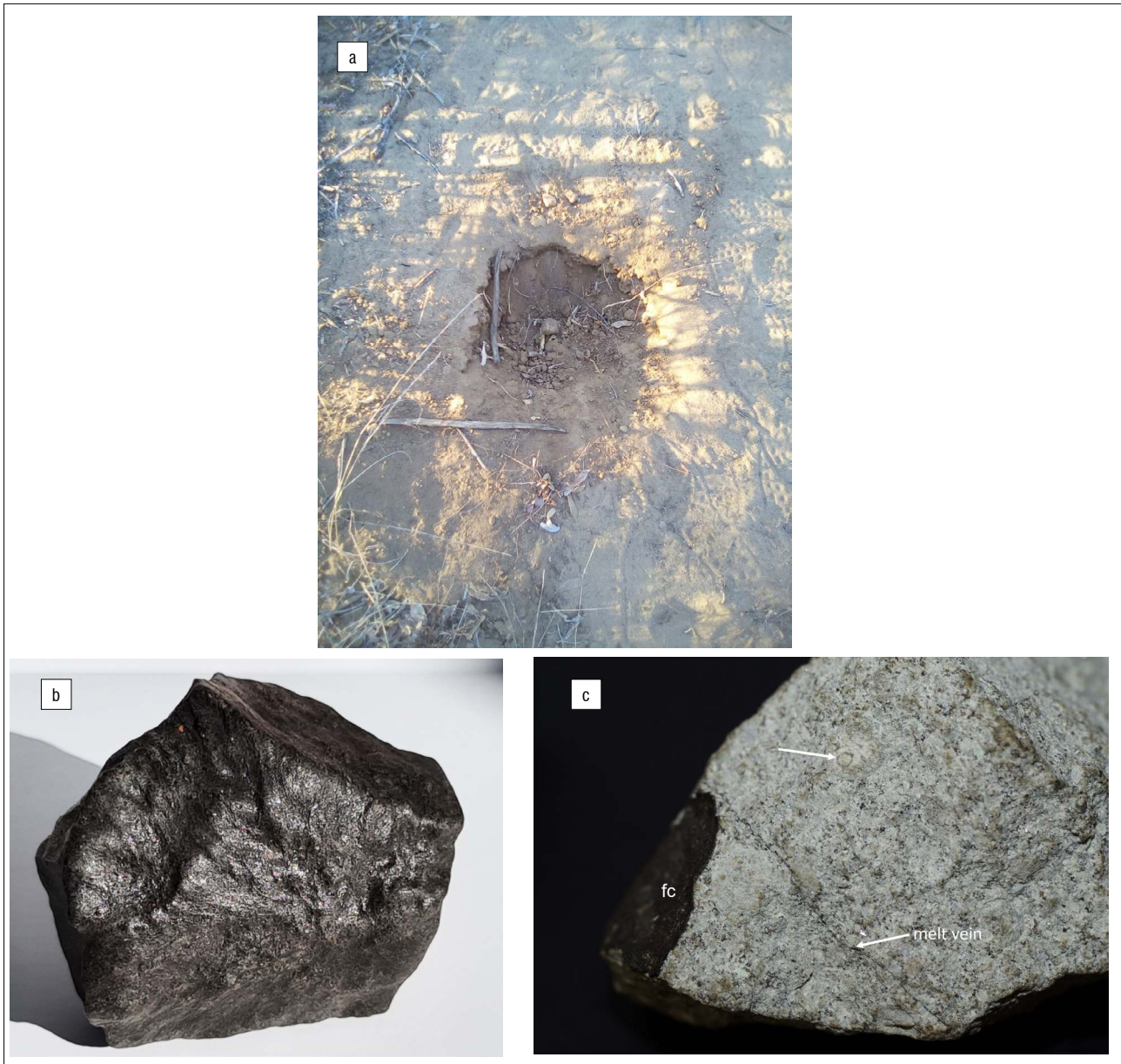


Figure 2: (a) Photograph of plunge pit in sandy soil reportedly caused by an ~1 kg stone at a site on the outskirts of Benenitra town, provided to R. Robinson by an anonymous Benenitra resident. The pit is ~40 cm in diameter and appears slightly elongated in a southeast to south-southeast direction (top of image). (b) Typical Benenitra meteorite stone showing the well-preserved black fusion crust with flow striae and relatively angular shape with sharp edges. Base is 43 mm. Photograph: T. Marais. (c) Close-up of stone 2018Ben-1 showing thin remnant fusion crust (fc), and interior comprising millimetre-sized rounded chondrules (arrow), metal-sulfide aggregates (dark or reflective spots), and thin melt veinlet. Sample was likely broken open by the person who found it. Base of photo is 35 mm.

In themselves, eyewitness accounts of bolides can be both contradictory and relatively unreliable as the unexpected and transient nature of the events challenges witness perspectives of direction, proximity, scale and time. Fortunately, the extremely energetic nature of bolide events makes their detection by a variety of ground- and satellite-based sensors possible. One such sensor array is the global network of 60 infrasound stations maintained by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) through its International Monitoring System. Whilst the International Monitoring System network is primarily directed at recording and locating atmospheric or ground-based nuclear detonations through detection of low-energy sound waves that are able to travel considerable distances through the atmosphere, it has also proved invaluable in recording and investigating large fireballs and bolides entering Earth's atmosphere.⁶ The specific design of infrasound stations allows both the direction and size of the energy source to be

measured. The Seismology and Infrasound Laboratory (LSI) at the IOGA monitors the I33MG station located west-southwest of Antananarivo (Figure 1). Following an enquiry, staff at the LSI were able to confirm that a significant energy release event had been detected by the infrasound sensors at ~17h15 UTC (19h15 local time) from a source lying southwest of the station (Figures 1 and 3).

The infrasound data could not precisely constrain the energy release event to the Benenitra vicinity. Additional information was thus sought through the AfricaArray seismograph network. Records for 27 July from the three active Malagasy seismographs, SKRH, VOI and FOMA (Figure 1) were examined. Only SKRH, located 77 km north-northwest of Benenitra, recorded a distinct signal (Figure 4) that further analysis (see below) showed to be compatible with an atmospheric, rather than tectonic, source (e.g. Roelofse and Saunders⁷).

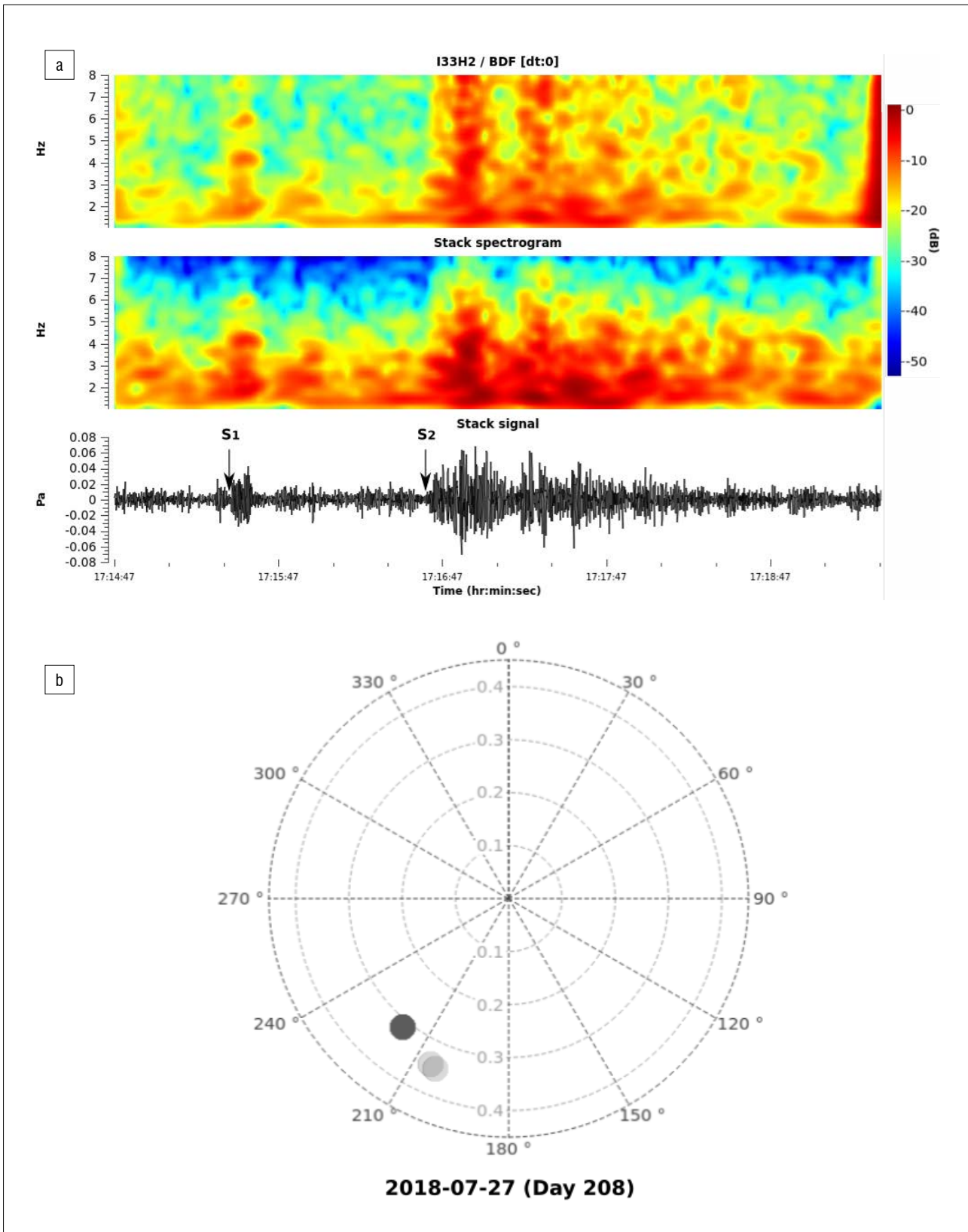


Figure 3: (a) Infrasound record of Station I33MG (19°00.65'S, 47°18.3'E; Figure 1) on 27 July 2018 showing a low-frequency (4 Hz) disturbance (S1) commencing at 17h15:27 UTC (19h15:27 local time) for 10 s and a second disturbance (S2) commencing at 17h16:24 UTC for 150 s. The upper spectrogram indicates the energy of the signal at one of the four elements (I33H2) at the station. The lower spectrogram is the signal stack of all four elements of the station. The low frequency and the prolonged nature of the signal are consistent with bolide-generated infrasound waves.^{21,29} (b) Polar diagram showing the azimuth of detection of the first (grey dots; at 206°) and second (black dot; at 220°) waves. Based on the bolide timing and hypocentre location established from the seismograph data and fall parameters, the calculated celerities of the two waves (0.305 km/s and 0.301 km/s, respectively) are consistent with stratospherically ducted waves.

The presence of the signal at SKRH and not at the other two stations provided independent confirmation of the location of the infrasound source and its proximity to Benenitra. Given the limited distance between Benenitra and the station, the arrival time of the signal at $\sim 16\text{h}48$ UTC (18h48 local time) constrained the bolide to no more than a few minutes earlier.

The final step was to prove that the stones were linked to the bolide. Because Earth's atmosphere acts as a shield against high-energy cosmic radiation that produces a range of short-lived isotopes in asteroids, the timing of a fall can be determined by measuring the amounts and proportions of these cosmogenic radionuclides still present within a meteorite. Analysis of fragment 2018Ben-1 at the Gran Sasso National Laboratory (Italy) in September 2018 established that short-lived radionuclides such as ^{48}V (half-life = 16 days), and ^{51}Cr (half-life = 27.7 days) were present in sufficient quantities to confirm a very recent fall.

Description of the Benenitra meteorite

Two broken fragments with small areas of fusion crust weighing 82 g (Sample 2018Ben-1) and 14 g (2018Ben-2), respectively, were available for initial inspection and petrographic analysis. Subsequent to this, two other stones, weighing 99.32 g (2018Ben-3) and 26.6 g (2018Ben-4), each preserving an almost complete fusion crust, were also made available for study. In total, as of February 2020, photographic or physical evidence exists of at least 75 stones, most of which exceed 50 g in mass, and almost all of which show $>95\%$ fusion crust. In February 2020, an 11.241 kg stone with complete fusion crust was advertised for sale on eBay⁸, consistent with the prior rumours of the large stone that landed in a cassava field outside the town. Preliminary estimates suggest a minimum total mass of ~ 22 kg of recovered material (T. Marais, unpublished data).

The stones are moderately to strongly magnetic. They are mostly angular to subangular, with somewhat flattened rectangular or asymmetric pyramidal to conical shapes (Figure 2b). Faces may be flat, slightly curved and locally scalloped, and edges relatively sharp or slightly rounded. Apart from rare broken fragments of larger stones (Figure 2c),

stones are mostly completely covered by a <1 mm thick bluish-black to brownish-black fusion crust that may display flow features (Figure 2b).

Broken fragments and chipped edges of stones reveal a slightly friable, grey-white rock with a granular appearance in which disseminated metal and sulfide grains up to 1 mm in size, and a few white, 1–5 mm, spherical to elliptical chondrules occur (Figure 2c). A very thin (<0.5 mm), subplanar, blue-grey to black veinlet occurs in Sample 2018Ben-1 (Figure 2c). Most of the exposure of stone interiors is attributed to damage upon hard impact with terrestrial rock outcrops but several stones were reportedly broken open manually. Given their immediate collection within minutes to days after the fall, the stones display a weathering level of W0.⁹

Transmitted and reflected light petrographic analysis of five thin sections from stones 2018Ben-1 (two), 2018Ben-3 (one) and 2018Ben-4 (two) confirmed the presence of 1–4.5 mm (mean of 2 mm) olivine and/or pyroxene-bearing chondrules and, thus, that Benenitra belongs to the chondrite class of stony meteorites. Electron microprobe analysis has indicated that the samples are dominated by olivine and low-Ca pyroxene, with minor feldspar, high-Ca pyroxene, sulfide and Fe-Ni metal¹⁰, confirming an ordinary chondrite^{11,12}. Based on its intermediate metal + sulfide content and its olivine and pyroxene mineral chemistry¹⁰ it can be classified more precisely as an L-chondrite^{13,14}. The homogeneous mineral compositions, slightly elevated CaO content of low-Ca pyroxene and evidence for relatively coarse (10–50 μm but locally to 100 μm), well-equilibrated, metamorphic textures confirm metamorphic stage M6.^{10,11,15–17} The predominance of fractures and patchy to undulose extinction in the main silicate minerals suggests an overall relatively low shock state (stage S3).^{10,18} Combining all criteria, Benenitra is classified as an L6 ordinary chondrite showing shock stage S3 and no weathering (W0).

Constraining the Benenitra bolide

A bolide is a bright fireball caused by the penetration of Earth's upper atmosphere by a decimetre- to metre-sized meteoroid travelling at hypersonic speed (>11 km/s). A meteoroid large enough to survive and maintain its hypersonic momentum deep enough into the

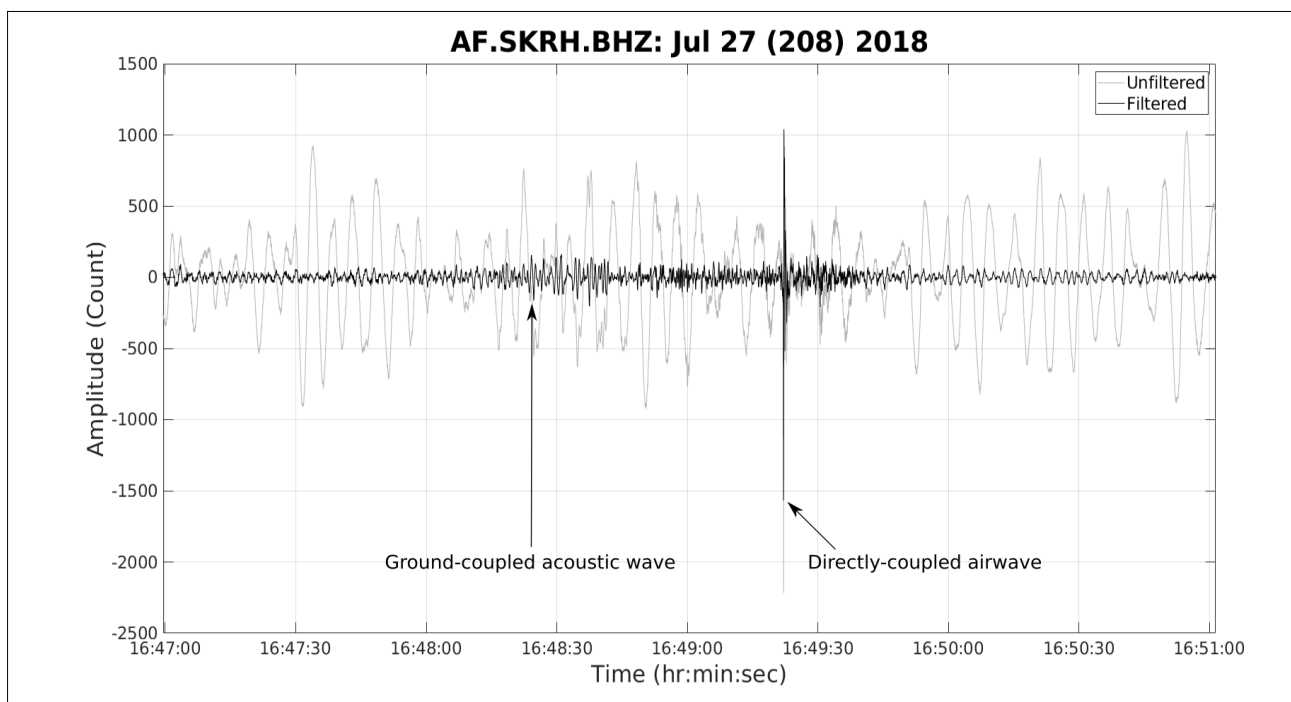


Figure 4: Seismic record from SKRH seismograph station, 77 km north-northwest of Benenitra (22.83°S, 44.75°E; Figure 1), on 27 July 2018, showing the unusual ground motion signature lasting ~ 100 s, consistent with a bolide source. Grey and black lines are the unfiltered and filtered (0.5–20 Hz) data, respectively. The air-coupled ground wave (see Figure 5) arrived at 16h48:08 UTC in the form of dispersed pulses within the frequency range of ~ 0.5 –5 Hz, consistent with Rayleigh waves.^{7,19} The sharp pulse at 16h49:22 UTC displays a W-shaped impulsive onset with downward first motion, consistent with overpressure, and has a frequency range of ~ 0.1 –10 Hz, consistent with a directly coupled airwave.³⁰

atmosphere is ultimately likely to explode spectacularly as stresses caused by increased atmospheric resistance and thermal effects force its catastrophic disintegration. If any meteoroid fragments survive this terminal burst, they will fall to Earth's surface at considerably slower terminal velocities (200–300 m/s). A bolide event (Figure 5) thus comprises: (1) an initial *luminous flight phase* typically lasting a few seconds as the meteoroid falls from ≥ 100 km altitude to below 50 km altitude at hypervelocity, becoming incandescent and ablating because of frictional heating, (2) the *terminal burst* at altitudes typically between 50 km and 30 km, and then (3) the *dark flight phase* that may last several minutes. Given that the hypersonic phase and airburst happen at extreme altitudes, the associated sonic booms, travelling at the speed of sound (0.343 km/s), would also only reach the ground up to several minutes after the fireball disappears.

Different observations and/or measurements relating to each of these three phases can provide information about key bolide characteristics, such as size, trajectory and terminal burst altitude. For instance, size may be estimated from fireball brightness (luminosity), total or terminal burst energy release, and radioisotope analysis of surviving fragments, whereas information about trajectory (azimuth and angle of inclination) may come from fixed camera footage and (reliable) eyewitness descriptions of the luminous flight phase as well as the distribution of stones within the strewn field^{3,4}, and the terminal burst altitude and hypocentre may be constrained from arrival times of different types of seismic signals^{7,19}. As an example, with the Thuat fall of 21 July 2002, the delineation of the strewn field, and internal distribution of stones within it, were instrumental in helping to constrain the azimuth and angle of incidence of the bolide.⁴ Conversely, astronomical, satellite, infrasound and fixed camera data were critical in first constraining the

trajectory and airburst altitude of the Central Kalahari (Botswana) bolide of 2 June 2018; these, in turn, were used to predict the location of the strewn field that guided the meteorite ground search teams.⁵

In comparison to these two bolide-fall events, reliable visual data for the Benenitra event is limited, but the fall of stones within Benenitra places the town close to the hypocentre of the terminal burst (Figures 1 and 5). Furthermore, eyewitnesses noted that the fireball was visible for several seconds, suggesting a moderately steep trajectory, and that it approached Benenitra from a broadly northwesterly direction. The latter is consistent with the infrasound source azimuth of 206–220° registered at I33MG (Figures 1 and 3b). Based on the wave amplitude, the combined radiative energy release during phases 1 and 2 of the bolide was estimated at an equivalent of 2.038 kt of TNT by LSI staff. Studies of data from other bolide-fall events^{6,19} suggest that the typical average entry velocity and angle of incidence of a bolide during phase 1 are likely to be ≤ 17 km/s and 45°, respectively. Thus, with the meteorite type (and therefore, its density) known, these parameters can be used to further constrain the Benenitra bolide via the Earth Impact Effects Program.²⁰ Assuming a spherical meteoroid, calculations suggest that an ~2 kt energy release would require an initial ~3 m diameter meteoroid and that the terminal burst would occur at an altitude of ~40 km. These figures must be regarded as a first-order approximation only. Accounts from the Benenitra witnesses (Robinson R 2018, written communication) that the fireball was 'bright/big like the sun' and 'bright like welding' and that the sound was 'as loud as a gunshot' might suggest a larger bolide or one that detonated at lower altitude either because of greater size or slower velocity. However, it is difficult to verify these observations without better-constrained audiovisual records.

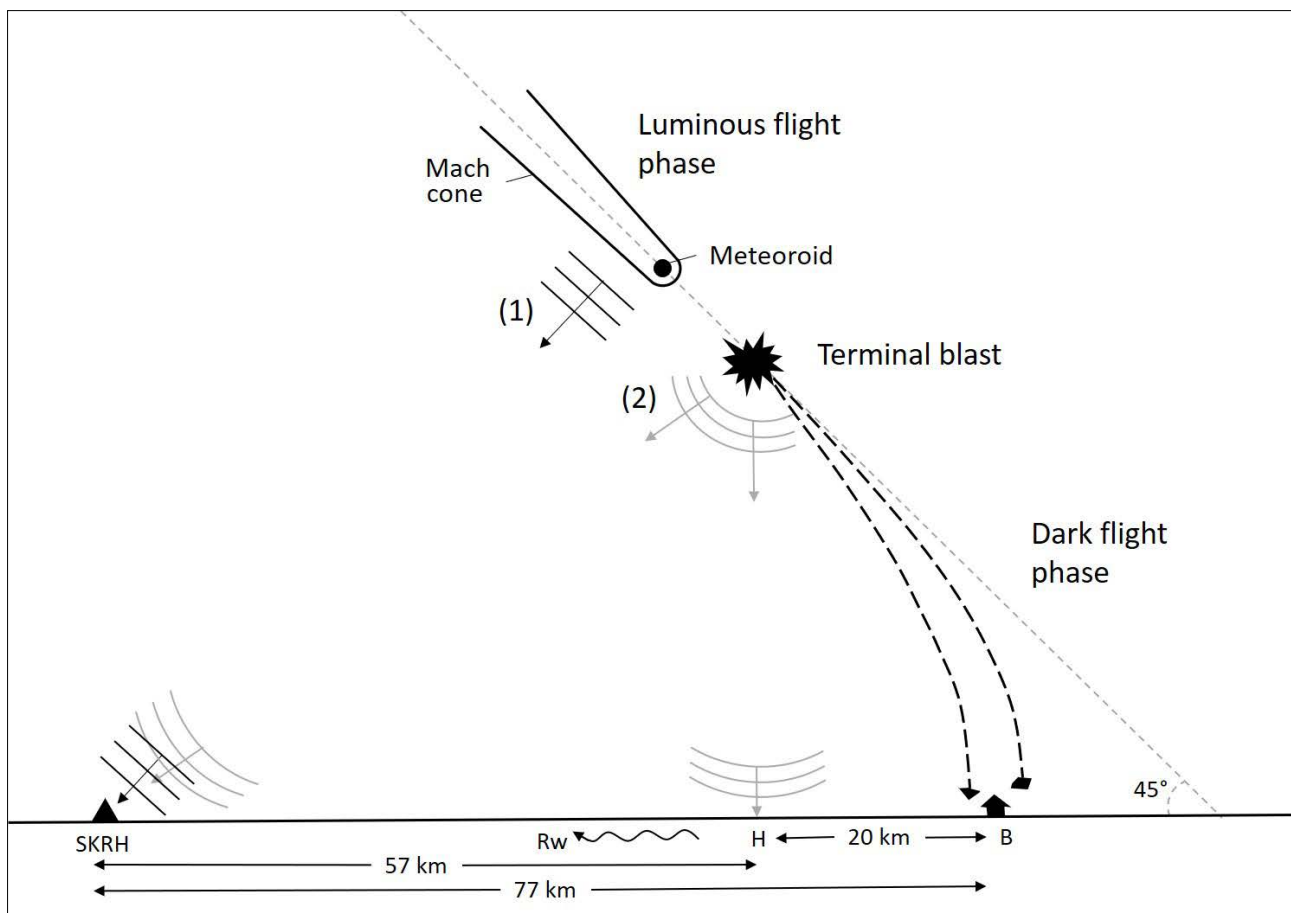


Figure 5: Model solution for the bolide-induced signal received at SKRH station (see Figure 4), involving a bolide travelling at a 45° angle and a terminal burst at 40 km altitude, 20 km north-northwest of Benenitra (B). The atmospheric pressure waves triggered by the bolide during hypervelocity flight (1) and/or the terminal burst (2) couple directly with the surface at the recording site (SKRH), but they arrive after the air-coupled Rayleigh waves (R_w). The latter are created when the acoustic waves of the terminal burst (2) couple with Earth's surface at the hypocentre (H) to form ground seismic waves which then propagate outwards. Because the velocity of the seismic waves in rocks is far higher (3–5 km/s) than in air (0.343 km/s), the air-coupled Rayleigh waves arrive before the direct airwave.

Combining the different arrival times of the ground-coupled seismic and acoustic waves at the SKRH station (Figure 4) with the results from the Earth Impact Effects Program can assist in constraining the bolide trajectory.²¹ In the simplest scenario, the bolide is considered to have travelled in a south-southeast direction along a direct line between SKRH and Benenitra at a 45° angle before detonating at 40 km altitude and depositing stones in the town (Figure 5). Following the terminal burst, stones would have been scattered downrange of the hypocentre along parabolic trajectories whose shapes depend primarily on mass. As a rule of thumb, mid-sized stones in the 0.1–1-kg range could be expected to travel approximately halfway between the airburst hypocentre and the projection of the line of the luminous flight phase trajectory to ground level (Lyytenin E 2020, personal communication; Figure 5). In the scenario presented, a terminal burst located ~20 km north-northwest of Benenitra would still lead to a fall of mid-sized stones within the town. From this geometry, the acoustic wave from the terminal burst at 40 km altitude would take 117 s to reach the ground at the hypocentre and then a further 19 s (based on a surface Rayleigh wave velocity of ~3 km/s)²² to reach SKRH. The acoustic wave from the terminal burst would travel hemispherically through the atmosphere at 0.343 km/s towards the SKRH station, a direct distance of 70 km (Figure 5), reaching the station after 204 s. The ballistic shock wave from the luminous flight phase, travelling essentially cylindrically perpendicular to the bolide path (Mach cone, Figure 5), would have to travel 69 km to reach the station and would take 200 s to arrive after being generated. Accepting that the sonic boom from the Mach cone actually originated no more than a few seconds before the terminal burst and, thus, that the difference in starting times of the various waves is negligible, the model predicts that the air-coupled ground wave should have arrived at SKRH 64–68 s before the direct airwaves. This timing is a surprisingly good fit to that observed in the SKRH record (74 s; Figure 4); the 6–10 s difference can be accounted for by a relatively small change in terminal burst altitude or shift in bolide trajectory. Although the model trajectory is unlikely to correspond exactly to the actual bolide trajectory, the good fit of the data suggests that it is a good first-order approximation of the bolide of 27 July 2018.

As Benenitra is a representative of the most common meteorite fall type and the velocity and incidence parameters are also the most commonly measured values for bolides, there is a high level of confidence in the proposed constraints on the Benenitra bolide's general trajectory and terminal burst altitude. A broadly northwest-to-southeast trajectory also places the bolide hypocentre over the largely unpopulated plateau north of Benenitra, explaining the lack of observational data of stronger bolide effects. This may also have restricted recovery of smaller stones, which would have fallen closer to the hypocentre.

Discussion

A total of 81 meteorites from southern Africa are listed in the Meteoritical Bulletin Database²³, with the overwhelming majority from South Africa (46), Namibia (19) and Botswana (12). Of these, falls constitute 20 of the South African meteorites, 2 each from Namibia, Zimbabwe and Madagascar, and 1 each from Botswana, Lesotho and Swaziland (Mozambique has no reported meteorites). In fact, the only meteorites recorded from Zimbabwe, Madagascar, Lesotho and Swaziland are falls. Owing to the limited nature of the reports, it is unclear whether these falls were directly linked to observed bolides. Furthermore, whilst bolides have been observed in recent years associated with falls in Lesotho (2002), Botswana (2018) and Madagascar (2018, this study), the last fall recovered in South Africa was in 1973. Disappointingly, southern Africa's largest recorded bolide, on 21 November 2009, which detonated in the vicinity of Alldays close to the border between South Africa, Botswana and Zimbabwe⁷, failed to yield any stones despite extensive search efforts, particularly in Botswana (McKenzie R 2009, personal communication). In South Africa, bolide sightings are regularly reported in the social and news media, but with no associated discoveries of stones. Such statistics are not exceptional, as Graham et al.² estimated that only five or six falls per year were recovered globally, although in recent decades this has increased to an average of approximately a dozen per year. The increased success rate can be attributed to factors such

as increased population density, dedicated scientific instrumentation and CCTV and other surveillance systems, as well as increased public awareness.²³ A total of 158 falls were recorded in Africa between 1801 and 2014¹, and a further 10 have since been added to the Meteoritical Bulletin Database²³; however, it is likely that many more in the more remote parts of the continent have gone unreported. In this context, it is clear that the Benenitra bolide and fall is a rare and significant event.

According to the Meteoritical Bulletin Database²³, the proportion of falls among meteorite discoveries in southern Africa (35%) is significantly higher than the global average of ~5%. The global average has become progressively lowered by the large numbers of meteorite finds in recent decades in northwest Africa and Antarctica. In fact, the exceptional number of northwest Africa finds actually skews Africa's ratio to only 4% falls.¹

Benenitra represents both Madagascar's second fall and second meteorite – the first being Maromandia on the northern coast on 5 July 2002 (Figure 1).²⁴ Whilst the single observer of the Maromandia fall reported seeing two stones with a combined mass of ~6 kg fall, no fireball or acoustic effects were reported. In contrast, the Central Kalahari bolide and fall of 2 June 2018 – less than 2 months before the Benenitra event – is one of the most comprehensively studied examples of these phenomena. Observational data related to the Central Kalahari event commenced with identification and tracking of its originating asteroid 2018 LA by the Catalina Sky Survey and ATLAS telescopes several hours before the fall. These accurately predicted that the asteroid was on a collision course with Earth, in addition to collecting important spectral and other data. Constraints on its actual atmospheric trajectory and terminal detonation altitude were obtained from CCTV and infrasound data that were then used to constrain its projected dispersal ellipse. Ultimately, several search expeditions were guided by this scientific trajectory analysis to locate and retrieve fragments of the meteorite.⁵

In the case of the Central Kalahari fall, it is indisputable that without the considerable data and resources to analyse the bolide trajectory, the meteorite itself would most likely never have been found. Benenitra and Central Kalahari thus represent two significantly different approaches in recovering meteorite falls. Between these extremes lies the Thuete event of 21 July 2002^{3,4} where excellent local communication networks were rapidly able to ascertain that an extraordinarily loud, sustained, noise heard over a broadly circular area some 250 km in diameter in Lesotho and central South Africa was linked to a bolide and smoke trail that was seen by only a few observers (owing to there being 80% cloud cover at the time). News of the meteorite fall itself actually only surfaced 3 weeks later, once a regional public-service police newspaper published complaints by villagers of stones falling from the sky that damaged several structures.³ The accessibility of the fall site to scientists from various universities and the Geological Survey of Lesotho then enabled extensive subsequent interaction between scientists and locals over the next 2 months, which raised public awareness and assisted in the collection of both observational data and more stones. This, in turn, allowed delineation of a 7.4 x 1.9 km, east-west-elongated, elliptical strewn field. Favourable field conditions (no rainfall, fallow winter fields and dry highveld grassland in a reasonably well-populated area) facilitated the collection over a 2-month period of at least 1029 stones, totalling 45.3 kg, one-third of which are smaller than 10 g.⁴ The thoroughness of the collection of stones in this case allowed for the reconstruction of key elements of the bolide⁴ that would otherwise not have been possible.

Deciphering the Benenitra mythology

Bolide and meteorite fall events are rare and highly unusual phenomena that disrupt, and can significantly challenge, the way in which witnesses view the natural world; simultaneously, as dramatic, widely and highly visible phenomena they present excellent opportunities for education. In the narrative of the field research conducted following the Thuete fall in Lesotho in 2002³, it is clear that initial responses to the fall varied from anger and suspicion of criminal acts to fear of possible supernatural forces that led to reports to the local authorities. In the case of Benenitra, no stones appear to have actually hit any buildings and no

injuries were reported; however, interviews revealed several myths and misconceptions concerning the fall:

Harbinger of the Apocalypse: The timing of the bolide and fall relative to the well-publicised total lunar eclipse later that evening led to immediate alarm and speculation among witnesses that the bolide and stones may have been derived from the Moon whilst it was being ‘devoured’ by a dark shadow. This ‘disintegration’ of the Moon, in turn, was seen as a sign that Armageddon or the Apocalypse had arrived. Concerned townspeople thus contacted the local authorities and the visiting IOGA scientists, who tried to allay these fears. Whether their explanation was sufficient or not, the ‘recovery’ of the Moon following the eclipse may have ameliorated these fears. Certainly, by the time the matter was reported in the *Triatra Gazette* a week later, more prosaic explanations of a failed military experiment (perhaps aided by the ‘144’ specimen that suggested some sort of human agency) or mischief were ventured and the matter was not speculated on further.

Stones too hot to touch: Eyewitness reports indicate that at least one of the large stones that was seen landing in the town was approached cautiously and not touched until ‘at least two minutes’ later. The eyewitness reports of the bolide confirmed that ‘bright sparks like fireworks’ that trailed smoke were seen descending from the final airburst. A direct connection was thus made that the objects that landed had ‘been on fire’ no more than a few minutes earlier, hence the caution. The first person to pick up the stone remarked that he was surprised at how ‘icy cold’ it felt, and that ‘it was still cold more than an hour later’. This misconception about meteorites being hot is common. Despite the brief fireball in which the outer surface of the bolide reaches temperatures in excess of 1700 °C that cause it to melt²⁵, the hypersonic velocity ensures that the melt is very efficiently stripped (ablated) from the surface into the atmosphere, thus continuously exposing fresh material to the frictional heating and high pressures. Beyond limited heating of their surfaces by solar radiation, asteroids in space would have an internal temperature of approximately -100 °C.²⁶ Consequently, once the bolide fragments were decelerated to speeds too slow to generate frictional heating after the airburst, the core of the bolide remaining after ablation would have been capable of quenching and completely cooling the last vestiges of the surface melt within seconds, and still remain significantly colder than air temperature for hours after landing.

Precious gems in the stones: Photographic evidence reveals that fusion crust preservation on almost all the Benenitra stones is generally >95%. However, it appears that several of the stones, including 2018Ben-1 (Figure 2c), were broken open by locals. Similar behaviour was reported for some Thuat stones³, with locals explaining that they believed the stones might have contained diamonds (much of Lesotho’s income is derived from diamond mining within the country or from employment on mines in South Africa). Benenitra lies within an area of alluvial sapphire mining and locals are well accustomed to ‘stones’ as an income opportunity. The connection that the stones that fell to the ground were initially glowing brightly after the fireball disintegrated likely prompted some witnesses to investigate whether the source of the glow might have been a precious gem within its interior.

Contagion from the stones: In advertising a sizeable number of Benenitra stones for sale on its website, one commercial meteorite dealer noted claims that several locals reported experiencing mild irritation after being in close proximity to stones:

But to the dismay of all, it seems that the stones gave off a gas with multiple effects, in contact, according to the sensitivity of people. For some, the contact with the stone causes a small irritation to the eyes and makes tears fall, while for others, irritation is felt in the nostrils and causes a momentary runny nose.²⁷

This story was also relayed to Marais by locals a few days after the fall, but not thereafter (Robinson R 2018, personal communication). The claims are somewhat similar to respiratory, vomiting and diarrhoea ailments experienced by residents of Carancas (Peru) who rushed to

examine a 14-m wide crater caused by a meteorite impact in clay soil near their village on 15 September 2007. These illnesses were linked to noxious gases emanating from the crater that had rapidly filled with water.²⁷ The initial claim that these were extraterrestrial toxins was later refuted by health experts who at first speculated that the impact may have liberated arsenic from the saturated soil. The most recent suggestion is that the large mass of the meteorite (estimated at 2 t) meant that it was still moving sufficiently fast when it impacted, that it had not lost all its frictional heat, and that sulfides in the hot surface layer then reacted with the water that flooded the crater, releasing toxic gases.²⁸

Summary

The fall of stones of an L6 ordinary chondrite meteorite in and around the town of Benenitra in southwestern Madagascar is linked to a bolide witnessed across the region at approximately 18h46 local time (16h46 UTC). Despite multiple stones falling in the town, no damage or injuries were reported. This is Madagascar’s second recorded fall, and second recovered meteorite. The bolide released an estimated 2.038 kt equivalent of energy on its transit through the upper atmosphere and final terminal burst, sufficient to be recorded by the I33MG infrasound station 542 km north-northeast of the town, and by the SKRH seismograph station 77 km to the north-northwest. Both signals show distinctive characteristics known to be associated with bolides. Data from both stations confirm eyewitness reports that the bolide was travelling in a broadly southeast to south-southeast direction. The reported recovered mass of stones of ~22 kg is likely to represent a small fraction of the total mass of the fall.

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Competing interests

We declare that there are no competing interests.

Authors’ contributions

R.L.G.: Project leader; conceptualised and managed the project and recruited other members; described meteorite petrography and mineral chemistry for classification; developed bolide trajectory model; wrote initial manuscript draft. T.M.: Collected samples and liaised with W.C.F. regarding initial research; primary South African contact for eyewitness reports; co-wrote introductory section of manuscript and edited drafts; prepared interpretive diagrams. L.D.A.: Described meteorite petrography and mineral chemistry for classification; assisted in writing of initial draft and significant further edits. F.A.: Located and interpreted seismic data; developed bolide trajectory model; wrote section on seismic data and made editorial comments on manuscript. A.R.: Located and interpreted seismic data; translated eyewitness questionnaire and correspondence into/from Malagasy from/to English. A.H.R.: Located and interpreted infrasound data; wrote relevant section and made editorial comments on manuscript. M.L.: Analysed cosmogenic radionuclides, contributed section in manuscript and editorial comments. A.Z.: Generated mineral chemical data for meteorite classification. W.C.F.: Liaised with T.M. regarding initial sample-based research; prepared interpretive diagrams.

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