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VIRTUAL IMPACT: Visualizing the Potential Effects of Cosmic Impact in Human History

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Abstract

Current models indicate that catastrophic impacts by asteroids and comets capable of killing more than one quarter of Earth's human population have occurred on average once every million years; smaller impacts, such the 1908 Tunguska impact that leveled more that than 2,000 square km of Siberian forest, occur every 200-300 years. Therefore, cosmic impact likely significantly affected hominine evolution and conceivably played a role in Holocene period human culture history. Regrettably, few archaeologists are trained to appreciate the nature and potential effects of cosmic impact. We have developed a conceptual model for an extensible set of educational and research tools based on virtual reality collaborative environments to engage archaeologists and the general public on the topic of the role of cosmic impact in human history. Our initial focus is on two documented asteroid impacts in Argentina during the period of 4000 to 1000 B.C. Campo del Cielo resulted in an energy release of around 2-3 megatons (100-150 times the Hiroshima atomic weapon), and left several craters and a strewn field covering 493 km^2 in northeastern Argentina. Rio Cuarto was likely more than 1000 megatons and may have devastated an area greater than 50,000 km^2 in central Argentina. We are focusing on reconstructions of these events and their potential effects on contemporary hunter and gatherers. Our virtual reality tools also introduce interactive variables (e.g., impactor physical properties, climate, vegetation, topography, and social complexity) to allow researchers and students to better investigate and evaluate the factors that significantly influence cosmic impact effects.

Key words: *virtual museum, asteroid impact, comet impact, natural disasters, ecosystem recovery, culture change*

1 Introduction

Disaster happens. And as evidenced by the enduring popularity of Hollywood disaster movies about earthquakes, exploding volcanoes, tsunami, burning sky scrapers, floods, hurricanes, sinking ships, tornados, nuclear war, alien invasions, overly rapid climate change, and even asteroid and comet strikes, many people clearly have an inherent fascination with the potential effects of natural and technological hazards (Kay and Rose 2006).

The publication in the *Proceedings of the National Academy of Sciences* on the hypothesized Younger Dryas impact around 12,900 BP has finally forced the archaeology community at large to take note of cosmic impact (Firestone et al. 2006; Kennett et al. 2009). If validated, the Younger Dryas impact may have been responsible for a dramatic 1300-year climate shift, megafaunal extinctions, and the rapid transformation of Clovis culture. Reactions in the archaeological community range between fascination, a strong desire to attack the possibility and to reject the evidence, and rare acceptance.

Planetary scientists who study near-Earth objects (NEO—asteroids and comets in orbits that threaten impact with the Earth), likewise express great skepticism toward the Younger Dryas and all other hypothesized recent major impacts (Kerr 2008; Pinter and Ishman 2008). As evidenced by the special session on the hypothesized Younger Dryas impact event at the 2008 Annual Meetings of the Society for American Archaeology, the recent cosmic impact debate is beset by discipline language barriers and by a lack of understanding on both sides of the nature of cosmic impact and the opportunities offered by its study (Masse 2007; Masse and Masse 2007; Masse, Weaver, Abbott, Gusiakov, and Bryant 2007; Barrientos and Masse 2009). Even more sobering is the realization that the hypothesized Younger Dryas impact could well be but one aspect of a much larger and more complex picture of the cosmic impact threat.

In in this paper, we explore ways in which cosmic impact can be better explained and visualized to the archaeological and anthropological community. The University of California Merced is developing a Virtual Heritage Center (VHC) based on virtual reality collaborative environments (display walls, virtual rooms and labs). A Virtual Museum (e.g., www.vhlab.itabc.cnr.it/flaminia) has been created inside the VHC, along with a simulation environment focused on Powerwall (display wall) technologies. The VHC provides scholars with new ways in which humanities-related data and knowledge can be searched, mined, displayed, taught, and analyzed. It employs multiuser domains (MUD), collaborative environments that allows a group of researchers or students to interact with each other and explore virtual worlds at the same time—unlike virtual reality systems that limit accessibility to a few users. Moreover, the VHC offers promise as a tool to teach students how to access, evaluate, and apply information in their studies as well as their lives beyond the academy.

But before plunging into this daunting challenge of figuring out how to apply this visualization technology to the study of cosmic impact, it is necessary to first make a few general observations about the relevance and importance to archaeology of disaster research and cosmic impact studies.

2 Natural Disasters and the Significance of Cosmic Impact

We do not have to go back very far into historical records to establish disaster as a fact of life. For example, in the four decades between 1945 and 1986 more than 2.4 million people died as the result of disasters, an average of 30 disasters and 56,000 lives lost per year (cited in Torrence and Grattan 2002:1-2). While these numbers stagger the imagination, they pale beside the estimated 48 million people who died in the decade prior to 1945 as the direct or indirect result of war. Not even the 236,000 people who died in the December 2004 Indian Ocean earthquake and tsunami (Bryant 2008) can change the perception that human technological and social factors—such as war—have played a far larger role in causing death and culture change during the past 4000 years of recorded history than have the cumulative toll of all natural disasters.

However, this does not mean that the scientific study of natural hazards is of little consequence in our modern world. In fact, because natural disasters not only kill people but also significantly damage infrastructure resulting in many billions of dollars of economic loss, a sizable industry has developed to predict, control, and mitigate the risks of natural disasters and industrial accidents (e.g. Gad-el-Hak 2008). From this largely economic perspective, risk specialists have devised a heuristic logarithmic scale of the scope of a disaster, based on the number of casualties and/or the size of the geographic area affected (Gad-el-Hak 2008:Table 2.1). As depicted in Figure 1, the five tiers of such a scale range from a "small" disaster, resulting in the deaths of less that 10 individuals and affecting an area less than a square km, to that of a "gargantuan" disaster involving either the deaths of least 10,000 individuals or affecting an area greater than 1000 km^2.

Archaeologists and anthropologists increasingly have become involved with the study of natural disaster (e.g., Oliver-Smith and Hoffman 1999; Bawden and Reycraft 2000; Hoffman and Oliver-Smith 2001; Torrence and Grattan 2002; Grattan and Torrence 2007; Gould 2008). This topic was initially stimulated in part by the publication 30 years ago by Sheets and Grayson (1979) of their ground-breaking edited volume, *Volcanic Activity and Human Ecology*.

Ironically, however, the risk industry and archaeologists in particular, have generally ignored the largest by far of all natural hazards on Earth, that of the impact of asteroids and comets. Research on near-Earth objects (NEOs)—comets and asteroids in Earth-crossing orbits that pose the potential risk of impact on Earth—by default has been the purview of the small NEO community of planetary scientists. Most NEO community members think it unlikely that any humans have been killed by a cosmic impact in recorded history, and assume that because larger impacts are rare, impacts did not play a significant role in late Pleistocene and Holocene culture history. The following comment by the well-respected NEO specialist Clark Chapman (2008:418) is typical regarding historic cosmic impact:

"There have been reports of doubtful credibility from antiquity, as well as more recent anecdotes, of death by meteorite falls. While such an accident is certainly possible, there has been no confirmed, credible report of a human being dying from a meteorite strike."

Table 1. Disaster scope according to number of casualties and/or geographic area affected (modified from Gad-el-Hak 2008:Table 2.1).

Level I	Small disaster	< 10 persons	or	< 1 km^2
Level II	Medium disaster	10-100 persons	or	1-10 km^2
Level III	Large disaster	100-1000 persons	or	10-100 km^2

Level IV	Enormous disaster	1000-10,000 person	or	100-1000 km^2
Level V	Gargantuan disaster	> 10,000 persons	or	> 1000 km^2

This remarkably simplistic and incorrect assumption is based on stochastic probabilities derived from the Solar System cratering record and the near-Earth asteroid population (e.g., Bottke 2007), and not on geological or archaeological and anthropological evidence, per se. In fact, such thinking is curiously antithetical to the NEO community's own models of cosmic impact risk. Globally catastrophic impacts capable of killing a quarter of Earth's human population (Chapman and Morrison 1994; Toon et al. 1997; Bobrowsky and Rickman 2007) are modeled to occur on average once per 500,000 to million years, well within the scope of human biological and cultural evolution. Such an impact generates an energy release $\geq 10^6$ megatons (MT), or roughly 67 million times that of the 15 kiloton Hiroshima and Nagasaki atomic weapons. At the other end of the scale are small impacts such as the 1908 Tunguska airburst which leveled 2150 km^2 of Siberian forest. These events occur on average every 100-200 years and yield 4-5 MT (4-5 x 10^{-1} MT), 267-334 times that of Nagasaki and Hiroshima (Boslough and Crawford 2008). In between are impacts with local (10^1-10^3 MT) and regional/continental (10^3-10^5 MT) effects, occurring on average between hundreds to hundreds of thousands of years.

General terrestrial impact effects (e.g., Melosh 2007) include thermal radiation as the projectile and target material are converted to incandescent gas or plasma; seismic shaking at and away from the impact site; the deposition of ejecta from the impact; and the airburst created by displacement, compression, and heating of the air near the impact which produces ballistic shock waves. Effects can differ depending on the composition of the impactor (comets vs. iron-nickel, stony chondrite, and carbonaeceous asteroids); the pre-atmospheric speed (ca. 50 km/sec for comets, 17 km/sec for asteroids) and size of the impactor; the location of the detonation (airburst, land, ocean/lake, ice); the geology of the target site of a land impact (volcanics, granites, limestone, loess); and the angle of the impact (vertical to oblique).

In addition to the great complexity of all these variables, we have an especially poor understanding of airbursts and oceanic impacts. Oceanic impact results in the creation and collapse of a large water cavity (Figure 1). The subsequent infilling of the cavity actually tends to destroy or reshape aspects of the crater rim and surrounding ejecta sediment blanket due to the surging water column.

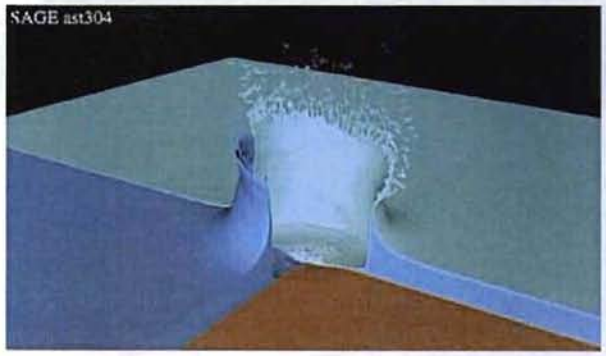

Figure 1. Three-dimensional simulation of the oceanic impact of a 1-km diameter asteroid.

Table 2 uses the University of Arizona Earth Impact Effects Program (Collins et al. 2005) to calculate a hypothetical logrithmic distribution of impacts during the past one million years. For ease of comparison, the calculated impacts are based upon the general parameters of composition as a stony (chronditic) asteroid entering Earth's atmosphere at a velocity of 17 km/second and an angle of trajectory of 45 degrees.

This table illustrates that many cosmic impacts should have occurred during the past million years, but more importantly that the vast majority have not yet been identified in the geological and archaeological record (as indicated by the small numbers of validated impacts in the last column). The potential impacts include many larger impacts that should have left substantial evidence in the geologic record. Table 2 also demonstrates that the issue of identifying oceanic impacts is particularly thorny in that no impact structure from any magnitude of impact (including globally catastrophic impacts) has yet been identified on the sea floor from the past 25 million years, although a few tektite strewnfields have been recorded, likely indicative of a nearby impact.

Table 2. Hypothesized impact rates during the past one million years for stony (chondritic) asteroids with an impact velocity of 17 km/second and an impact angle of 45 degrees. [Adapted from the Earth Impact Effects Program, Collins et al. 2005, with the exception of Tunguska estimate].

IMPACTOR DIAMETER [METERS]	ENERGY RELEASE IN MEGATONS	CRATER DIAMETER (KM)	RECURRENCE INTERVAL (YEARS) BETWEEN IMPACTS	NUMBER OF WATER IMPACTS PER MILLION YEARS	NUMBER OF LAND IMPACTS PER MILLION YEARS	VALIDATED IMPACTS YOUNGER THAN A MILLION YEARS AS OF 2009* [IDENTIFIED THUS FAR ONLY ON LAND]
<36	<1	Airburst				(1) Haviland
36	1 1 MT is 67 times larger than Hiroshima	Airburst	132	5303	2273	(9) Sikhote Alin Wabar Sobolev Whitecourt Morasko Odessa Boxhole Dalgaranga Veevers
30	5	Airburst	200	3500	1500	Tunguska – Boslough and Crawford 2008
59	5	Airburst	413	1695	726	(4) Campo del Cielo Kaalijärv, Ilumetsä, Henbury
75	10^1	Airburst	718	975	418	(7) Barringer (Ariz.) Amguid Tswaing Kalkkop Wolfe Creek Monturaqui
210	10^2	1.6	7,700	91	39	(2) Tenoumer Lonar
360	10^3 [1 GIGATON]	4.3	27,000	26	11	(1) Rio Cuarto
730	10^4	8.3	140,000	5	2	
1550	10^5	16.3	780,000	1	0	(1) Zhamanshin
3330	10^6	32.1	4,600,000	0	0	

16 km	**10^8**	**170**	**170 million**	**0**	**0**	**Chicxulub**

*Validated Impacts derived from the University of New Brunswick Earth Impact Database as of April 2009 [http://www.unb.ca/passc/ImpactDatabase/].

3 The Campo del Cielo and Rio Cuarto Argentina Asteroid Impacts

The Campo del Cielo (Field of the Sky) crater field is in northeastern Argentina (Figure 2). This portion of the Gran Chaco is semi-arid, hot, very flat, and covered equally by savanna, scrub, and dense thorn forests. The Campo del Cielo crater field contains at least 20 small, generally elongated impact craters within a northeast-trending ellipse (N63°E), 4 km wide and 19.2 km long (Cassidy et al. 1965; Cassidy and Renard 1996; Liberman et al. 2002; Wright et al. 2007).

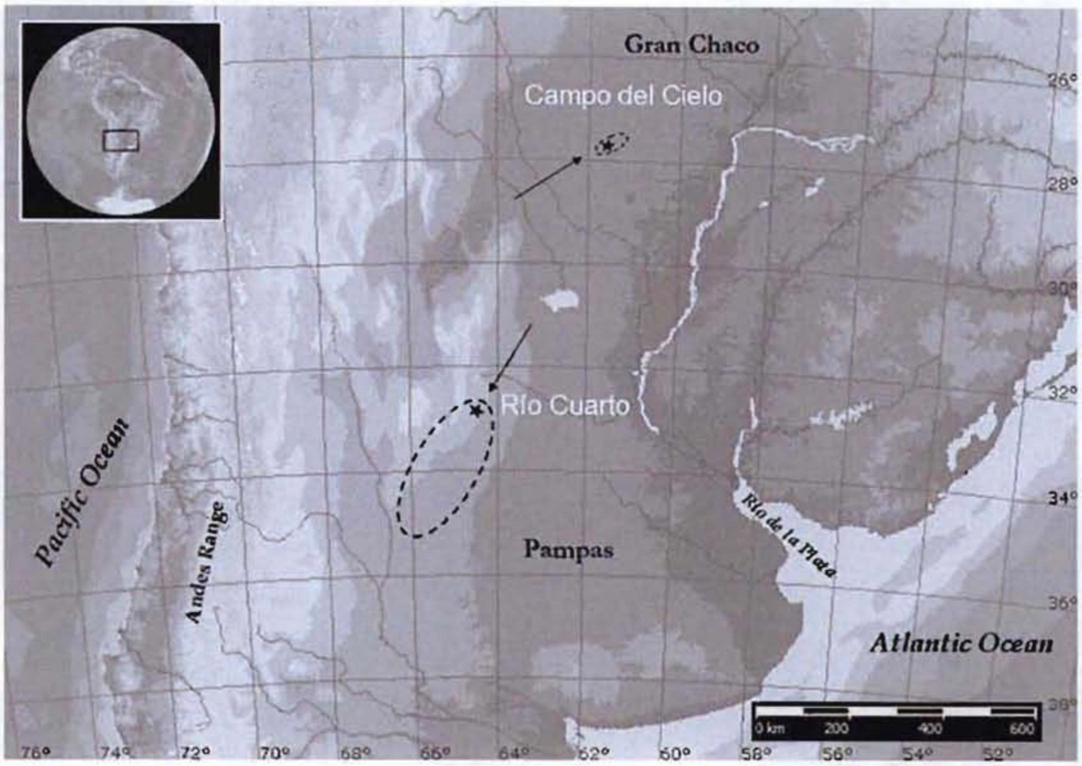

Figure 2. Location of the Campo del Cielo and Rio Cuarto crater fields in Argentina. The stars represent the crater fields, the arrows the estimated direction of impact infall, with the dashed line for Rio Cuarto representing the approximate limits of the melt glass strewnfield.

The largest crater is 115 x 91 m. The largest surviving meteorite, dubbed El Chaco, is more than 2 m in diameter and weighs an estimated 37,000 kg (Figure 3). The shallow impact in-fall angle was calculated at 9° from the horizontal. The main concentration of craters is at the southwestern end of the ellipse. The four largest and least elongated craters were formed by ground explosions spread along a 6-km line. The smaller craters did not experience explosive impact but instead contain meteorite penetration funnels, four of which have been excavated.

Figure 3. The Campo del Cielo "El Chaco" meteorite.

Calculated impact velocities range from 1.7–4.3 km s^{-1}. Analysis of impact effects yielded a pre-atmospheric entry velocity of 22.8 km s^{-1}, a diameter greater than 6.0 m, and mass minimally at 840,000 kg. Impact glass melts have not been recovered from the Campo del Cielo crater field, likely indicative of the small size and relatively slow speed of the impactors. An elliptical strewn field extends 60 km beyond the craters, and small meteorites have been recovered all along the path.

Three charcoal specimens were recovered from Campo del Cielo (Cassidy and Renard 1996: Table 4). Two samples bracket the impact, while the other is believed to be from an ignition fire caused by the impact itself. The most recent sample was recovered from Crater 1 post-impact infill, yields a calibrated (2σ) date range of A.D. 900-1431 (Barrientos and Masse 2009). The earliest sample, from a soil horizon buried by the ejecta blanket of Crater 2, yields a calibrated (2σ) date range of 5209-4264 B.C. The third sample was recovered from the beginning of the impact tunnel at the bottom of Crater 10 and yields a calibrated (2σ) date range of 2840-2146 B.C. That this sample may date the actual impact is consistent with the location of Crater 10 near the middle of the distribution of explosive craters (Wright et al. 2007:Fig. 1).

Río Cuarto, in central Argentina (Figure 4), has been proposed as a Holocene shallow angle asteroid impact zone containing at least 11 elongated craters (Schultz and Lianza 1992). The largest is about 1.1 x 4.5 km. The region contains extensive deposits of loess and dune sand which can be altered by wind and readily melted by cosmic impact. Schultz and Lianza (1992) noted that the Rio Cuarto structures could be interpreted to be of aeolian origin; however, they also note the presence of impact glass melts (locally referred to as *escorias* or slag-like rocks) in and around some of the putative craters (Figure 5).

A series of alternate interpretations have been proposed in response to the original claims of impact formation for the Río Cuarto elongated depressions. Cione et al. (2002) argue for a non-impact origin, and state that Argentine geologists have long supported the aeolian formation of these depressions, pointing out that the alignments match prevailing wind patterns during the period(s) of their formation. Bloom (1992) has argued that the glass melts are unlikely to be of impact origin. He suggests that natural and anthropogenic fires, such as the burning of fields as part of the agricultural cycle, can produce the melts described by Schultz and Lianza (1992).

Figure 4. The Rio Cuarto crater field illustrated in 1992 on the cover of the journal *Nature*.

Figure 5. Holocene *escoria* glass melt from Rio Cuarto. The white bar scale is 1 cm.

Using aerial photography, Bland et al. (2002) also suggest that the Río Cuarto structures are part of a widespread set of several hundred elongated aeolian depressions associated with parabolic sand dunes that formed in the Argentine Pampas during the mid-Holocene. Unlike Bloom (1992) and Cione et al. (2002), Bland et al. (2002) support the impact origin of the Río Cuarto glasses; however, their interpretation is that the glasses represented the distal ejecta of a Pleistocene (ca. 480 ka B.P.) age impact occurring several hundred kilometers away.

Schultz and his colleagues (2004) are part of an ongoing systematic NSF-funded study to understand the nature and distribution of the impact glasses found in the Argentine loess. Their research includes detailed petrological and electron microprobe analyses, along with geochemical analyses (x-ray florescence and instrumental neutron activation analysis) of the Argentine glass melts. They demonstrated that temperatures in excess of 1700 °C would be necessary to completely melt all constituents including quartz grains. The specimens exhibit rapid quenching of the melt, a condition unlikely in a field fire or wildland fire. Also, the glasses are in stratigraphically-restricted contexts, unlike the expected more widespread and haphazard distribution if they were instead the result of lightning or field fires.

Masse and Masse (2007) note that the physics of wildland fire—and by analogy field fire—also argues against the anthropogenic burning of fields as the origin of the glass melts as suggested by Bloom (1992) and San Cristóbal (1999). Pyne et al. (1996:20-23) state that the theoretical maximum temperatures that can be achieved by the burning of combustible gases generated from wildland fuels is around 1900–2200 °C. However, most wildland fires more typically burn at average temperatures of between 700–980 °C with the maximum actually measured for an exceptionally intense fire being not much greater than 1650 °C, below the melt threshold determined by Schultz et al. (2004) for the Río Cuarto glass melts. In addition, the burning of fields in preparation for agriculture, including the presence of smoldering fires, would typically yield temperatures lower than the average wildland fire due to the differences in fuels.

In their initial exhaustive analysis of the melt glasses from the Pampas, Schultz et al. (2004) identified melts from five separate Quaternary impacts with four of the impacts dating back to the Pleistocene period between 570 ± 100 ka B.P. (corresponding to the material identified by Bland and his colleagues) and 114 ± 26 ka B.P., along with a Holocene glass melt. Schultz and his colleagues (2006) also identified two separate late Miocene vesicular impact glasses from the Pampas, for a current total of eight distinct late Cenozoic impact melt breccia deposits dating between 9.24 Ma and 6 ka B.P. (Harris and Schultz 2007).

Of significance is the robust documentation of the age of the Holocene impact glasses by three dating techniques: 10,000-4000 B.P. based on geological context (stratigraphy and preservation state); 2300 ± 1600 B.P. by fission track dating; and 6000 ± 2000 B.P. by radiometric $^{40}Ar/^{39}Ar$ dating. The combined suite of dating techniques implies a date for the impact of approximately 6000-3000 B.P., encompassing the date range for Campo del Cielo.

The Campo del Cielo has a crater field of approximately 45 km^2, and a meteorite strewn field of perhaps another 448 km^2 (assuming an ellipse 9.5 x 60 km). Comparisons with other known and intensively studied small impacts, such as Tunguska, the 1947 Sikhote Alin meteorite shower also in Siberia, and the 49,000 year old Meteor Crater in Arizona suggests that the impact energy release of Campo del Cielo was likely around 2-3 MT (Barrientos and Masse 2009). Because of the considerable size of the craters and strewn fields, the atmospheric airburst detonations would have been several kilometers above the ground surface It is uncertain if a fireball was created by the atmospheric detonation (...mythology suggests that a fireball and associated debris cloud did occur, as noted below), but impact ground temperatures were apparently insufficient to create glass melts. We suggest an average fatality rate of 50% for any humans who may have been present within the boundaries of the 493 km^2 Campo del Cielo impact crater and strewn field (presumably a higher percentage in the crater field, lower in the meteorite strewn field).

The Río Cuarto impact event is both qualitatively different from and quantitatively larger than Campo del Cielo, and indeed likely several magnitudes larger than the Tunguska event. The way we presently understand the modeling and interpretations of P. Schultz and his colleagues and those of their critics (see above), there are four different rough scenarios by which to interpret Río Cuarto (Barrientos and Masse 2009), with the accumulated data strongly supporting the following two scenarios.

The first scenario, consistently favored by P. Schultz over the years (pers. comm. 2008) based in part on extensive modeling and simulation associated with oblique projectiles (e.g., Schultz 1991), accepts the reality of the original hypothesized Río Cuarto crater field and views the distribution of Holocene glass melts as most likely representing impactites spread out by the explosive contact that created the craters. If the relationship between the crater field location and orientation and the defined Holocene glass melt distribution (Figure 2) continues to be supported by the geologic data—and Schultz (pers. comm. 2008) wisely cautions that there is still much work to be done to verify this apparent relationship—then this would strongly suggest that the craters and melts are indeed intimately related, and that an area of nearly 50,000 km^2 was seared by the impact, much like a rolling nuclear explosion. The low angle of entry may have also caused devastation on the ground by the bow shock wave in front of and below the impactor for many kilometers prior to actual impact.

The second scenario views the Holocene glass melts as the in situ residue of an airburst, rather than as ejecta from a cratering event. Airbursts are objects that explode and release most of their energy in the atmosphere above the Earth's surface, such as the Tunguska event. The frequency and magnitude of airbursts and other classes of cosmic impact are still critical topics of research (Bland and Artemieva 2003; Morrison et al. 2003; papers in Bobrowsky and Rickman 2007), as demonstrated by the recent downsizing of the magnitude of Tunguska and increasing the frequency of this class of impact event. Wasson (2003) suggests that airbursts can be created by weakly-structured objects much larger and therefore much more energetic than that of Tunguska, exceeding 1000 MT. An example of such an object would be Comet Shoemaker-Levy 9 that due to tidal forces from Jupiter broke up into 21 separate fragments before colliding with the planet in July 1994. Wasson argues that a super-Tunguska impact could produce such a large fireball on detonation that the ground surface over a brief period of time would reach temperatures greater than 2000 °C, thus melting anhydrous soils such as loess and dune sand. Boslough and Crawford (2008) have similarly modeled chondritic asteroids capable of producing similar effects but with considerably less energy necessary to produce the airburst glass melts. Wasson (2003) suggests that his largest modeled airbursts could impact surface areas greater than 100,000 km^2, a figure twice that of the tentatively defined Río Cuarto Holocene glass melt field.

It is difficult for us to choose between the first scenario (Río Cuarto cratering impact) and the second scenario (airburst), but both scenarios better fit our existing data than do scenarios that deny the reality of the impact or that the glass melts are the result of crater formation elsewhere in central Argentina. The airburst and cratering impact scenarios seemingly imply more than 1000 MT of energy release (based on current modeling programs such as that by Collins et al. 2005). Not only would the Rio Cuarto devastation be considerably larger than the area devastated by the Campo del Cielo impact, but also the mortality rate in these areas should be much greater than that calculated for the Campo del Cielo impact, perhaps approaching 90% fatalities. That this conservative figure is not set at 100% takes into account topography and other situational and physical variations of the impact event.

Using data published by Binford (2001), some approximations about relevant parameters of the kind of societies likely involved in the Rio Cuarto impact can be made. From his database of 339 hunter-gatherer groups, Barrientos and Masse (2009) isolated the 19 that inhabit the area between 32° and 36° of latitude (both north and south) in order to calculate the approximate number of individuals and cultural groups or societies which could be directly affected by the impact. The hunter-gatherer societies that lived at that latitudinal strip during historical times (6 at different parts of Australia, and 13 in the American Southwest) exhibited a quite restricted residential mobility (0-9 annual movements, with a median of 0.1 and a interquartile range between 0 and 7), a diet mainly composed by gathered resources (with a median of 50%), and a highly variable total population size (a median of 2,124 people, with a interquartile range between 889 and 3,500 people) and population density (a median of 18.0 inhabitants/100 km^2, with a interquartile range between 5.12 and 43.75 inhabitants/100 km^2).

The hunter-gatherer societies living in central Argentina at the time of the impact event are believed to have been mostly low-dense at the regional scale of analysis. Taking this into account, some filtering of the data was necessary in order to get more realistic approximations (Barrientos and Perez 2005). First, after standardizing the quantitative data, a *k*-means cluster analysis was performed using three of the variables coded by Binford (2001:117)—total population, population density per 100 km^2, and the average number of annual residential moves so as to analytically separate two more internally homogeneous groups. The analysis discriminated between a first cluster of 8 cultural groups with higher total population, higher population density and lower residential mobility, and a second cluster composed by 11 groups with lower total population, lower population density, and higher residential mobility. The members of the latter cluster were selected for further analysis.

Considering that the area directly affected by the impact was approximately an ellipse of 48,106 km^2, a median number of 3 (interquartile range between 1 and 11) cultural groups or societies with such characteristics may have been extirpated by this sudden, unpredictable event. This implies a median number of about 1,000 individuals (interquartile range between 500 and 1,908) affected in some way by the impact, 900 of which (90%) probably died. Applying this demographic model to Campo del Cielo, and our estimate of 50% lethality for the impact area results in a death toll of around 5 individuals. These estimates could be even much higher, especially for Campe del Cielo, because they do not include the effects of fast-moving wildland fires radiating out from the impact zones, which would have killed additional individuals and further depleted the resources necessary for human maintenance and recovery.

Summarizing, the two mid-Holocene cosmic impact events in Argentina had the potential of being very destructive. However, the Río Cuarto impact would seem to be both qualitatively different from and quantitatively larger than Campo del Cielo as well as the most likely potential contributor to any major environmental and population disruption in central Argentina during the mid-Holocene. Using the criterion of size of the affected areas as suggested in the disaster scope scale outlined in Table 1, the Campo del Cielo impact would be categorized as an "enormous" disaster while that of Rio Cuarto would be categorized as a "gargantuan" disaster.

4 Using Mythology to Investigate the Possibility that the Campo del Cielo and Rio Cuarto Impacts Created Major Wildland Fires

Planetary scientists have debated the capacity of impacts to start ignition fires (e.g., Jones and Lim 2000; Svetsov 2002; Jones 2002; Durda and Kring 2004). Witnessed meteorite falls, and the limited archaeological record of impact sites support the notion that wildland fires are associated with some smaller impacts. A key would be fuel availability and suitable weather/climatic conditions for the spread of the fire. Mythology also provides a surprising window on the relationship between Campo del Cielo and Rio Cuarto and potentially devastating wildland fires.

During the past few decades, there has been a growing trend to use the natural sciences to re-examine the context, structure, and meaning of myth (e.g., Vitaliano 1973; Blong 1982; Barber and Barber 2004; Piccardi and Masse 2007; Masse, Barber, Piccardi, and Baber 2007; Cashman and Giordano 2008; Van der Sluijs 2009). This approach demonstrates that there is a powerful historical core to myth that can be objectively retrieved and studied. The messages and data contained in myth are not just simple curiosities but instead provide important insights into the development of human cognition in relation to both science and religion.

Even more critical is the fact that catastrophe myths contain a record of significant natural disasters (earthquakes, tsunami, volcanic eruptions, floods, plagues, cosmic impacts) in recent Earth history. These can be used to provide insights for natural hazard analysis and planning, and can even be applied to the question of whether or not the Earth is significantly at risk from impact by comets and asteroids. Myth data suggest that cosmic impact has played a significant role in recent cultural evolution.

Valuable for our interests in cosmic impact are a set of 4,259 myths from 20 major cultural groups east of the Andes gathered by the University of California at Los Angeles (Wilbert and Simoneau 1992). These myths are the contribution of 111 authors, translated into English as necessary, and published over the course of 20 years as a set of 23 separate volumes. The cultural groups themselves are from widely distributed portions of South America (Figure 6).

Masse and Masse (2007) analyzed these 4,259 myths, concentrating on those describing various local, regional, or worldwide natural catastrophes that led to the deaths of members of a given cultural group. Events that led to the deaths of small numbers of individuals include local floods, fire, lightning—and in the case of two myths from the Brazilian Highlands, the observed thunderous fall of a meteorite into a river that killed several youths then swimming in the river. Several other myths from the Brazilian Highlands, and the Northwest talk about meteorites as being capable of causing human death—including, poignantly, the overall eventual destruction of the world—but do not describe actual impact events themselves.

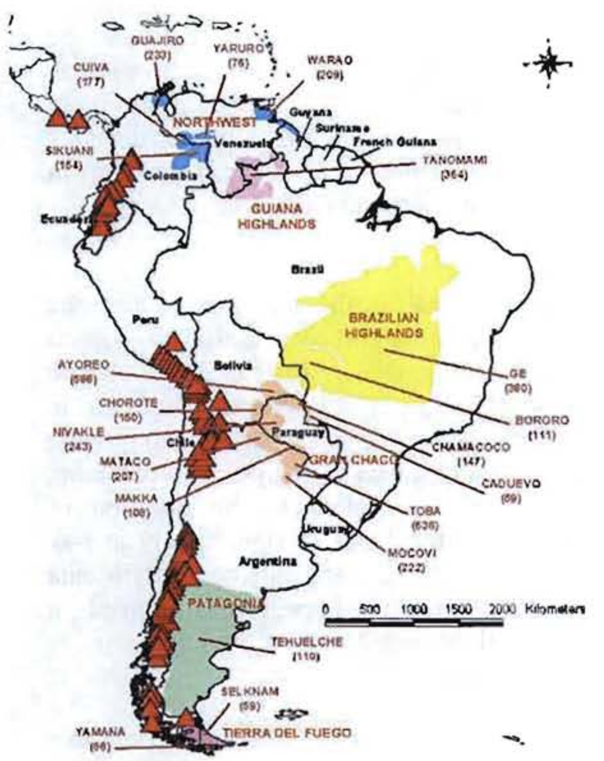

Figure 6. Distribution of cultures and associated myths in the UCLA *Folk Literure of South America* series.

Of particular interest is a set of 284 myths that have as their primary motif a single major cataclysm stated as having led to the deaths of most or all members of one or more cultural groups—typically referred to as having led to new creations of humanity (Table 3). While one might scoff at the rational basis of such "new creations," it should be remembered that these cultural groups typically were small, a few hundred or at most a couple thousand people, and that while their overall territorial ranges may have been large the cultural group only occupied a small portion at any given time. Therefore, rare large-scale cataclysms such as plinian eruptions, mass fires, and torrential monsoons of unusual duration could indeed decimate such groups.

Table 3 organizes these myths by cultural group and by five defined categories of cataclysm. The stories, particularly those from the Gran Chaco, appear to be divided into relative time within the overall set of 284 myths, with certain cataclysms being stated as having occurred before or after other cataclysms. Thus myths about a lengthy time of darkness and a similar set of myths combining darkness with the sky falling or collapsing on top of people, houses, and forests are said to have occurred most recently (but still in the distant past), while myths of a "great" or "worldwide fire" occur in the middle of the myth cycle, and myths about a "great flood" occur at the beginning of the myth cycle, the latter sometimes coupled with a period of "great cold" stated as having occurred immediately after the flood.

Table 3. "Worldwide" catastrophe myths in the UCLA *Folk Literure of South America* series.

CULTURE & LOCATION	GREAT FLOOD [EARLIEST IN MYTH CYCLE]	GREAT COLD [AFTER FLOOD MYTH]	WORLD FIRE [MIDDLE OF MYTH CYCLE]	SKY FALL–DARKNESS [LATEST IN MYTH CYCLE]	GREAT DARKNESS [LATEST IN MYTH CYCLE]
NORTHWEST					
Cuiva	13			4	
Guajiro	9				1
Sikuani	10				
Warao	3				
Yaruro	10				
GUIANA HIGHLANDS					
Yanomami	17			11	2
BRAZILIAN HIGHLANDS					
Bororo	4		1		
Ge	11		6		1
GRAN CHACO					
Ayoreo	17		2		1
Caduevo					
Chamacoco	10		1	1	
Chorote	10		7	1	
Makka	2				1
Mataco	12		5		1
Mocovi	7		3		
Nikvale	6	1	6	9	
Toba	24	5	27		12
PATAGONIA					
Tehuelche	2				
TIERRA DEL FUEGO					
Selknam	1				
Yamana	3	1	2		1
TOTALS	171	7	60	26	20

Elsewhere it has been shown that the recent "sky fall" and "great darkness" myths likely capture a major Plinian eruption of Bolivia's Nuevo Mundo volcano during the past two thousand years prior to the arrival of Europeans in South America (Masse and Masse 2007). The myths of a great flood and great cold arguably relate to the observed effects of an oceanic comet impact around 4800 years ago (Masse 1998, 2007, 2009).

The myths of the world fire are of interest here for four basic reasons. First, although these stories are almost entirely limited to the South American regions most subject to natural wildland fire and anthropogenic field burning (i.e., the Gran Chaco and the Brazilian Highlands), the myths describe the unique rapid spread and severity of the fire(s). The following two Gran Chaco myths, respetively from the the Toba and Mataco groups are particularly illustrative:

The people were all sound asleep. It was midnight when an Indian noticed that the moon was taking on a reddish hue. He awoke the others: "The moon is about to be eaten by an animal" [a lunar eclipse]. The animals preying on the moon were jaguars, but these jaguars were spirits of the dead. The people shouted and yelled. They beat their wooden mortars like drums, they thrashed their dogs....They were making as much noise as they could to scare the jaguars and force them to let go their prey. Fragments of the moon fell down upon the earth and started a big fire. From these fragments the entire earth caught on fire. The fire was so large that the people could not escape. Men and women ran to the lagoons covered with bulrushes. Those who were late were overtaken by the fire. The water was boiling, but not where the bulrushes grew. Those who were in places not covered with bulrushes died and there most of the people were burnt alive. After everything had been destroyed the fire stopped. Decayed corpses of children floated upon the water. A big wind and a rain storm broke out. The dead were changed into birds. The large birds came out from corpses of adults, and small ones from the bodies of children [Métraux 1946:33; in Wilbert and Simoneau 1982a:68].

Once, a very long time ago, the life-style of the Mataco developed into near anarchy... All was chaos. Then one day a big black cloud gathered in the south, and lightning and thunder began. When the cloud had covered the entire sky it began to rain a bit here and there, but the drops that fell were not like rain but like fire. The people tried to jump into the river to save themselves, but the water was boiling. Tokhuah [a Mataco trickster character] was among them, but he saved himself because he could go wherever he wished, and he decided to go underground. All died but a very few, and they did not know why they had survived. Bits of fire continued to fall from the sky

> and everything, including the entire forest, burned; nothing remained except a few people here and a few there. They did not understand why they were still alive and what they were to do next [Fock, in Wilbert and Simoneau 1982b, p. 126].

The second reason that these stories are of interest is that the cultures with these stories are hundreds of kilometers removed from the nearest active Holocene volcanoes (the red triangles in Figure 6), thus largely eliminating explosive eruption as a potential natural cause for the storyline descriptions. In this regard it is noted that migration stories are largely absent from the oral traditions of these cultures, thus suggesting that the Gran Chaco and Brazilian Highlands are the likely setting for the storied events.

Third, the Campo del Cielo crater-strewn field is less than 100 km south of the edge of the historic distribution of the Toba and Mataco tribes.

The fourth and most obvious reason is that the Toba provide a very specic cause for the events described in the world fire myths:

> Moon...is a pot-bellied man whose bluish intestines can be seen through his skin. His enemy is a spirit of death, the celestial Jaguar. Now and then the Jaguar springs up to devour him. Moon defends himself
>
> with a spear tipped with a head carved of the soft wood of the bottletree..., which breaks apart at the first impact. He also has a club made of the same wood which is too light to cause any harm. The Jaguar tears at his body, pieces of which fall on the earth. These are the meteors, which three times have caused a world fire [Métraux 1946:19].

Analysis of the complete set of world fire myths (Masse and Masse 2007; Barrientos and Masse 2009) indicate a clear link between these myths and the Campo del Cielo impacts, and possibly also that of Rio Cuarto and a hypothesized airburst in the Brazilian Highlands.

5 Capturing Cosmic Impact in a Virtual Museum

Based on the above discussion, it is readily apparent that topics such as natural disasters, cosmic impact, and natural science-based mythologies are extraordinarily complex and inherently imbued with language and methods of study that are difficult for the physical sciences, natural sciences, and social sciences to bridge and meaningfully discuss. These, then, are the challenges that must be faced and surmounted in attempting to present such topics in a virtual reality visualization format.

Our proposed project explores a common educational theme in studies of virtual reality—that of finding visually creative ways in which to interest people in a body of scientific (in this case archaeological) data. However, rather than simply trying to interest a group of students or the general public in appreciating and understanding archaeological sites and landscapes as historically interesting features and phenomena...which in itself is certainly important in our roles as archaeologists and students of history and the humanities...we have chosen a case study that presents unusual real world challenges in terms of bridging differences between cultures and crossing barriers between scientific disciplines. Not only does this attempt at bridging create technological challenges as to how virtual reality data are viewed and processed, but the research questions that lie at the heart of this case study have profound implications for the study of cultural and biological evolution.

We envision that our methodological approach for the visualization of cosmic impact is to create a network of virtual heritage and collaborative environments between UC Merced, Los Alamos National Laboratory (LANL), the University of

La Plata, and other cooperating institutions, reconstructing the past through simulation virtual processes and multiuser digital spaces.

Our scenario is to have collaborative environments for students, scholars and visitors where the users can interact in a 3D virtual space exchanging data and information of eco-cultural and archaeological content. Advanced research, education, communication, learning will be the key words representing the contents of the virtual heritage. The term "virtual heritage" means the virtual ontology of the cultural heritage. In practical terms, the VHC model should open new important perspectives for a network of excellence and for a matrix of research in this field.

The ultimate outcomes of this collaborative research project are summarized in the following six key actions:

- Experimenting with advanced simulation processing within virtual reality collaborative environments between different labs and research teams.
- Teaching and focusing research through virtual collaborative environments.
- Reconstructing sites and event sequences of the past, stressing the relationships between cultures, ancient societies, environmental data and ecosystems.
- Creating pilot case studies for approaching new methodological guidelines in the field of virtual heritage and in the validation of the reconstruction and dynamic simulation process of the past, within the framework of an ecological perspective.
- Integrating skills, methods and competences of different labs and cross-disciplinary teams.
- Simulating by virtual immersive environments complex phenomena related with archaeological and environmental datasets.

6 The Steps for Capturing Cosmic Impact in a Virtual Museum

Our case study builds on research that examines the effects of the Campo del Cielo and Rio Cuarto asteroid impacts on 3rd millennium B.C. Argentine hunting and gathering societies (Masse 1998, 2007; Masse and Masse 2007; Barrientos and Masse 2009). Except for limited work on the late Holocene Kaali impact in Estonia (Veski et al. 2007), and the 800,000 bp Australasian tektite strewfield impact on *Homo erectus* (Langbroek and Roebroeks 2000; Langbroek 2004), and recent precocious studies in relation to the hypothesized impact at the beginning of the Younger Dryas climatic ordeal 12,900 years ago (Firestone et al. 2007; Kennett et al. 2009), there has been no systematic study of a validated cosmic impact by archaeologists. The biggest hurdle will be that of demonstrating to archaeologists that the methods and theories of the archaeological discipline can actually contribute to a better understanding of cosmic impact.

We envision the following steps towards the establishment of a working "virtual impact" environment.

Step I. Gathering detailed information and the creation of a virtual reality package involving core cosmic impact textual concepts and associated visual illustrations is a necessary basis, augmented where possible with animations and pertinent internet links. Among these would be: (1) Discussion of the Solar System including the nature and orbital characteristics of comets and asteroids. (2) Pertinent definitions such as meteor, meteorite, bolide, meteor showers and storms, etc. (3) Presentation of the visually-impressive known cratering record in our Solar System outside of the Earth itself. (4) Discussion of the nature, effects, and implications of the 65.5 million year old Tertiary-Cretacious (KT) geologic period boundary Chicxulub impact. (5) A review of the major types of impact events/processes known on Earth, including airbursts, simple terrestrial impact structures, complex terrestrial impact structures, and oceanic impacts. (6) A review of the known cratering record on Earth. (7) A discussion of the process of validating impact structures. (8) A review of the current accepted astrophysical model of impact rates on Earth. (9) Visualizations highlighting the rather profound discrepancy that exists between the models of impact rates and our current validated lists of impacts.

Thorough integration of these aspects of astrophysics and interactions with the Earth will provide an intellectually stimulating environment for scientific exploration and learning.

Step II. The study of the Rio Cuarto and Campo del Cielo sites and their potential to inform on impact processes is enhanced by local mythology and oral tradition that has captured important aspects of the cosmic impacts, such as the likelihood that the impacts created largescale wildland fires. Thus a discussion and set of visualizations of a natural science approach to mythology and oral tradition, geomythology, and related topics will be integrated into our project.

Step III. Simulation of the Mid-Holocene Argentina impact events would be built, including physical effects and processes. This includes a discussion of the overall Argentine impact record based on the work of Peter Schultz and his colleagues (e.g., Schultz et al. 2004, 2006). The Campo del Cielo case study builds from the modeling and visualization already accomplished by William Cassidy (University of Pittsburgh) and his colleagues. The Rio Cuarto case study will build upon the modeling and visualization already accomplished by Peter Schultz (Brown University) and his colleagues.

We anticipate that colleagues at Los Alamos National Laboratory (LANL) may be able to contribute to our virtual impact visualizations of the Rio Cuarto and Campo del Cielo impacts by building on previously designed "SAGE" codes, developed by LANL and Science Applications International Corporation (SAIC) that have simulated aspects of cosmic impact in both 2D and 3D format.

A majority of large simulations come in one of two constructs: Lagrange, in which a grid or mesh of mathematical points matches with and follows molecules or other physical variables through space; or Eulerian, in which the mesh is fixed in space, thereby permitting researchers to follow fluids as they move from point to point.

The power of the SAGE (SAIC's Adaptive Grid Eulerian) code lies in its flexibility. The mesh can be continuously refined to increase the level of detail the code provides about specific physical elements in the mesh. Newer SAGE simulations use increasingly realistic equations to represent physical variables such as the atmosphere, seawater and ocean crust when modeling, for example, tsunami propagation from oceanic impact, such as illustrated in Figure 1.

Although a goal of such simulation is that of developing better and better resolution of event physical processes, application of the data from these huge calculations by broad multi-disciplinary sets of researcher require excellent visualization and interactive work techniques, such as the three-dimensional power walls used at LANL and UC Merced.

These SAGE models will then be applied to the reconstructed environment and human demography of the mid-Holocene Campo del Cielo and Rio Cuarto impacts. The preliminary modeling of Barrientos and Masse (2009) will be expanded to better capture the potential effects of these two impacts on their contemporary human societies.

With sufficient data gathered from the Argentine paleoenvironment and human demography, it will also be possible to introduce simulations structured on agent-based models. For example, researchers at the Santa Fe Institute during the past decade have developed relatively robust tools such as the "Artificial Anasazi Project" (Gumerman et al. 2002). This simulative experiment was designed to provide empirical evaluation of the principles and procedures associated with a bottom-up, agent-based computer simulation to illuminate human behavior in a real world setting.

A potential Artificial Argentina Impact Project could create landscapes from reconstructed environmental variables and would be populated by families, households, or tribal bands as artificial agents. It would draw upon detailed environmental reconstructions of the Rio Cuarto and Campo del Cielo impact sites as impinged upon by low- and high-frequency paleoenvironmental variability in order to study how changing physical and social conditions play out in terms of long-term settlement patterns. We then could systematically alter the quantitative parameters or make qualitative changes that introduce subtle, completely new, and even unlikely elements into the artificial world of the simulation.

In this specific case we would introduce the effects of asteroid impact vis-à-vis Campo del Cielo or Rio Cuarto. By allowing the alteration some of the physical variables of impact, we can use visulation technology to explore and better understand those parameters most likely to affect regional ecosystems and the demographic characteristics of imbedded human populations.

Step IV. This is a long-term visionary step that would attempt to build on present largely static interactive programs that help to visualize the physical effects of impact in order to achieve dynamic interactive programs focusing on variables pertaining to ecosystems and human population dynamics.

For example, a current popular and useful web-based program for estimating the regional environmental consequences of an impact on Earth is that of the Earth Impact Effects Program (Marcus, Melosh, and Collins 2005), which was used to estimate the impact rates listed in Table 2. The Earth Impact Effects Program estimates the ejecta distribution, atmospheric blast wave, ground shaking, and thermal effects of an impact as well as the size of the crater producted. This is determined by choosing a stipulated distance from the impact, and then inputting a specific series of impactor parameter such as the size and density of the impactor projectile, the impact velocity, the degree of impact angle, and the nature of the target location such as water depth if an oceanic or lake impact, sedimentary rock (e.g. loess, sand, sandstone), or crystalline rock such as surface volcanic magma flows and metamorphic rocks.

It would be useful to enhance the visualization of and interaction with information derived from the Earth Impact Effects Program by the use of 3D GIS topography layers. For example, the program would benefit by the use of Google Earth-like imagery that translate the calculated effects into visualized landscapes based on a range of specific target locations.

More critical is the fact that the Earth Impact Effects Program does not include most of the significant physical effects associated with oceanic impact, a significant omission in light of the fact that water and ice cover 70% of the Earth's surface. These effects not only include the obvious potential for tsunami propogation, but also include such things as the amount and types of particulates injected into the upper atmosphere.

Impacts larger than 1000 megatons may produce striking environmental and climatic effects in addition to those physical effects described above (Toon et al. 1997; Birks et al. 2007; MacCraken 2007). Particularly poorly understood are deepwater oceanic impactors in the range of 10^4-10^7 megatons in terms of their injection of large quantities of particulates and water vapor into the upper atmosphere that may trigger and sustain long-lived cyclonic storms, including super-hurricanes.

In a similar vein, since ocean surface heating is a major factor in initiating El Niño climatic events, could a modest impact (10^3-10^5 megatons) in a sensitive oceanic location trigger a major El Niño event? And what would happen if a larger-sized impact hit the glacial ice of Greenland or Antarctica? Not only would this inject a large amount of water vapor so as to considerably disturb the atmosphere, but how might the pulse of melted freshwater effect ocean currents, atmospheric-oceanic couplings, and oceanic food webs?

We also have much to learn about the potential signature(s) of impact in the global climate change record, including tree-rings, ice cores, and paleobotanical and pollen records (e.g., Baillie 1994, 2007).

Also missing from these physical parameters for the Earth Impacts Effects Program are parameters that deal with the potential for igniting or spreading wildland fires such as vegetation type (tropical forest, open woodland, savanna, taiga); climatic conditions (e.g., drought, monsoon, temperate); terrain/topography categorization; fuel loads (such as used in wildland fire matrices); temperature; time of day; and wind conditions.

And critically missing are ecosystem and human demographic and social complexity variables that are key for calculating effects of impacts on human populations. What types of societies are present in the impact target area? Are they hunter and gatherers, semi-sedentary or sedentary agriculturalists, urban civilizations, or a mix of these gross societal categories? What is the population density, and are populations clustered or evenly scattered out over the landscape?

Catastrophic impacts constitute a largely unstudied bottlenecking mechanism from a human and biological evolutionary perspective. Just exactly what does "globally catastrophic" or any other magnitude of cosmic impact mean for past cultures and ecosystems? We need to focus on the role of cosmic mega-killers ($\geq 10^6$ MT) in human evolution (e.g., Australasian and Younger Dryas impacts); on possible extinction thresholds for smaller impacts on hunting and gathering societies (e.g., Rio Cuarto); on the ways in which impacts of various sizes might have caused the collapse of past complex societies (e.g., Courty et al. 2008); and on the potential evolutionary role of recent cosmic impact in climate and ecosystem change. Archaeologists and kindred historical and evolutionary disciplines can also contribute to dialog regarding issues of disaster planning and recovery, which typically omit consideration of cosmic impact (e.g., Gad-el-Hak 2008).

7 Conclusions

Archaeologists conduct fieldwork worldwide and employ exquisite micro-stratigraphic, paleoenvironmental, and chronological controls to explore major aspects of human history. We model population dynamics and cultural behavior. And we deal with documentary records and oral traditions. This places us in an ideal position to scrutinize and evaluate the Pleistocene and Holocene historical and sedimentary record of cosmic impact, and to fill in some of the gaps that currently exist in the planetary science community's models of the rates, risks, and effects of impact.

This new research endeavor likely will at first seem very foreign and intimidating to many archaeologists and for most members of our kindred discipline of anthropology. We do tend to be very nervous when it comes to working with data and methods requiring application of detailed knowledge of physics, mathematics, and chemistry.

The Virtual Impact visualization package is intended to break down some of the apparent barriers that now currently exist on the road to this new line of historical inquiry. We suggest that not only will it serve as a useful tool as archaeologists begin to consider how cosmic impacts have affected past human populations and ecosystems, but also it can open doors for additional fruitful dialog with the physical and planetary science communities.

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