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Mapping an Iron-Meteorite Impact Site with a Magnetometer, and Implications for the Probability of a Catastrophic Impact on Earth

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ABSTRACT

The Wabar meteorite impact site in central Saudi Arabia, first visited by Henry St. John (Abdullah) Philby in 1932, is unique in several ways. It is one of only 17 impact sites on the Earth where part of the original object is still present. The Wabar impact event also took place entirely in sand, permitting a much clearer and simpler reconstruction of the physical processes of a hypervelocity impact. A careful magnetic survey conducted there adds crucial information to this reconstruction: almost none of the >3,500 metric tons of the original iron-nickel object remains in or beneath the known impact craters. The magnetic data were difficult to acquire because of the hostile environment, and the processing was non-trivial for what in effect was a magnetic survey of a ferrous junkyard. The event sequence, which took place in just a few seconds, generated a unique binary set of impactite that includes a black glass (90% local sand and 10% meteorite) and a shock-generated, coarsely laminar bleached-white sandstone we have informally named "Instarock." Very little of the original object survived intact, save some small fragments apparently spalled off by the reflected impact shock-wave against the back of the meteoroid. Most of these fragments are in the form of so-called "shale-balls" buried beneath a shallow sand cover. Despite a ~6,400 year fission-track date, field relationships suggest a much younger age, a conclusion supported by thermoluminescence dates as low as 250 years. Along with several other small meteoroid impact events that have come to light in the past few decades, this very young age-date suggests a need to reconsider the frequency of these types of "city-buster" impacts.

Background

It is now reasonably well established that the Cretaceous-Tertiary marker event that extinguished the age of the dinosaurs was caused in large measure by an asteroid impact in what is now the Gulf of Mexico about 65 million years ago (Alvarez *et al.,* 1980; Hildebrand *et al.,* 1991; Sharpton *et al.,* 1992). Over the past several decades, there has been accumulating evidence of highly destructive meteorite impacts of smaller but still substantial energy in remote areas of the Earth. These include Tunguska (1908), Rupununi (1930), Rio Curacá (1935), and Sikhote-Alin (1947). The Tunguska event alone witnessed the destruction of over 2,200 km^2 of forest by a detonation in the middle stratosphere that is estimated at 20 megatons TNT equivalent (Vasilyev and Andreev, 1989; Sky and Telescope, 1972; Chyba *et al.,* 1993). These "city-buster" events all fortuitously occurred in extremely remote places, but because of their much greater than expected numbers appear to represent a more serious and immediate threat than previously thought.

When Henry St. John Bridger (later "Abdullah") Philby first visited the Wabar impact site in 1932, his al-Murra bedouin guides assured him he would see an ancient city destroyed by God for the impiety of its king (referred to in the Qu'ran, Sura 46:21–27). This ancient city was called 'Ubar (عبر), which Philby (1933a) transliterated as Wabar. The Wabar site is located in the center of the vast Empty Quarter of the Arabian Peninsula (Fig. 1). When he arrived, Philby could find no evidence of city walls or any other human artifacts, but instead saw several craters in the sand surrounded by a black, lava-like slag. While examining a piece of scorched, ablated iron the size of a rabbit, it occurred to Philby that while the site could not be a destroyed ancient city, it certainly was a site of immense physical destruction. At the time of his visit, the astronomic and geologic communities were fiercely contending about the apparent contradiction of craters covering the face of the Moon but the singular lack of craters on the Earth. Philby carried with him a report speculating that Lake Bosumptwi, a 10-km-diameter circular feature in what is now Ghana, was an impact crater caused by an asteroid impact (Lake Bosumptwi is now called the Ashanti Crater). As Philby turned over the iron in his hands, it dawned on him that it represented a visitor from beyond this world. Some of the glass brought back by Philby was later dated using the fission-track method as being 6,400 years old (Storzer, 1971).

When the authors first visited the site in 1994, there was abundant evidence, including fragile glass filagree and

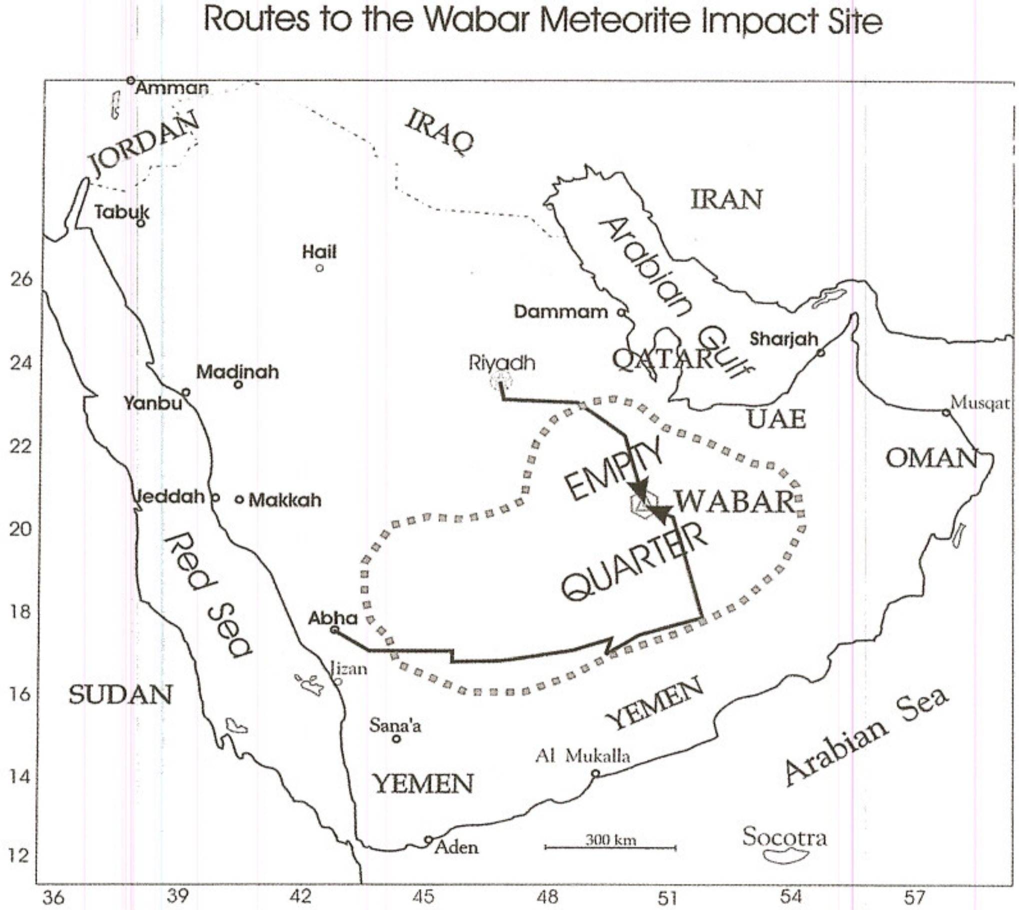

Figure 1. Index map showing the Empty Quarter desert of Saudi Arabia (dashed line) and the location of the Wabar impact site. The solid lines indicate different routes taken to the Wabar site.

documented crater-fill rates, that indicated the site must be much younger than 6,400 years. Philby mapped two craters (which following his original sketch map will be called here "Philby A" and "Philby B"), and felt that there might be several more. His bedouin guides had been to the site before and reported an object they called the "Camel's Hump," but Philby was unable to find this in the shifting dunes inundating the site. This object was subsequently recovered during an expedition in 1965 (Abercrombie, 1966). It is a Group IIIAB octahedrite iron meteorite, weighing about 2,200 kg, and shows strong evidence of ablation and air-braking. In December 1994 one of us (JCW) discovered a previously unreported impact relic now called the "11 Meter" crater (Wynn and Shoemaker, 1998).

Perhaps because of the extreme conditions encountered in the Empty Quarter, the first systematic scientific examination of the Wabar impact site took place only recently. Our team of scientists and engineers visited the Wabar meteorite impact site in the Ar-Rub' Al-Khali (Empty Quarter) desert in Saudi Arabia three times during 1994 and 1995. The Wabar site is more difficult to access than almost any other place in the world, including Antarctica. Rotary aircraft cannot be used because of the long distances involved, and the very high temperatures and consequent density-altitude problems. Fixed-wing aircraft cannot be used because almost the entire route to the site (about 750 km southeast of Riyadh) lies over constantly shifting sand dunes. It is extremely difficult to drive to the site even with 4WD vehicles because the loose sand constantly traps even experienced drivers. Because of this inaccessibility, remarkably little was known about the site in 1994. There are few documented expeditions on record, and only a few samples had been collected, but no systematic mapping had ever been done—something that can probably be ascribed to winter temperatures that routinely reach 50°C or more. During a magnetic profile conducted in May 1994 the air temperature in the shade reached 61°C.

When first seen, Wabar is a startling site. After driving over hundreds of kilometers of nearly featureless sand dunes, one encounters a site approximately 500 m by 1,000 m densely covered by a stark bimodal distribution of black slag and shocked white sandstone. The density of the ejecta is such that it has anchored (by preventing winnowing) the pre-impact dune structures much like a lag gravel. For this reason three of the original crater rims are still apparent as raised ring-like structures—when infrequently exposed by the constantly shifting sand dunes passing through the site. Excavation revealed that there is nothing solid beneath these rims but sand to depths of at least 4 meters.

The Wabar site has three distinct craters, and there is a definite type and size pattern to the ejecta surrounding them. An asymmetric distribution of the shocked white sandstone (informally named "Instarock") suggests a shallow oblique incoming trajectory. The object must have arrived from about 300 degrees (N60W) at an angle probably less than 22 degrees from the horizontal in order to provide this asymmetry (Roddy *et al.,* 1977). The size distribution of the black glass surrounding the craters suggests strong wind-sorting of the post-impact explosion cloud. About 10 months of the year the diurnal wind from the north begins blowing around noon and reaches its peak at sunset. During the early spring monsoon season in the Arabian Sea, however, the wind direction changes to south-southeast; this coincides with the sandstorm season in the Arabian peninsula. The size-sorted black glass is distributed northwest of the craters, indicating an early spring event. A cluster of spalled iron fragments, the asymmetry of the white Instarock ejecta, and the magnetic data (below) together suggest that there is probably at least one additional large crater buried beneath the dunes near 250NW, 400SW on the map (Fig. 2). In this and subsequent figures, the numbers around the margins are a local N60W grid established in December 1994, with distances in meters, keyed to GPS-derived UTM coordinates (the survey mast at station 0,0).

The "Philby A" crater is about 64 meters, and "Philby B" about 116 meters in diameter. Using a computer program provided by Prof. Jay Melosh (University of Arizona, written comm., 1997), the original object has been conservatively calculated from these crater diameters to comprise more than 3,500 metric tons of iron-nickel. This translates to a spherical meteoroid more than 10 meters in diameter. There are historical reports (*e.g.,* Philby, 1933b) of a huge fireball seen passing over Riyadh in 1863 heading in the direction of what is now known to be the Wabar site. Several meteorites recovered along this track are chemically indistinguishable from the Wabar object.

Field evidence and the historical records suggest that the object traversed several hundred kilometers of the Earth's atmosphere before impact. The meteoroid probably touched the upper atmosphere with a velocity in excess of 20 km/s, but due to the shallow angle it was air-braked and probably impacted at around 7 km/s (estimate by Gene Shoemaker). The kinetic energy it carried on arrival is conservatively estimated at roughly 5×10^{13} joules, about 12 kilotons of TNT equivalent—about the same as the Hiroshima atom bomb.

Acquisition and Processing of Magnetic Data

In order to better understand the physics of the impact and subsequent explosion (the interaction between the bolide and the underlying sand and rock), detailed geologic and magnetic surveys were conducted over 6 days during March 1995. A magnetic base station was set up to correct for diurnal variation of the Earth's field during the survey, and tie-lines were added on opposite sides of the survey area to allow for careful leveling. The magnetic survey was conducted using a 2.5-m aluminum pole to separate the sensor from the ground, and covered a smaller area than the over-all geologic map of Fig. 2. This was due to the limited time available on the site (logistical constraints), and the desire for 5-m grid spacing for maximum resolution.

The original data, after removing the base-station diurnal correction, can be seen in Fig. 3. This heavy "herringbone" banding is the result of the surface and near surface being covered with several thousand metric tons of iron, mostly in the form of the ubiquitous black "glass." The situation was further aggravated by the iron being within 2.5 m of the magnetic sensor. The situation is not unlike making a magnetic survey in a junkyard: a few centimeters' horizontal motion of the sensor could give variations of several nTesla in the measurements. This required unusually careful data-acquisition procedures. When tie-line corrections were incorporated and the data hand-leveled, Fig. 4 is the result. While the quality of these data still appear to be poor, they apparently accurately map the magnetic field at the site. Microleveling was then done in an effort to improve the image further, using the Oasis Montaj[1] geophysical data processing system, giving us Fig. 5.

What the Magnetic and Field Data Tell Us About the Impact Event

The final magnetic map (Fig. 5) clearly illustrates a basic consequence of a hypervelocity impact: very little of the nickel-iron meteorite was left in the known craters after the impact detonation and atmospheric sorting. There is also some suggestion that more ferrous material may underlie the sand-covered zone on the left (southwest) and "up" (northwest) side of the figure. Consequently it is probable that during the next several years, as the dunes continue migrating in the southwest direc-

[1] Use of manufacturer's names is for descriptive purposes and in no way implies endorsement by the Dept. of Interior or U.S. Geological Survey.

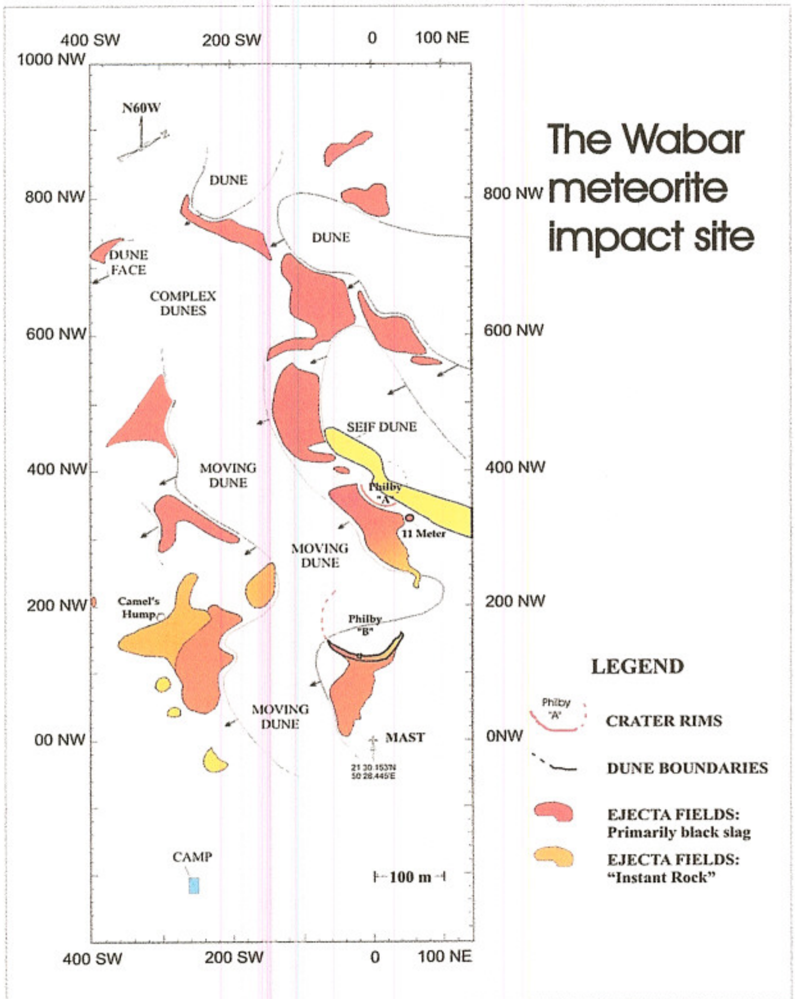

Figure 2. Geologic map of the Wabar impact site, showing the known crater rims and the migrating sand-dune positions as of March 1995. The asymmetry of the ejecta field, suggesting a shallow 300-degree incoming trajectory, is indicated by the colors, where red indicates the black "glass" mixture impactite and yellow-orange indicates the white shocked "instarock."

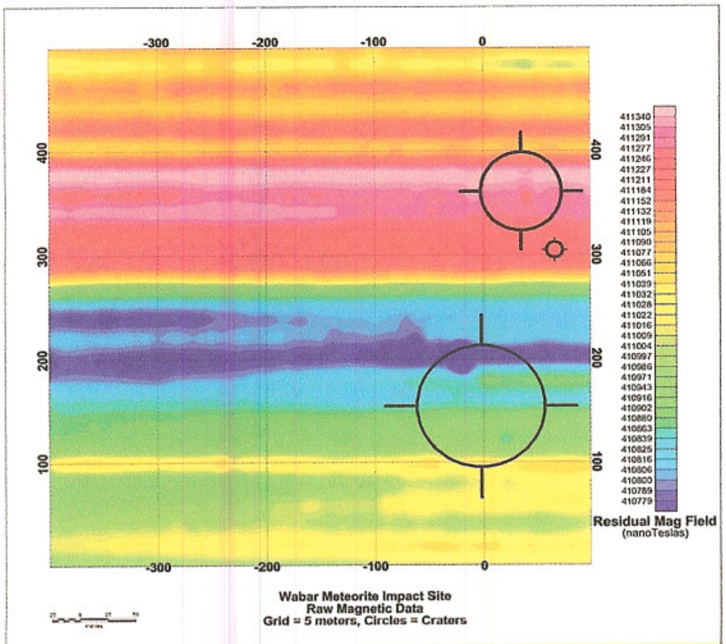

Figure 3. Residual magnetic data acquired at the Wabar impact site in March 1995. Base station diurnal corrections have been subtracted. Known crater rims are indicated by circles. Station spacing (left-right) is 5 meters, line spacing (top-bottom) is 10 meters. Final grid is 5 m by 5 m.

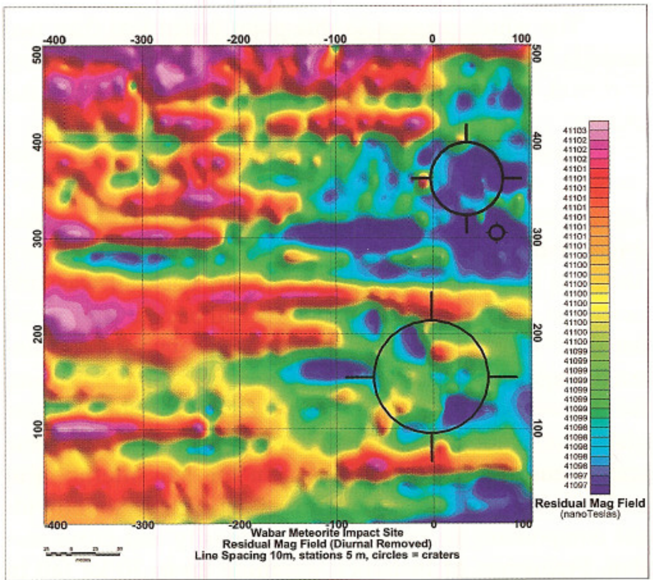

Figure 4. Residual magnetic data from the Wabar impact site after tie-line corrections have been applied.

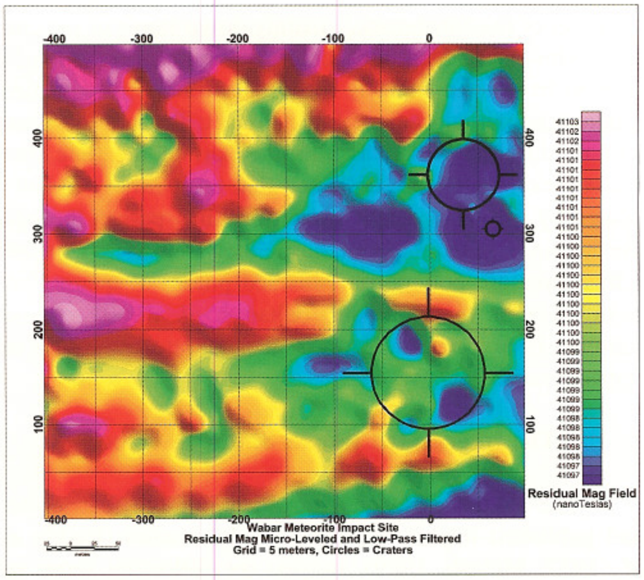

Figure 5. Residual magnetic data from the Wabar impact site after additional micro-leveling and a Hanning filter have been applied. This figure demonstrates a basic principle of hypervelocity impacts—that most of the impacting iron-nickel body has been ejected from the original crater.

tion, more ejecta and perhaps even raw meteorite material will be exposed.

The lack of ferrous material in the known craters reinforces current understanding of the physics of a hypervelocity impact. After initial burial, the huge kinetic energy had to go somewhere, and the resulting explosion distributed almost all of the original meteoroid, in one form or another, outside the known crater rims. A few metal fragments survived close to the rims, almost always on the up-range side. These contain about 94% iron and 4% nickel and likely resulted from spalling, caused by the reflection of the impact shock front against the back side of the meteoroid. What was initially thought to be excavated sandstone bedrock turns out to be a uniformly shocked, instantaneously formed rock composed entirely of local sand. There is no evidence of bedrock within 10 kilometers of the impact site, and thus almost all of the kinetic energy of the event must have been partitioned into heat, precipitating a complex mixing process. The result of this partitioning is that more than 99 percent of the meteorite was converted into a uniform melt of 90 percent local sand and 10 percent iron-nickel meteorite. This melt and associated vapor was ejected via jetting and explosive convection into the stratosphere, and then rained down as molten glass under the sorting influence of the late-afternoon to early evening diurnal sandstorm. These estimates of the height of the explosion cloud are necessarily approximate, because much of the site is buried episodically by dunes passing over it under the influence of these same diurnal winds. If you had witnessed this event you probably wouldn't have survived it, as a molten glass rain fell at least 850 m away from the nearest known crater. Beyond that distance, encroaching dunes obscure any further ejecta (see Fig. 2).

In addition to the glass, there is an asymmetric dis-

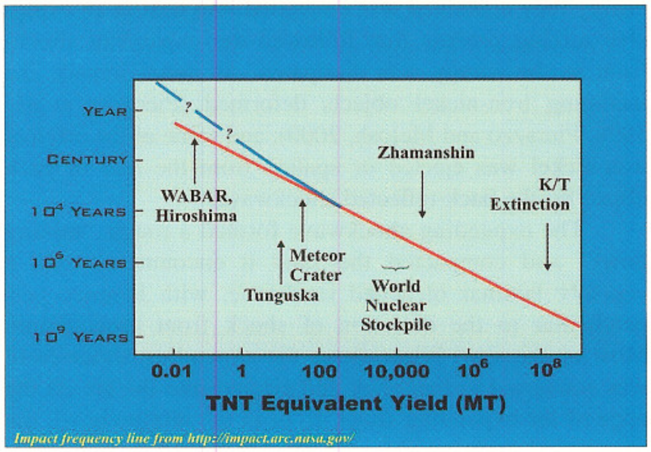

Figure 6. A diagram comparing impact energy (in megatons equivalent of TNT) with the expected frequency of impact for different sizes of bolides whose orbits intersect the Earth. The red line is from a diagram published by NASA; the blue line represents a suggested greater impact frequency calculated from impact events in remote areas of the world that have recently come to light.

tribution of the "Instarock," mainly down-range of the craters. This is a bleached, coarsely laminated sandstone formed from local sand by the shock front as it expanded around the buried center of the impact. Probably at least half of this Instarock was airborne part of the time: numerous examples were collected that are partially to fully coated by the black glass, suggesting they passed through the curtain of jetted material during their trajectory. Coesite, a high-pressure polymorph (shocked phase) of quartz, has been found in these samples (Chao *et al.,* 1960); coesite has only been found on Earth in nuclear detonation sites or impact craters.

The Interpreted Impact Event Sequence

The evidence gleaned from mapping the Wabar site, and published impact explosion model studies (Roddy *et al.,* 1977; Melosh, 1989), suggest the following series of events took place:

The original bolide passed over Riyadh at a shallow oblique angle during the late afternoon to early evening hours one day in the early spring of 1863. By the time it hit the Earth, it had already been air-braked, and fragmented or separated under the force of the air stacked up in front of the object against the vacuum dragged behind it. At less than a kilometer before impact, the object was already in at least four separate pieces, one of which (the so-called "Camel's Hump") was air-braked sufficiently that it bounced when it hit (but was still hot enough that local sand was fused onto its front surface). At least three other fragments buried themselves in the sand, and the kinetic energy they contained was converted into heat in an explosive mixing process that followed the expanding shock-front as the energy was dissipated. At initial impact, the incoming iron-nickel objects deformed (Pierazzo *et al.,* 1998; Pierazzo and Melosh, 2000), and some of the original iron-nickel was ejected or spalled from the rear of each object by the back-reflected shockwave.

The expanding shockwave formed a rough "mixing bowl" and compacted the sand it encountered into a coarsely laminar bleached sandstone, with laminae perpendicular to the direction of shock front propagation. Most of the sand lying above the expanding shock-front was converted to Instarock and ejected into the air. At the edge of the expanding shock-front in the mixing bowl, the iron-nickel body mixed with the local sand at high temperatures and was ejected perpendicular to the hemispherical shock-front into a jetted curtain of glass composed of 90 percent local sand and 10 percent iron-nickel meteoroid. Almost all of the original object was converted into this glass. The termination of the expanding shock front in each crater is marked by a hemispherical bottom-rind of weakly fused sand that can best be seen in the "11 Meter" crater.

The whole process to this point lasted less than two seconds for the largest object (which gave rise to the Philby B crater), and a proportionally shorter time for the smaller craters.

Elements of the Instarock ejecta and the glass jet curtain subsequently reached the stratosphere in a turbulent explosion cloud that would have been visibly indistinguishable from that caused by a nuclear bomb. Very little fell back into the craters, but this backfall was sufficient to obscure the hemispherical impactite rind in all but the "11 Meter" crater. Where the jet curtain encountered fragments of airborne Instarock and engulfed them, the Instarock was further converted to a bubbly white glass froth, not unlike reticulite, suggesting the extreme temperatures of the jetted glass. In the late afternoon to early evening breeze, wind-sorting separated the individual components according to their density and cross-section. Fragments of Instarock weighing up to 30 kg fell in a zone no more than 150 meters to the south and east of the Philby B crater. Black glass beads, some still molten at touchdown because they fused to grains of the sand they fell on, landed at least 850 meters north of the Philby A crater, and probably farther.

Size vs. Frequency—the Greater Hazard From Small (10–100 m diameter) Objects

The flux of impacting objects has been estimated previously by Shoemaker (1983), and Bottke *et al.* (2000); this distribution is graphically represented by the red line in Fig. 6. It shows that smaller objects carry less kinetic energy, but they are also proportionately more frequent. The red line was based on mapping of crater-frequency on the moon, and is resolution-limited to about 1 kilometer. The age of the Wabar event is thus crucial to understanding the threat to modern civilization from these smaller, house-sized meteoroids. Field work suggests that the Wabar bolide probably impacted the Earth very recently—not 6,400 years ago. Several lines of evidence, including field relationships, fragility of glass samples, incomplete oxidation of buried iron fragments, historical reports of a fireball passing over Riyadh in the direction of Wabar with associated ("Nedj") meteorites indistinguishable from the Wabar samples, historical crater-filling rates, and thermoluminescence dating, all are consistent with an event that took place in the early Spring of 1863. If true, it adds significantly to the number of objects that could destroy a city that have fallen in the past century or so.

Relatively little is known about the flux of such small "city buster" objects and therefore their potential threat. Tunguska was calculated to be an 80-m-diameter stony asteroid that detonated high above central Siberia in 1908 and destroyed 2,200 square kilometers of forest (Chyba *et al.,* 1993). Similar if smaller events occurred at Río Cuyuní, Brazil (1930), Rupununi, Guayana (1935), and Sikhote Alin, Russia (1947)—see Vasilyev and Andreev, 1989, Chyba *et al.,* 1993, and Poveda *et al.,* 1999a, 1999b. On October 1, 1990, there was a large air-blast event in the southwestern Pacific described by witnesses as causing a "second sun" that lasted for several seconds, followed by a deafening boom (Beatty, 1994). Asteroid 2002 MN passed within the Moon's orbit on 15 June, 2002, and was estimated to be about 100 meters in diameter. This is comparable to or larger than the Tunguska object, but it was recognized only two days after its close fly-by. It is reasonable to expect that more events have occurred, but have either not been recognized for what they were or otherwise went unreported. Since 75% of the Earth's surface is covered by water, it is likely that there have been many more impacts during the past century, possibly as many as 30 or 40 (see Beatty, 1994) that could be considered potential "city busters." This suggests a substantially higher flux for smaller objects based on a reasonable extrapolation of the available record; this is represented by the blue line on Fig. 6.

This blue line represents iron-nickel meteoroids, since stony or chondrite objects smaller than about 100 meters in diameter are prevented from impacting the Earth's surface by the atmosphere. M-class (iron-nickel) asteroids comprise about 8% of the known asteroids (NASA estimate); it is reasonable to expect that the same percentage applies to Near Earth Asteroids (NEA's). Below 100 meters in diameter, these metallic objects will still penetrate the Earth's atmosphere and reach the surface (though Campo del Cielo in Argentina, Henbury and Wolf Creek in Australia, Sikhote-Alin in Siberia, and Canyon Diablo and Odessa in the United States, among others, all seem to suggest that even metallic objects will break up shortly before impact). Bottke et al (1994; fig. 12) provide a curve representing NEA impact probabilities for the Earth. For objects 10 meters in diameter, this is about 70 objects per century. If 8% of these are iron-nickel objects, this translates to about 5.6 impacts per century for the entire Earth, or slightly more than one per century on land. The record of events listed above suggests that this calculated value is substantially less than the actual impact flux. A reasonable conclusion is that the presumed size-frequency distribution curve, developed for the much larger objects that can be readily detected, steepens substantially for smaller (10–100 m diameter) objects.

The energy released by the Chicxulub impact at the Cretaceous-Tertiary boundary ("K/T" in the figure) is huge, and a similar impact today would certainly destroy modern civilization, and probably most life on Earth. Most studies of NEA's (Rabinowitz *et al.,* 2000; Poveda *et al.,* 1999b; Bottke *et al.,* 1994; Bottke *et al.,* 2000; and Jewitt, 2000) consider only the discovery-rate and frequency of objects larger than one kilometer. This is because objects smaller than this are nearly impossible to resolve with any but the very largest optical telescopes, most of which are programmed for other tasks. Radar is not normally considered for asteroid detection purposes because the reflected signal strength falls off as one over the distance to the fourth power. Simply put, there are no direct observations of smaller objects such as the Wabar bolide.

The impact crater record for the Earth suggests that for non-iron objects, the Earth's atmosphere is an effective shield for meteoroids smaller than about 100–200 m in diameter. The Tunguska bolide, a stony object estimated to have been about 80 meters in diameter, did not penetrate to the Earth's surface, but nevertheless burned and flattened a forest the size of the state of Rhode Island when it detonated in the upper atmosphere. Smaller iron-nickel objects such as Wabar can easily penetrate the atmosphere to the Earth's surface and cause enormous local damage. It seems clear that the threat from smaller (10–100 m diameter) objects is realistically greater, at least during our lifetime, than the larger NEA's now being identified and mapped by Spacewatch, Spaceguard, LINEAR, and other asteroid-mapping programs.

Summary

The Wabar object penetrated the Earth's atmosphere and detonated as a kinetic-energy bomb beneath the sands of the Rub' al-Khali desert in 1863. Almost all of the original object was converted to a glass made up of local sand (90%) and nickel-iron (10%). A detailed magnetic survey strengthens our understanding of the physics of one of these hypervelocity events, among other things by showing that almost none of this material remains within the original impact craters, but was blown into the stratosphere and wind-sorted by the local diurnal winds. The relatively young age of this event, combined with other recently events, suggests a larger flux of these smaller meteoroids than has been previously estimated. The impacts and near-misses described in this paper together suggest a modified impact frequency curve for smaller objects (Fig. 6). This curve represents a significant increase over previous estimates of the potential danger of meteoroid impact to modern civilization for these house-to-stadium-size objects. It is unclear where on the blue line in Fig. 6 lies the destructive-danger-cutoff sizes for stony/chondrite or iron-nickel objects. Below a certain size, the atmosphere acts as a effective protective blanket, especially if the object is non-metallic. The major immediate threat thus is not from "Texas-sized asteroids," but from a populations somewhere in between. Unfortunately, the smaller and far more frequent 10–100 m diameter objects are probably undetectable until they come into the near vicinity of the Earth, too late to do anything about them. While not as frequent as famine and some other natural disasters, the huge potential loss of life requires us to seriously consider meteoroids as a major hazard to the survival of civilization (Jewitt, 2000).

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