



## THE METEORITE FALL NEAR BOUMDEID, MAURITANIA, FROM SEPTEMBER 14, 2011

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**Abstract:** On the evening of September 14, 2011 at 21:00 GMT a bright bolide was observed by hundreds of eyewitnesses in the area north and west of the town of Kiffa, in the department of Assaba, in south Mauritania. A terminal fragmentation and sound phenomena were observed near the end point of the trajectory. At least one mass of 3.5 kg was observed to impact and recovered the morning after the fall near Boumdeid (or Bou Mdeid), around 60 km north of Kiffa. Subsequently a large number of eyewitness accounts were recorded and mapped by GPS. The present paper provides a scenario for the trajectory of the Boumdeid (2011) meteorite based on the available parameters and wind data at the relevant altitudes. In addition the paper presents the results of the mineralogical and chemical analysis of the recovered meteorite which is consistent with a classification as ordinary chondrite of type L6, shock stage S2, and a weathering grade of W0. Following its analysis and classification, the meteorite was published under the official name Boumdeid (2011) in *Meteoritical Bulletin*, no. 100, MAPS 49(8), (2014). Gamma-ray spectroscopy was conducted 84 days after the fall and the detection of short-lived radionuclides such as <sup>56</sup>Co and <sup>46</sup>Sc confirmed the recency of the event. Derived from the data of <sup>60</sup>Co, <sup>54</sup>Mn and <sup>22</sup>Na the approximate preatmospheric radius of the meteorite body was 10–20 cm. The report is also intended to serve as a case example for post-event data recovery and trajectory reconstruction in areas not covered by sky-camera networks and with limited scientific infrastructure.

**Keywords:** Boumdeid (2011); meteorite fall; Mauritania; trajectory scenario; L6 chondrite; cosmogenic radionuclides

### INTRODUCTION

Although Mauritania has a land surface that is triple the size of the neighbouring Western Sahara, and double the size of Morocco, Mauritania's meteorite finds are only a fraction of the two countries. Prior to the Boumdeid (2011) event, a total of only 18 meteorites were known for Mauritania. Among the latter were 14 finds and four falls. In comparison, the data base of the *Meteoritical Bulletin* currently lists 879<sup>1</sup> meteorites for Morocco (including 6 falls), and 106 meteorites for Western Sahara (including 3 falls). The reasons for the disparity in meteorite finds are manifold. While geological and geomorphologic differences are

relevant to some extent, the actual cause is determined by social factors such as population density, education level, limited access to modern information technology, lack of infrastructure, and the absence of an established commercial market for rocks, minerals and fossils in Mauritania. In combination, these conditions provide an environment in which the general interest in the subject is low, and in which the scientific potential of Mauritania's meteorite heritage is yet to be recognized. Thus, one of the objectives of this work is to raise the awareness for meteorites in Mauritania and to offer an example for the future investigation of meteorite falls and finds within the country.

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<sup>1</sup> This number includes meteorites with NWA (Northwest Africa)-designation for which no find locations are recorded. It is widely assumed that some of these undocumented finds were found in neighboring countries.

## GEOGRAPHY, GEOLOGY AND TOPOGRAPHY OF THE FALL AREA

Assaba region and department are located in southern Mauritania and governed by its capital Kiffa, one of the larger Mauritanian department towns with currently around 36,000 inhabitants (The mean population density in Mauritania is 1.7 persons per km<sup>2</sup>). The Assaba department borders the neighbouring departments of Brakna and Tagant to the north, the department of Hodh El Gharbi to the east, the border to Mali to the south, and the Mauritanian departments of Gorgol and Guidimaka to the west. Kiffa is also a major local market place with the important east-west road from Mauritania's capital Nouakchott to the city of Nema passing through its center. Boumdeid is lo-

cated around 93 km north of Kiffa and connected to it by the Tidjikja – Kiffa road (Fig. 1a).

Kiffa, and Boumdeid, are situated in the Taoudeni Basin, the largest sedimentary basin in Northwest Africa, which covers two thirds of the West Africa craton. The basin that makes up most of Mauritania's east and northeast is composed of a sequence of essentially flat-lying, undeformed Upper Proterozoic and Palaeozoic sedimentary rocks with total thickness reaching 6 km. In the Assaba region, the Taoudeni Basin is masked by overlying Mesozoic to Cenozoic sandstone sediments (Blanchot, 1975; Mattick, 1982). West of Boumdeid, the Taoudeni Basin borders the Palaeozoic Maurita-

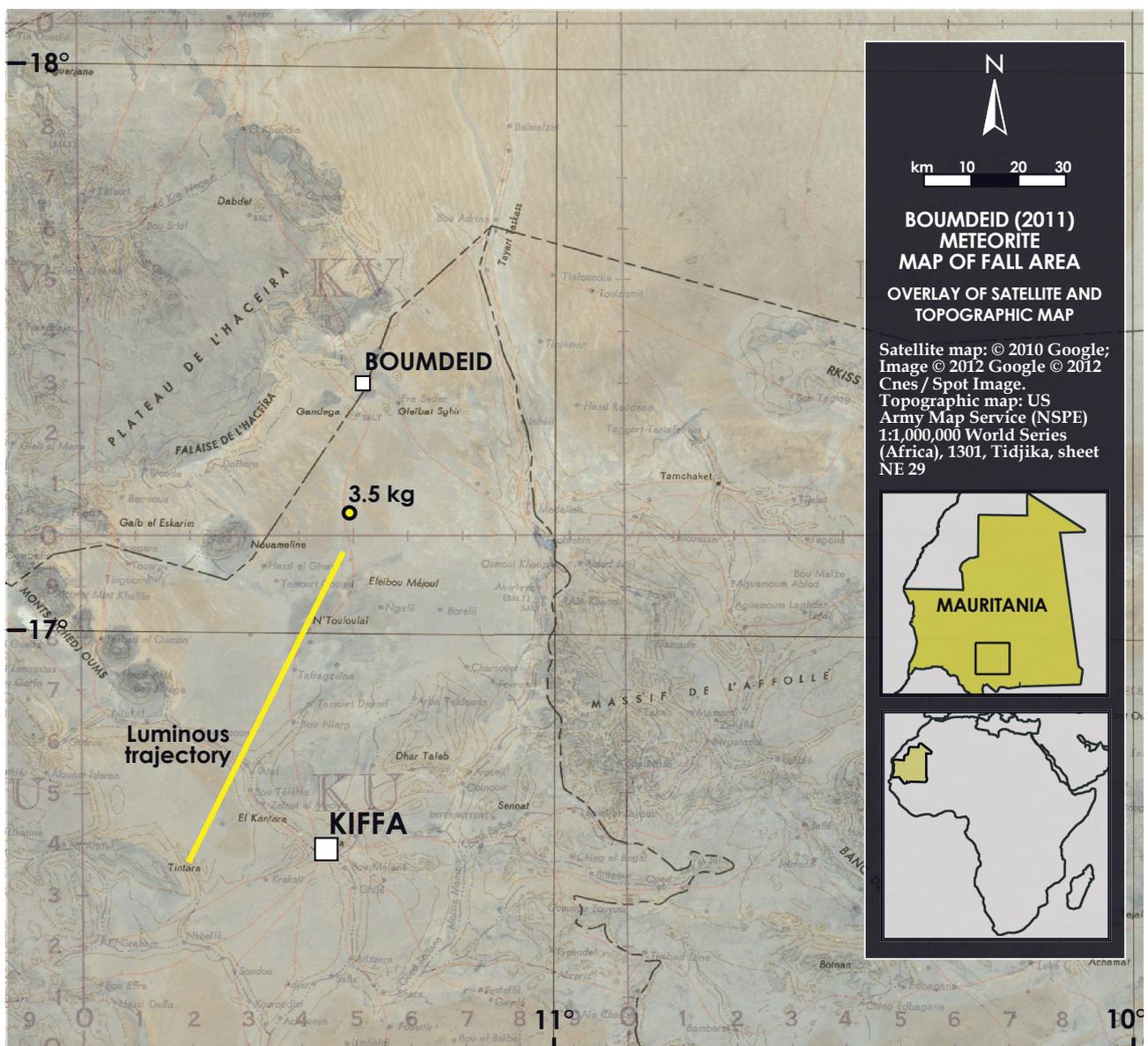


Fig. 1a. Boumdeid (2011) meteorite, map of fall area. Overlay of satellite chart and topographic map, compiled by S. Buhl. Satellite map: © 2010 Google; Image © 2012 Google © 2012 Cnes / Spot Image. Topographic map: US Army Map Service (NSPE) 1:1,000,000 World Series (Africa), 1301, Tidjikja, sheet NE 29.

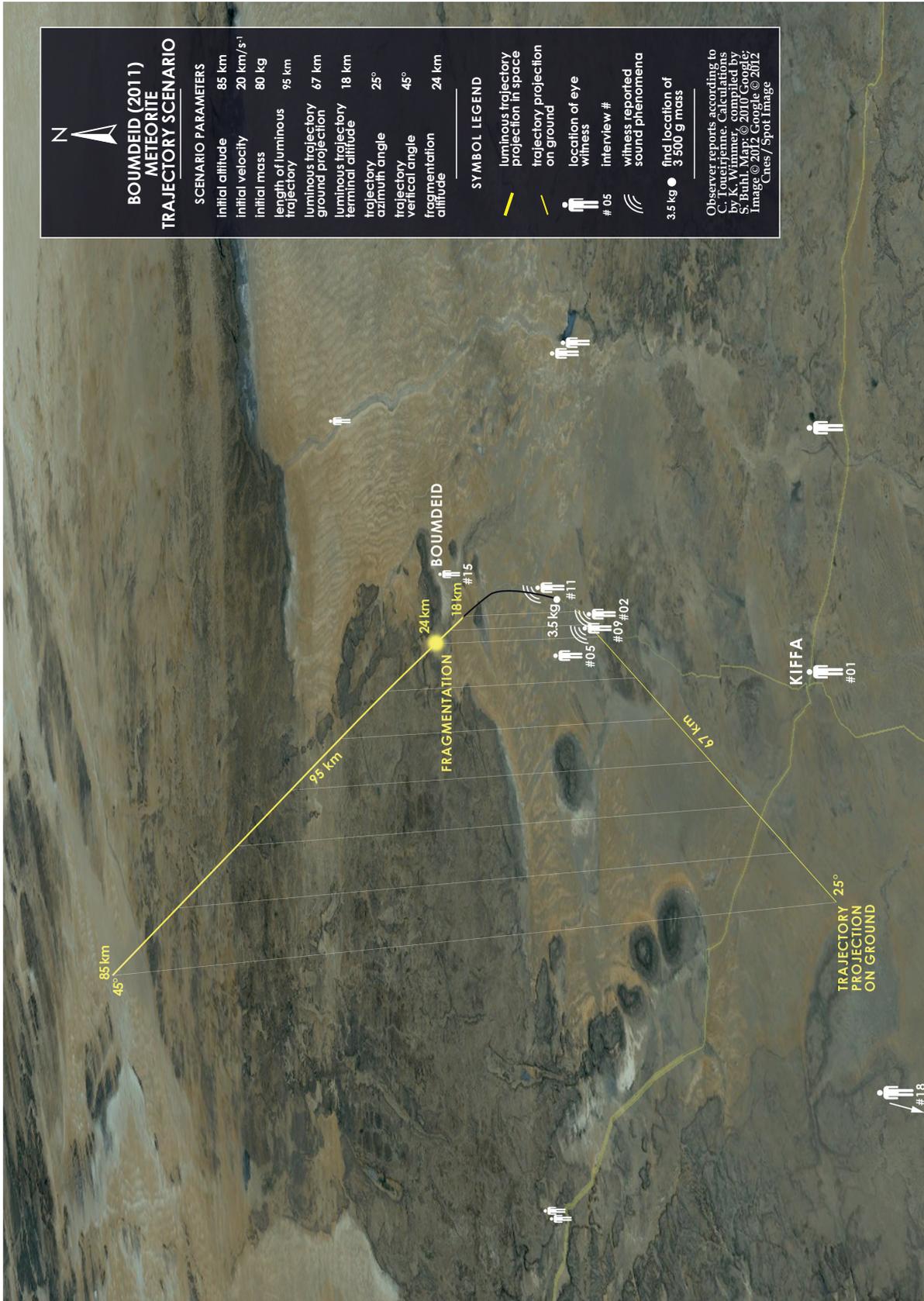


Fig. 1b. 3D-trajectory scenario of the Boumdeid (2011) meteorite fall of September 14, 2011, 21:00 GMT. For further parameters and comments see table 1. Observer reports according to C. Toucirjenne. Calculations by K. Wimmer, compiled by S. Buhl. Map: © 2010 Google; Image © 2012 Google © 2012 Cnes / Spot Image

nides chain (or greenstone belt), mainly composed of deformed sedimentary, igneous and metamorphic rocks of the Precambrian to Palaeozoic age. Boumdeid is situated between the inselbergs of the Mauritanides chain and near a seasonal drainage system extending from the plateaus in the west into the lower plains of the basin. The topography of the closer Boumdeid area is dominated by a cover of continental sands and shales as well as Holocene desert deposits which cover much of the Palaeozoic sequence in a nonconforming manner (Mattick, 1982).

The surface geomorphology of the immediate fall area is determined by Pleistocene alluvial deposits and Holocene Ergs with abundant SW-NE oriented barchan systems. Most of the topography of the Boumdeid area is flat, dipping gently to the SE, with the exception of the isolated mesas in the northwest and

south of the town. The Assaba region is extremely arid with very little annual rainfall. At Kiffa, the mean annual rainfall is 350 mm, however, slightly farther north at Tidjikdja only 140 mm falls per year (Hughes & Hughes, 1992).

The vegetation at the fall site is sparse. The most abundant plants are *Ziziphus Mauritania*, the grass *Panicum turgidum*, the desert melon *Calotropis procera* and the small tree *Capparis decudea*. Acacia species are confined to the rocky beds of wadis and the gravel alluvium of outwash fans (Wickens, 1995). Migrating flocks of camel and goats are frequently abundant and litter the surface with their excrements, which, as reported by locals, makes the visual recognition of the very similar looking recently fallen meteorites particularly difficult.

## FIRST MEDIA REPORTS

A very early note on the incident was released by the national press agency of Mauritania, Agence Nouakchott d'Information (2011), on September 15, 2011, one day after the fall. According to the report, a luminous body fell from the sky near Boumdeid on the evening of September 14. It was observed from as far as Kiffa and near its endpoint, explosions were heard that terrified the local population (ANI, 2011, see appendix no. 1).

The news of the event spread quickly among local

media and found its way on several websites and blogs within hours. According to the website of *Carrefour de la République Islamique De Mauritanie* (CRIDEM), the "large meteorite that fell in the vicinity of Boumdeid" illuminated a large area "before causing a loud explosion", which created "panic among the population." According to the source, the event remained unclear at the time of publication whether it was caused by "a meteor or a piece of a satellite" (CRIDEM, 2011, see appendix no. 1).

## WITNESS ACCOUNTS

While in Kiffa and Nouakchott speculations on the cause of the event were still ongoing, one of the authors, Cheikhalhoussein Toueirjenne, Director of COMSTAT, decided to investigate the event in person to collect and record first hand accounts in the field. It is due to Mr. Toueirjenne's diligent and thorough efforts, that this recent meteorite fall in Mauritania could be comprehensively documented in the week following the event.

The evening of Wednesday, September 14, was cloudless and bright, being just the second night after full moon. The nomads in the Boumdeid area had lit their campfires and most people were still outside their tents preparing dinner. In Kiffa, 93 kilometers south of Boumdeid, the streets were busy with traffic on the main roads and many people who enjoyed the cool evening breeze were outside. At 21:00 UTM, people west of Kiffa and in the city spotted an intensely bright object that appeared in the west and that was

quickly moving to the north, illuminating the streets "like during the brightest day" (witness #01, see appendix no. 2). Observers located further north and closer to the trajectory reported a south to north moving body that "exploded" along its path, after which "three smaller stars" continued in slightly diverging directions (witness #02, see appendix no. 2). The trajectory azimuth and general direction reported for the fan shaped spreading of the detonation fragments was later found consistent with the find location of the single mass recovered. Other observers located near the endpoint of the trajectory reported explosive sounds. One group of witnesses camping in close proximity of the fall site reported "three or four explosions from the south" and the swishing noise of a falling object followed by the sound of its impact (witness #11, see appendix no. 2).

In total 30 interviews were conducted and 18 accounts were recorded in detail (see appendix no. 2).

With the exception of witnesses #05 and #09, those observers that gave a direction of movement for the light phenomenon reported a south to north trajec-

tory. One witness who observed the bolide directly overhead was unsure about its direction.

## TRAJECTORY AND STREWNFIELD

It is well established practice to predict strewn fields by model calculations based on at least two independent camera records. In contrast it is virtually impossible to do the same based on visual observations alone. Eye witness reports, even by astronomically experienced observers, are rarely precise enough and sometimes even contradictory (e.g. Bronshten, 1999; Pugh et al., 2004; Beech et al., 2007). Thus, additional facts are required, like the coordinates of the recovered meteorites, to enable at a minimum a fall scenario and strewn field constraints.

Fortunately, that is the case with the Boumdeid (2011) fall where the location of one recovered meteorite is well documented. This position serves as an anchor point for the analysis of visual and acoustic observations (Fig. 1b). One of the first steps in building an accurate trajectory model is to account for wind drift during the dark flight of the meteorite. All available wind data was collected from sounding stations as far as 500 to 730 km from the fall area (mainly stations 61442 GQNN Nouakchott, 61291 GABS Bamako and 61641 GOOY Dakar at 12:00 and 00:00 GMT) as obtained from the NOAA/ESRL Radiosonde Database Archive. Therefore, the interpolation in space and time is subject to an element of uncertainty. The resulting scenario, however, appears to be quite consistent. The model shows very little wind in the high atmosphere, predominant wind direction from nearly east (from about 100°) and an average wind speed of 7 ms<sup>-1</sup> in the relevant altitudes.

With these data, a dark flight calculation based on the single body theory (Ceplecha et al., 1998) yields an offset from the projected trajectory of only about 1 km from the actual impact location of the 3.5 kg mass. The shift defines a point about 1 km east of the find location through which the ground projection of the extrapolated trajectory has to go.

The next parameter necessary for a reconstruction of the trajectory is its azimuth angle. The combination of visual observations #1 and #2 with acoustic observations #2 and #9 leads to a SSW to NNE directed trajectory with an azimuth angle around 25°. Interestingly, and in contrast to the other observers, the two witnesses #5 and #9 report an incident direction “from North to South”. These conflicting reports are very common in similar scenarios where observers directly under the trajectory have difficulty perceiving the true

direction of movement. Also there is the possibility that their description may refer to the direction of observation rather than to the direction of the meteor movement, a misunderstanding that occurs frequently with non-standardized interviews. From personal experience (K. Wimmer), another explanation might be that the shadow movement on the ground dominated the observer’s perception, who, surprised by the extremely fast phenomenon overhead and out of normal visual range, looked up too late.

The initial height of fireballs of comparable size is typically in between 80 km and 90 km (e.g. Popova et al., 2009). Assuming a statistically average height of 85 km and combining it with observation #1 from Kiffa the vertical angle of the trajectory can be estimated to be approximately 45°. Using these values, the resulting total length of the luminous trajectory is about 95 km and its ground projection about 67 km. Assuming a typical initial velocity of 20 kms<sup>-1</sup> this corresponds to a meteor duration of about 5.9 s.

According to observer #2 the fireball released three major fragments upon its explosion. This fragmentation happened at an altitude of about 24 km or below as indicated by the locations where the sonic boom was perceived (Fig 1b). The fragment becoming the recovered meteorite was visible down to 18 km. Due to the lack of data regarding precise velocity and direction of flight we have no information about the total mass on the ground or the mass of other fragments. Derived from radionuclide measurements of <sup>60</sup>Co, <sup>54</sup>Mn and <sup>22</sup>Na, the preatmospheric meteoroid radius can be constrained to 10-20 cm. With a bulk density of 3500 kgm<sup>-3</sup> this corresponds to an initial mass between 14 kg and 114 kg for a spherical body. Allowing for a non-spherical shape the upper limit may be up to about 150 kg.

The mass loss by ablation during the atmospheric passage increases strongly with the meteoroid velocity. Using the maximum initial mass of 150 kg and a minimum final mass of 3.5 kg, i.e. the recovered meteorite, we can constrain the upper limit for the initial velocity. With the typical ablation coefficient of 1.4·10<sup>-8</sup> s<sup>2</sup>m<sup>-2</sup> for ordinary chondrites we find an initial velocity lower than 23 kms<sup>-1</sup>, compatible with our assumption.

With one meteorite already found, the strewnfield with the highest probability for meteorites in the mass

range from 100 g to 10 kg with typical drag and shape factors (Wimmer, 2009) can be constrained to an area of 8 km × 2.5 km.

No information on time delays between the termination of the fireball, the visible fragmentation and the observed sound phenomena were reported. Those eyewitnesses reporting sound phenomena explained though, that the explosion noise and the hissing sound of a falling object were perceived subsequent to the

visible fragmentation and termination of the fireball. Also, no durations for these sounds were given.

Despite the lack of data, the resulting deductions are plausible as they are consistent and similar to other well-understood meteorite falls. Due to the lack of objective records, however, these results are considered to only be the most likely scenario based on existing assumptions and uncertainties. Table 1 gives an overview over its parameters with their most probable ranges.

## THE FIND

The encampment of Sidi Mahmoud Ould Belkheir Ould Eabeid (witness #11), a camel herdsman in the service of Sidi Ould Sidibrahim of Tejkanet, is situated 31 km south of Boumdeid at 17°10'29.748"N, 11°20'28.8"W. It was in his family's "backyard" that the recovered mass fell, amidst a flock of camels, and just seven meters from where he and his company were camping (Fig. 2).

This is how Sidi Ould Eabeid described the event: "We were preparing dinner when suddenly the torch I was holding was no longer necessary as night had become bright day. We became very frightened as it appeared that the day of the last judgement had begun. Just after the light had passed there were three or four explosions from the South, and after this we heard an *ishshsh*-like sound that terminated in a big thud. We searched for the object that obviously had fallen upon us but we only discovered a hole in the soil." On the morning following the event, a man named Sidi

Mohamed Ould Alharthi, called Albadad, arrived and said he had found the meteorite. The 3.5 kg stone was then broken apart and pieces of it were distributed as souvenirs "to everybody who asked for one." (witness #11, see appendix no. 2)

The find location of the single recovered mass was some 30 meters downhill from the camp in the direction of flight. No photos of the complete mass are known. The mass of the recovered stone prior to breaking it apart was given with around 3.5 kg. It was described as an angular stone with smoothly rounded edges covered in a dull black skin showing several thumbprint-like indentations. According to the finder the main fragment of around 1.6 kg was handed over to local authorities that kept the stone for further investigation. The second large fragment of 1.59 kg was later obtained by one of the authors (S. Buhl) and is shown in Fig. 3.

## EXTERIOR MORPHOLOGY

Fragments of the Boumdeid (2011) meteorite reveal a thin but well developed (0.4 mm) primary fusion

crust and on one surface a less thick (0.1 mm) secondary fusion crust. The surfaces indicating primary

**Table 1.** Values and probable ranges of the Boumdeid fall scenario parameters.

Parameter	Value	Range	Comment
Initial altitude	85 km	80 – 90 km	assumption, typical range
Initial velocity	20 kms <sup>-1</sup>	< 23 kms <sup>-1</sup>	assumption, upper limit calculated from mass loss
Initial radius		10 – 20 cm	<sup>60</sup> Co, <sup>54</sup> Mn and <sup>22</sup> Na data
Initial mass	80 kg	14 – 150 kg	assumption, range derived from initial radius with bulk density 3500 kgm <sup>-3</sup>
Trajectory azimuth angle	25°	15° – 35°	
Trajectory vertical angle	45°	35° – 55°	
Fragmentation altitude	24 km	25 – 19 km	from sonic boom observation
Luminous trajectory terminal altitude	18 km	17 – 19 km	from recovered meteorite mass
Length of luminous trajectory	95 km		
Length of luminous trajectory ground projection	67 km		
Meteor duration	5.9 s		based on assumptions above
Dark flight duration	157 s	135 – 175 s	for the recovered meteorite



Fig. 2. Find location of the 3.5 kg Boumdeid (2011) meteorite. The car marks the spot where the camp of Sidi Mahmoud Ould Belkheir Ould Eabeid (witness #11) was located in the night of September 14/15. The meteorite was found on the opposite slope of the ridge, approx 30 m behind the tall acacia next to the car. Photo: A. Mohamed

atmospheric ablation show few distinct regmaglypts with an average diameter of 12 mm and an average depth of 6 mm. No visible oxidation is present on the fusion rind and only minor rust spots are visible on the fragmented surfaces.

The largest fragment remaining from the shattered ~3.5 kg mass shows an elongated and rounded shape with one angular-edged surface as an exception. The



Fig. 3. Image of the 1.59 kg fragment that was broken from the 3.5 kg mass recovered near Boumdeid on the morning of September 15, 2011. Fractions are caused by the finder who broke the individual meteorite apart to look inside. Note the prominent impact marks on the right of the specimen. Scalecube is 1 cm. Photo: S. Buhl

flat fusion crusted fragmentation plane indicates that the meteorite broke apart along a pre existing fracture plane prior to or during atmospheric ablation. The large size of the fraction plane indicates that at least one other fragment detached from the initial mass prior or during the ablation phase. This observation is consistent with the eyewitness report, which stated that the meteor parted into 3 fragments.

## COSMOGENIC AND PRIMORDIAL RADIONUCLIDES

Of the fragments broken from the ~3.5 kg stone, several were obtained by one author (S. Buhl) and submitted to institutions in Italy and Switzerland for further analysis. The head of the Special Techniques Service at the Gran Sasso National Laboratory, Matthias Laubenstein, conducted measurements of cosmogenic radionuclides. Beda Hofmann from the Natural History Museum in Bern subsequently conducted the chemical and petrological analysis and classification. Both institutes worked with the same 53.60 g partially crusted sample fragment (NMBE 41388).

The concentrations of short-lived cosmogenic radionuclides, as well as long-lived cosmogenic  $^{26}\text{Al}$  and natural radioactivity, were measured using non-destructive gamma-ray spectroscopy. One fragment of the ordinary, L6 chondrite Boumdeid (2011) was measured in the STELLA (SubTerranean Low Level Assay) facility of the underground laboratories at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, using a high-purity germanium (HPGe) detector of ca. 400 cm<sup>3</sup> (Arpesella, 1996). The specimen was measured at LNGS 84 days after the fall, so that short-

lived radionuclides such as  $^{56}\text{Co}$  (half-life = 312.13 d) and  $^{46}\text{Sc}$  (2.6027 y) could still be detected. The counting time was 12.616 days. The counting efficiencies were calculated using a Monte Carlo code. This code is validated through measurements and analyses of samples of well-known radionuclide activities and geometries. The uncertainties in the radionuclide activities are dominated by the uncertainty in the counting efficiency, which is conservatively estimated at 10%. The average density and composition were taken from Britt and Consolmagno (2003), and from Jarosewich (1990), respectively.

Table 2 lists the measured activity concentrations for the detected short- and medium-lived cosmogenic radionuclides ( $^7\text{Be}$ ,  $^{58}\text{Co}$ ,  $^{56}\text{Co}$ ,  $^{46}\text{Sc}$ ,  $^{57}\text{Co}$ ,  $^{54}\text{Mn}$ ,  $^{22}\text{Na}$ ,  $^{60}\text{Co}$ ,  $^{44}\text{Ti}$ ,  $^{26}\text{Al}$ ). The given activities are already calculated back to the date of fall following the simple decay law, and taking into account the time that passed between the fall of the meteorite and its measurement. In order to derive an approximate size of the meteorite body, the data of  $^{60}\text{Co}$ ,  $^{54}\text{Mn}$  and  $^{22}\text{Na}$  were used. Assuming the  $^{59}\text{Co}$  concentration in Boumdeid

**Table 2.** Summary table for the detected cosmogenic radionuclides in the specimen of the Boumdeid (2011) L chondrite

Sample Weight [g]		NMBE 41388 55.2
radionuclide	half-life	specific activity [dpm·kg <sup>-1</sup> ]
<sup>7</sup> Be	53.22 d	91 ± 20
<sup>58</sup> Co	70.38 d	4 ± 1
<sup>56</sup> Co	77.236 d	4 ± 1
<sup>46</sup> Sc	83.788 d	9.0 ± 0.8
<sup>57</sup> Co	271.8 d	8.9 ± 1.4
<sup>54</sup> Mn	312.13 d	71.7 ± 7.3
<sup>22</sup> Na	2.6027 a	91.9 ± 9.5
<sup>60</sup> Co	5.27 a	< 0.47
<sup>44</sup> Ti	60 a	< 2.5
<sup>26</sup> Al	7.17×10 <sup>5</sup> a	57.1 ± 6.1

(2011) to be 600 ppm (Jarosewich, 1990), the resulting specific activity was directly compared to the calculations of Eberhardt et al. (1963), and Spergel et al. (1986). This comparison gave a possible range for the radius of <20 cm. The <sup>22</sup>Na data was compared to the calculations of Bhandari et al. (1993) for H chondrites, correcting obviously for the differences between L and H chondrites in composition. The resulting possible range in the radius is (10–15) cm. Finally, the data of <sup>54</sup>Mn was normalised to the concentration of its main target Fe and then compared to the calculations of Kohman and Bender (1967), giving a range for the radius of ≤13 cm. Combining the radius estimates from the three radionuclides tests results in a conservative range for the radius of a spherical meteoroid of 10 to 20 cm. This range corresponds to a parent meteoroid mass of 14 to 114 kg. Assuming the production rates in L chondrites for <sup>26</sup>Al to be that of Leya and Masarik (2009), the expected saturation values for the above determined size range are 48 dpm·kg<sup>-1</sup> and 62 dpm·kg<sup>-1</sup>, respectively, for the radii 10 cm and 20 cm. Thus, taking the measured value for <sup>26</sup>Al of 57.1 ± 6.1 dpm·kg<sup>-1</sup>, the results fall well within the range obtained for the radius. Since no noble gas data is available, these estimates have to be taken as preliminary. Additionally, given the stringent

**Table 3.** Results for the naturally occurring radioactive elements Th, U, and K in the sample of the Boumdeid (2011) L chondrite. The reported uncertainties are expanded uncertainties, the upper detection limits are given with a confidence level of ca. 68%

Sample Weight [g]		NMBE 41388 55.2
radionuclide		concentration [ng·g <sup>-1</sup> ]
<sup>238</sup> U		14 ± 2
<sup>232</sup> Th		38 ± 5
radionuclide		total K concentration [mg·g <sup>-1</sup> ]
<sup>40</sup> K		0.89 ± 0.09

low value of <sup>60</sup>Co in the specimen, the sample could also have come from the outermost surface of a bigger parent body.

The decay of the short-lived radioisotopes, with half-lives less than the orbital period, represents instead the production integrated over the last segment of the orbit. The fall of the Boumdeid (2011) L chondrite occurred in the preparatory phase of the current solar cycle 24 as indicated by the publicly available neutron monitor data (Bartol, 2012). As in the case of e.g. the Jesenice L chondrite (Bischoff et al., 2011), the galactic cosmic ray flux was therefore moderately high in the six months before the fall. The activity for the very short-lived radionuclides <sup>57</sup>Co and <sup>54</sup>Mn are expected to be close to maximal following the sunspot number as reported in Bischoff et al. (2011) and the references cited therein. This is confirmed by our measured values for <sup>57</sup>Co and <sup>54</sup>Mn, normalised to their primary targets of Co, and Fe/Ni respectively.

The specific activities are given in dpm (decays per minute, 60 dpm = 1 Bq) per kg. The reported uncertainties are expanded uncertainties, the upper detection limits are given with a confidence level of ca. 68%. Radionuclide concentrations are normalised to the date of fall (September 14<sup>th</sup>, 2011). The concentrations of the natural radionuclides <sup>232</sup>Th and <sup>238</sup>U as well as for <sup>40</sup>K in the meteorite specimens are listed in Table 3. They are well in accordance with the average concentrations given in Wasson and Kallemeyn (1988) for L chondrites.

## CHEMICAL AND PETROLOGIC ANALYSIS AND CLASSIFICATION

Boumdeid (2011) is an ordinary chondrite of type L6, shock stage S2, weathering grade W0. In thin section, Boumdeid (2011) shows a brecciated texture (Fig. 4). Both breccia matrix and clasts are strongly recrystallized (Fig. 5a, b) with only few well outlined chondrules preserved, and feldspar is coarse-grained (up to 100 μm), indicating petrologic type 6. The recognition of former chondrules is made difficult by

both metamorphism and brecciation. However, several quite well preserved chondrules of barred olivine, porphyritic olivine and radial pyroxene type are visible (Fig. 6). The strong brecciation of this chondrite is quite difficult to see on broken surfaces, but is very evident in thin section. Individual clasts are up to 10 mm in size and are well delimited against a clastic, but well recrystallized matrix.

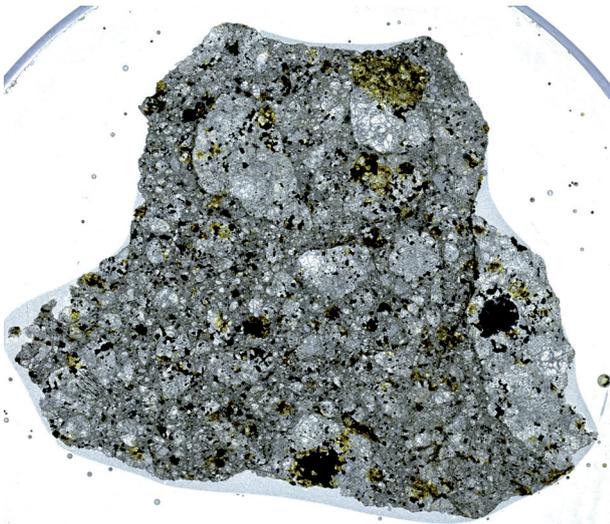


Fig. 4. Scan of polished thin section showing the brecciated nature of Boumdeid (2011) with only marginally visible chondrules. The dark grain (middle right) is the Cr-Al-rich chondrule, all other opaque grains are metal/troilite. Maximum width of section is 19 mm. Mosaic of images taken with digital microscope (Keyence VHX). Image: B. Hofmann

A single Cr-Al-rich chondrule (1.0 mm) with sodium-rich plagioclase ( $An_{25}$ ), spinel-chromite solid solutions, ilmenite-geikielite and micron-sized baddeleyite is present in the largest clast of the analyzed thin section. Near the center of this chondrule, spinel is Al-rich, with increasing Cr-concentration to the rim (Fig. 7). Similar Cr-rich chondrules have been reported from a number of ordinary chondrites (e.g. Brearley et al., 1991; Krot & Ignova, 1992) but appear to be quite rare.

Electron microprobe analyses and backscattered electron images showed that olivine is homogeneous and has a mean composition of  $Fa_{23.9}$  (identical value confirmed by XRD), homogeneous orthopyroxene has a composition of  $Fs_{20.2}Wo_{1.6}$ . The mineral chemistry is consistent with equilibrated ordinary chondrites of type L. Shock effects are generally minor, and the only common effect observed is the weak undulatory extinction of olivine. Some olivines show a partially recrystallized texture reminiscent of mosaicism, and some remnants of planar fractures are also visible, indicating a pre-metamorphic shock event largely masked by recrystallization. A single narrow shock vein cuts the thin section, showing melting of troilite. A cut metal grain shows an offset of  $\sim 250 \mu m$ . This vein appears to be younger than the metamorphism causing silicate recrystallization.

Metal grains reach 1 mm in size and often represent intergrowths of kamacite and taenite, sometimes with numerous troilite inclusions. Troilite (typically  $100\text{--}200 \mu m$ ), generally monocrystalline, and chromite ( $100\text{--}300 \mu m$ ) are common accessories. Ilmenite

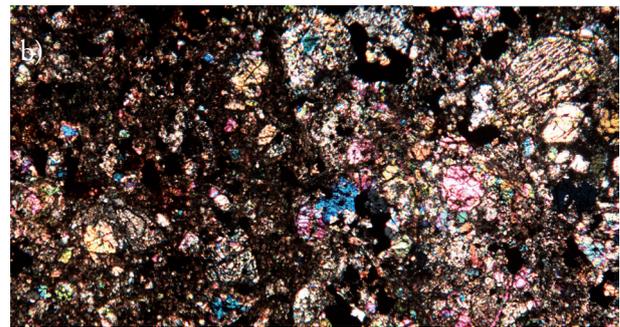
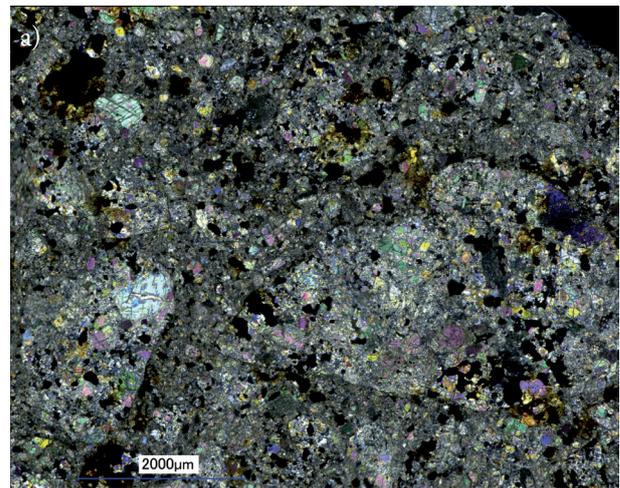


Fig. 5. a) Transmitted light image (cross polarized light) of thin section of Boumdeid (2011) at low magnification showing brecciated texture with well-delineated clasts. No chondrules are visible. Mosaic of images taken with digital microscope (Keyence VHX). Image: B. Hofmann; b) Transmitted light image showing the transition from matrix to a breccia clast. Transmitted light, crossed polarizers, image width is 4.9 mm. Photo: B. Hofmann

was observed in contact with metal. Native copper is very rare and was observed at kamacite-taenite and metal-troilite contacts (Fig. 8).

Besides some minor rusty specks up to 2.5 mm in diameter around metal grains, observed macroscopi-

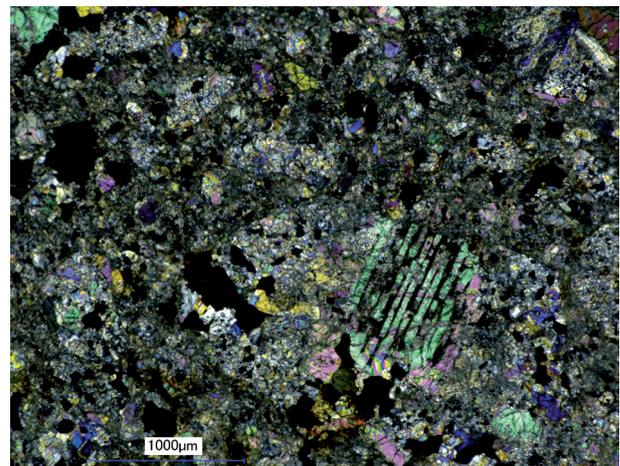


Fig. 6. Transmitted light image (cross polarized light) of thin section of Boumdeid (2011) showing brecciated texture and well-preserved barred olivine chondrule. Mosaic of images taken with digital microscope (Keyence VHX). Image: B. Hofmann

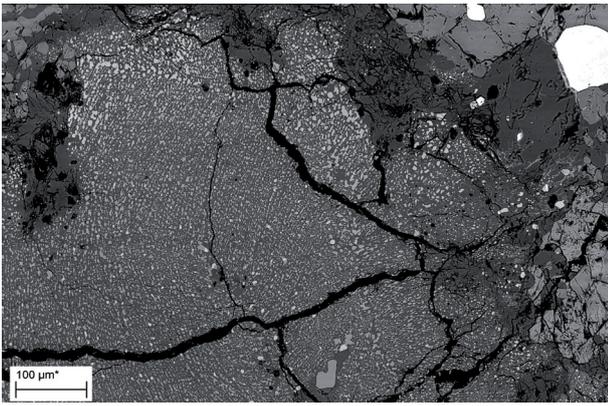


Fig. 7. Backscattered electron image showing a section of the Cr-Al rich chondrule. Dark groundmass is feldspar, bright inclusions are spinel with increasing Cr-concentrations to the rim of the chondrule (indicated by higher brightness in BSE-image). Bright inclusions include metal, ilmenite-geikielite and baddeleyite. Image: N. Greber

cally and in thin section, the meteorite is unaltered (W0). In a single grain of kamacite, corrosion to an apparent depth of 15  $\mu\text{m}$  was observed, while bordering taenite was unaffected.

## DISTRIBUTION

- ~1600 g Mauritania [seized by local authorities, unconfirmed]
- 752.00 g S. Buhl, Hamburg, Germany
- 735.80 g M. Jost, Brügg, Switzerland
- 53.60 g Naturhistorisches Museum der Burgergemeinde Bern, Switzerland
- 50.20 g Don Hurkot, Monarch, Canada
- 8.60 g K. Wimmer, Nördlingen, Germany
- Fragments of unknown weight distributed by the finder

## CONCLUSION

Boumdeid (2011) is the 5th confirmed meteorite fall in Mauritania. Prior to the Boumdeid (2011) event a total of two crater structures and 18 meteorites were known for Mauritania. Among the latter are 14 finds and only four falls. Aioun el Atrouss, a polymict diogenite weighing 1 000 g fell at Gounquel in south-east Mauritania on April 17 in 1974 (Lomena et al., 1976, Graham, 1979). Kiffa, an ordinary chondrite with a TKW of 1 500 g fell on October 23, 1970 at 14:55 hrs, not far from the recent event (Clarke, 1971). Boumdeid (2003), a mass of 190 g, fell ~30 km north of the village of Boumdeid and was also classified as an L6 chondrite. Despite sharing the same petrologic

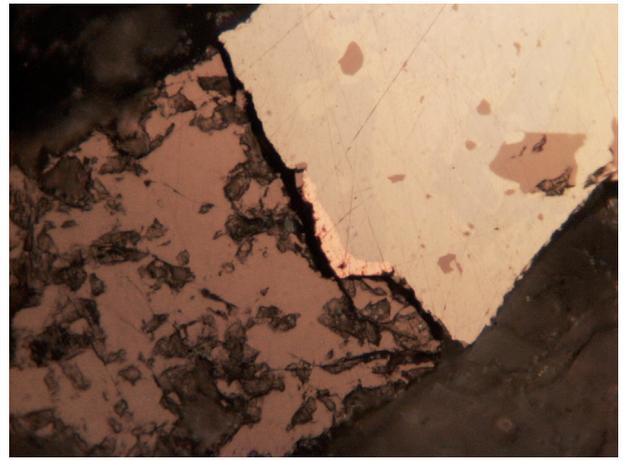


Fig. 8. Reflected light image (oil immersion) showing native copper at the border between metal and troilite. Image width 120 micron. Photo: B. Hofmann

Parallel to the completion of this paper, the meteorite was submitted to the Nomenclature Committee by one of the authors (B. Hofmann) and subsequently published under the official name Boumdeid (2011)<sup>2</sup> in Meteoritical Bulletin (Ruzicka et al., 2014).

The TKW is reported by the finders with around 3500 g (one single mass recovered).

One author of this report (S. Buhl) contacted the department of Earth Sciences at the University of Nouakchott repeatedly with a request for further information on the recovered mass and with the offer to share the collected data as well as sample material. However, as of August 2013, no reply was received.

type, month of the fall and, despite the fact that the fall location differs by only 59 kilometers, both meteorite falls, Boumdeid (2003) and Boumdeid (2011) are separate events and the similarities are based on coincidence only. Bassikounou, the fourth registered fall in Mauritania, an ordinary chondrite (H5) with

<sup>2</sup> Following nomenclature protocol, the year 2011 was added to the meteorite's name in order to distinguish it from Boumdeid (2003), a mass of 190 gram that fell on September 24, 2003, 30 km north of the village of Boumdeid (Ruzicka et al., 2014).

a confirmed total known weight of 93.8 kg, fell on October 16, 2006, 04:00 UTC, and is at present the largest witnessed fall in the history of the country (Conolly et al., 2007; Buhl et al., 2008). While the Bassikounou meteorite can be considered a well documented fall, particularly in terms of the recording of the recovered material, only a few eye witness reports were collected and only very little information on the trajectory of the detonating fireball is known.

Boumdeid (2011) is presently the second largest meteorite fall in the country and, due to the efforts of Mr. Toueirjenne, a substantial number of eye witness accounts were collected. These were sufficient to constrain a scenario for the trajectory of the bolide that is consistent with the find location of the recovered 3.5 kg mass and the values derived from the measurements of cosmogenic radionuclides. In this scenario the incident direction of the bolide is within a range between 15° and 35° and its vertical angle between 35°–55°. The luminous track started in 85 km altitude and ended in 18 km altitude, with a fragmentation event occurring at 24 km altitude. The luminous trajectory has a most probable length of ~95 km, its projection on the ground has a length of ~67 km. The impact site

of the recovered 3.5 kg mass is shifted ~1 km to the west of the trajectory due to wind drift.

The mineralogy, texture and mineral chemistry of Boumdeid (2011) is fully consistent with a classification as ordinary chondrite of type L6, shock stage S2, and no weathering (W0). The meteorite is brecciated and contains Al-Cr-rich chondrules. Remnants of stronger shock metamorphism indicate strong recrystallization with near complete obliteration of older shock metamorphic features.

The availability of a 56 g sample shortly after the fall enabled the measuring of cosmogenic radionuclides 84 days after the event and facilitated the retrieval of a new suite of radionuclide values of a freshly fallen chondrite. The data obtained from the measurements of the short-lived radioisotopes are consistent with a fall event on September 14 and confirm that the meteoroid underwent its last orbital segment during a period with a moderately high cosmic ray flux due to the preparatory phase of the current solar cycle 24. Based on previously determined production rates in L chondrites for <sup>26</sup>Al the measured values for <sup>26</sup>Al in the Boumdeid (2011) meteorite are well within the expected saturation values for preatmospheric radii of 10–20 cm.

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## APPENDIX 1. MEDIA REPORTS

Agence Nouakchott d'Information (ANI): Mauritanie: **L'explosion d'un corps étrange secoue la ville de Boumdeid**, Nouakchott Sept. 15, 2011

Mauritanie: L'explosion d'un corps étrange secoue la ville de Boumdeid

*Selon des témoins oculaires, l'explosion d'un « corps étrange et lumineux tombé du ciel » a secoué la ville de Boumdeid, dans la soirée du mercredi [Sept. 14]. Un habitant de la ville a précisé qu'il « s'agit d'un corps, dont émanait une lumière aveuglante, ayant chuté non loin de Boumdeid et dont l'explosion a secoué les habitants et provoqué chez eux une psychose.*

*Ce témoin a souligné que les habitants de kiffa ont également pu observer la lumière émanant de ce corps « étrangement terrifiant »*

English translation:

Mauritania: Explosion of a strange body shakes city of Boumdeid

*According to eyewitnesses, the explosion of a “strange and luminous body which fell from the sky” shook the city of Boumdeid, on the evening of Wednesday [Sept. 14]. A local resident said it was “a body, which gave off a blinding light, falling near Boumdeid and whose explosion shook the people and caused in them a psychosis.” This witness*

*said that the inhabitants of Kiffa have also observed light from this “strangely terrifying” object.*

Carrefour de la République Islamique De Mauritanie (CRIDEM): **Chute d'une grosse météorite dans les environs de Boumdeid**. Sept. 15, 2011, published on [http://www.cridem.org/C\\_Info.php?article=59988](http://www.cridem.org/C_Info.php?article=59988), 2011

*Le village de Boumdeid, en Assaba risque d'être la destination prise par les prochains de experts et des passionnés des secrets du cosmos. Selon le site alakhbar, citant des sources dans cette localité, une grosse météorite est tombée dans les alentours de Boumdeid, illuminant dans sa chute la zone avant de faire une forte explosion, suivie d'une forte panique chez les populations.*

*S'agit-il d'une, foudre, d'une météorite ou d'un morceau d'un satellite désintégré dans l'espace ? En attendant de savoir au juste de quoi il s'agit, seul les gens du cosmos peuvent éclairer l'opinion sur un événement qui attire les scientifiques comme les éclipses et qui est très rare.*

*Est-on également en présence d'une nouvelle météorite comme celle du Nord de l'Adrar découverte par Théodore Monod. Notons qu'on ne sait pas encore si cette présumée météorite a fait des dégâts.*

NAM (Stagiaire)

English translation:

### Fall of a large meteorite near Boumdeid

*The village of Boumdeid in Assaba may be the next popular destination of experts and enthusiasts researching the secrets of the cosmos. According to the site Alakhbar, citing sources in this locality, a large meteorite fell in the vicinity of Boumdeid, illuminating in its fall the surrounding area before causing a loud explosion, followed by a sharp panic among the population.*

*Is this a lightning, a meteor or a piece of a satellite disintegrated in space? Until we know exactly what it is, only people of the cosmos can enlighten public opinion on an event that attracts scientists similar like eclipses, and which is very rare.*

*Is it also in the presence of another meteorite like the one discovered in northern Adrar by Theodore Monod. Note that we do not yet know whether the alleged meteorite did damage.*

*NAM (Intern)*

## APPENDIX 2. EXCERPTS FROM WITNESS ACCOUNTS

Ahmed Ould Ahmedwali (witness #01) observed the event from 16°35'33"N, 11°23'4.908"W, just south of the town Kiffa: "I was looking to the north and saw the star during its complete duration from when it appeared in the west until it ended in the northeast. Everything was lighted like during the brightest day."

Limam Ould Ekhou (witness #02) camped with his brother Mohamed Lemine Ould Ekhou and his sons short east of the dirt track from Kiffa to Boumdeid at position 17°3'46.752"N, 11°21'26.784"W. His report, which is confirmed by his brother, is particularly interesting, because it describes the fragmentation of the Boumdeid bolide from a location relatively close to the trajectory: "Suddenly the night became day and we saw a flying star crossing the sky from south to north until the star exploded. After the explosion three smaller stars continued in slightly diverging directions." Witness #02 described the movement of the three fragments as "fan-shaped".

Mohamed Ould Enebbie (witness #05), located 36 km southwest from Boumdeid at 17°8'22.968"N, 11°24'46.272"W, stated that: "The fireball came from north to south". Mr. Ould Enebbie also reported a second observation by Dedahi Ould Chamad (witness #16), a young boy who saw the bolide approaching "almost above his head" and moving in a steep angle towards the zenith. No precise coordinates for the location of Ould Chamad are reported, but from the description of Mr. Ould Enebbie his position can be estimated – 15 km southeast of Boumdeid, which places the boy approximately on the axis of the trajectory, but north of the end point of the luminous path.

Salem Elbooussaty Abou Cheikh (witness #09) and his family camped west from the dirt track leading from Kiffa to Boumdeid at 17°3'55.572"N, 11°22'30.792"W, not far from the position of witness #02: "We saw it move from north to south and when it disappeared we heard a big explosion". This report

was later confirmed by the son and the sister of Mr. Abou Cheikh, although no direction of movement was mentioned.

Sidi Mahmoud Ould Belkheir Ould Eabeid (witness #11) gave the following account: "We were preparing dinner when suddenly the torch I was holding was no longer necessary as night had become bright day. We became very frightened as it appeared that the day of the last judgement had begun. Just after the light had passed there were three or four explosions from the South, and after this we heard an *ishshsh*-like sound which terminated in a big thud. We searched for the object that obviously had fallen upon us but we only discovered a hole in the soil. In it was some kind of ash-like dust which we could also smell, and which was different from the camel's urine [which soaked the ground around the animals]. Early the next morning I told the story to Eli who in turn told it to Albadad [Sidi Mohamed Ould Alharthi]. Albadad arrived later during the day and actually found the stone, broke it apart, and gave pieces of it as souvenirs to everybody who asked for one."

List of other witnesses:

- Mohamed Lemine Ould Ekhou, brother of Limam Ould Ekhou (witness #03),
- Edaya Ould [?] from Aoulad Boumalek (witness #04),
- Cheikh Ould Aabda from Hseytinne: (witness #06),
- Brother of Cheikh Ould Aabda, also from Hseytinne (witness #07),
- Mohamedvadel Ould Cheikh Saadbouh (Cheikhna), who witnessed the event with the finder of the meteorite (witness #08),
- Son (Cheikh Ould Salem) and sister of Salem Elbooussaty Abou Cheikh (witnesses #10 and 10b)
- Ould Sidbrahim (witness #12),
- Sidi Ahmed Ould Sweidy and family (witness #14),

- Dhahbi Ould Alaarbi Ould Moulay Zeine and brother who witnessed the event in Boumdeid (witness #15),
- Mohamed Ould Elhassen Ould Adermaz (witness #17),
- Mahfoudh Ould Naha who witnessed the event in Selibabi (witness #18).