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Air blast produced by the Meteor Crater impact event and a reconstruction of the affected environment

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Abstract–Using scaling relationships determined from nuclear explosions, the radial extent of the air blast produced by the Meteor Crater impact event is estimated. The wind velocity at a distance of 5 crater radii (3 km) from the point of impact should have exceeded 2000 km/h. Hurricane force winds would have existed as far away as 20 to 40 km, depending on the exact explosive energy of the impact event. To determine how this event may have affected the environment surrounding the crater, the topography, vegetation, and animal life that existed at the time of the impact are reconstructed. For example, if the coniferous woodlands were 100 m lower than they are presently and they had moved farther out onto the plains, then the air blast would have flattened trees within a 16 to 22 km radius of the point of impact and damaged them over an area of 4100 to 8500 km^2. The distance over which the damage occurred may have been up to 2× larger in some directions around the crater because of additional effects produced by the ballistic shock wave. Unfortunately, since the trajectory of the projectile is not well known, the direction of the ballistic shock wave effects cannot yet be determined.

INTRODUCTION

It has become increasingly clear that impact cratering can alter local and regional environments and even change global climatic conditions. Thus far, most studies have explored the effects associated with the Cretaceous-Tertiary boundary in general or with the Chicxulub Crater impact event specifically. However, since smaller impact events occur more frequently and are thus more likely to affect Earth in the near future, a series of baseline studies are needed to determine when the environmental thresholds that affect life are exceeded. Consequently, it is useful to study smaller impact events to determine the extent to which they have affected the environment and, ideally, how specific plants and animals reacted to those environmental changes.

One of the classic impact sites in the world is Meteor Crater, Arizona, which is a 1.2 km diameter bowl-shaped depression ~180 m deep and surrounded with a rim that rises 30 to 60 m above the surrounding plain (Shoemaker, 1987). It is very well exposed in an arid region that is only lightly vegetated. It is relatively young, 49000 ± 3000 years (Sutton, 1985) and very well preserved. It is also the size of crater-forming impact event that is expected to occur once every 1600 years on Earth or every 6000 years on a continental region of Earth (Neukum and Ivanov, 1994). While this impact event probably had no regional or global consequences, it is clear it would have devastated the local environment, at least for a short period of time. Indeed, Nininger (1956, p. xiii) described it this way:

> The grazing bands of deer, elk, and antelope face southwest into the roaring wind as twilight deepens across the grassy plain. Suddenly, the fields are lighted with the brilliance of noonday. A deafening swishing roar from out of the northern sky brings each head erect and frightened eyes watch, as 20 miles away a giant blazing sun screams downward, spewing an exploding train of fiery sparks as from a raging blast furnace.
>
> A blinding flash, a billowing fountain of flame, and a swirling, blazing, mushroom cloud shoots skyward into the stratosphere. Five, ten, fifteen miles, and up it goes while a deadly pall of smoke and dust covers the spot where the blazing sun dived to its doom.
>
> The wide eyes stare, their terror-stricken owners frozen into statues. Sharp ears strain forward to catch the faintest sound of the momentarily quiet air.
>
> A searing blast of heat and wind. The straining ears are deaf, the sharp eyes sightless bulges on the crushed and roasted heads. The herds have vanished in a stench of burning hair and flesh, and on the charred grass, so lately green, lie twisted, blackened hulks, insensible to roaring wind and to the warm drizzle of tiny molten droplets which are blanketing the land.
>
> And 20 miles away, steam and smoke swirl from the gaping mile-wide hole and from the mountain of shattered rocks and twisted bits of metal that now strew the land.

Nininger did not try to quantify the effects he described, but it is clear that he was influenced by the qualitative effects of nuclear explosions. Indeed, Nininger visited Yucca Flats at the Nevada Test Site in 1953 December and drew analogies between the shock-metamorphic products there and those at Meteor Crater (Nininger, 1956, p. 129). Shoemaker (1960) also drew comparisons between Meteor Crater and the craters produced by nuclear explosions, specifically the ~90 m diameter craters produced by the ~1 kiloton (kT) Teapot Ess and Jangle Uncle explosions, to determine the penetration mechanics of the Canyon Diablo asteroid. The overturned stratigraphy seen in the rim of Meteor Crater is also seen in the rim of a 300 m crater produced by the 30 kT Schooner nuclear explosion, which was then used, like Meteor Crater, for Apollo astronaut training (Moore, 1977).

Building on this analogy with nuclear explosion craters, the effects of one of the environmental perturbations, the air blast, will be quantified below for the Meteor Crater impact event using scaling relationships derived from nuclear explosions. The air blast is likely to be the most destructive component of the impact event beyond the overturned sequence of ejecta. In the case of the 1908 Tunguska event, for example, the air blast damaged trees throughout ~2150 km^2 of the Siberian taiga (Vasilyev, 1996). The damage associated with the Meteor Crater impact event could conceivably have been more severe than that produced by the Tunguska event, because the energy of the explosion may have been larger (as discussed below). On the other hand, other factors like the topography around the impact site can alter the severity of the blast damage. Consequently, geologic data regarding the local topography 50 000 years ago also will be compiled below. In addition, an assessment will be made of the vegetation and animal life as it existed 50 000 years ago before drawing any conclusions about the environmental effects of the air blast. The reconstruction of the pre- and postimpact environments will be necessarily incomplete, however, because paleontological analyses of critical stratigraphic sections in the Colorado Plateau region have not yet been studied in sufficient detail. (A similar situation plagued interpretations of K/T boundary sections a few years ago, although, in that case, the situation is constantly improving.) It is hoped that this study will prompt additional studies of sediments in Meteor Crater and in surrounding lakes to further evaluate the environmental consequences outlined below.

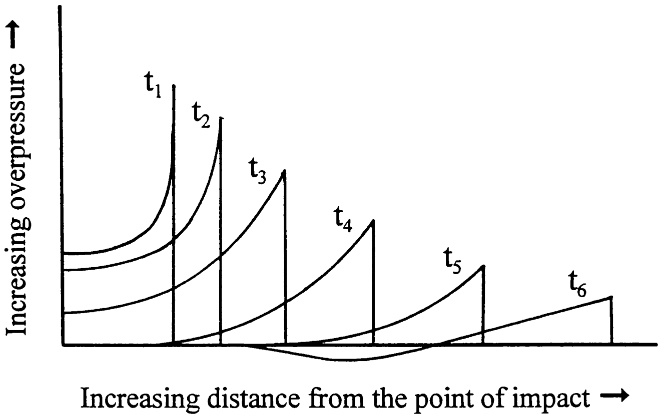

FIG. 1. Schematic diagram illustrating the variation of overpressure in air at successive times (t_1, t_2, *etc.*) and as a function of distance. (After Glasstone and Dolan, 1977.)

IMPACT AIR BLASTS

In the explosive collision that produced Meteor Crater, most of the local damage would have been produced by a blast wave that radiated across the landscape from the point of impact. At any particular point on the ground, the pressure would have increased nearly instantaneously when the shock front arrived. The pressure produced by the shock front is usually characterized in terms of overpressure, which is the amount of pressure that exceeds the ambient atmospheric pressure (14.7 psi for standard sea level conditions and 12.2 psi for the 1680 m elevation of Meteor Crater). Relatively small amounts of overpressure can be catastrophic. For example, an 8 to 12 in thick concrete or cinder-block wall can be shattered by overpressures of only 1.5 to 5.5 psi (Glasstone and Dolan, 1977, p. 221). As the shock front travelled away from the point of impact, the peak overpressure would have decreased, as shown schematically in Fig. 1. In addition, at any particular point along the ground, the peak overpressure would have decreased after the shock front had passed. Eventually, the overpressure behind the shock front would have become negative and a partial vacuum would have been created.

A strong wind, with the capacity to injure or destroy plants and animals, would have been produced when the blast wave arrived at any particular point along the ground. Under ideal conditions, a peak overpressure of 5 psi, for example, could produce wind velocities of ~260 km/h (Glasstone and Dolan, 1977, p. 82) or ~2× the velocity of a hurricane force wind. This would have been a transient wind that soon reversed its direction after the overpressure became negative and the momentum of the air moving away from the point of impact had dissipated (Fig. 2). This phase of negative overpressure would have also passed and the wind would have again blown away from the point of impact before ambient wind conditions returned.

Another important way to characterize the blast wave is in terms of its dynamic pressure, which is proportional to the square of the wind velocity and the density of the air behind the blast wave. This pressure reflects the fact that the degree of damage to objects is sometimes a function of a drag force which is, in turn, a function of the shape and size of an object or its components. For example, the drag on a deciduous tree with leaves (*e.g.*, in the summer months) is greater than the drag on the tree when it is barren (*e.g.*, in the winter months). Similarly, the damage to a coniferous forest may be less severe than a deciduous forest because needle boughs have less drag than deciduous leaves.

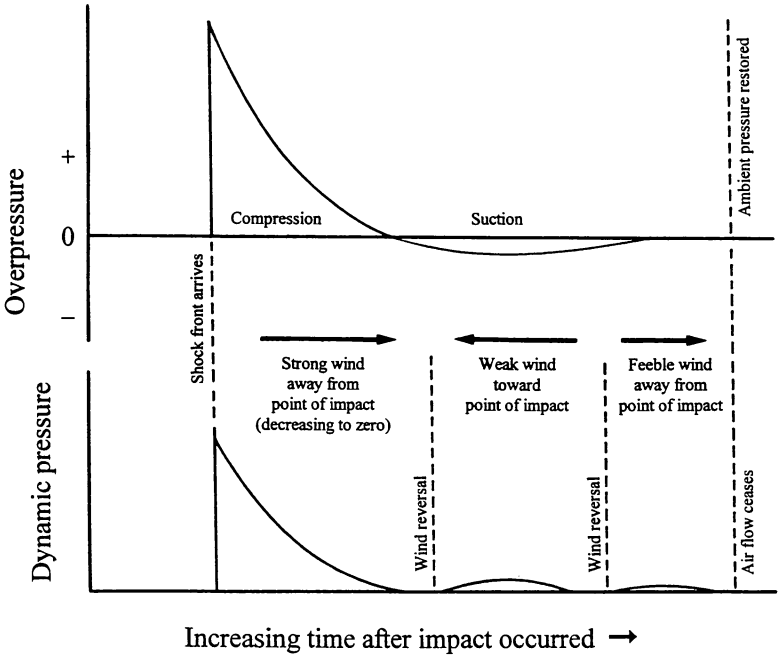

FIG. 2. Schematic diagrams illustrating the variation of overpressure as a function of time at a fixed location (top) and the variation of dynamic pressure as a function of time at a fixed location (bottom). (After Glasstone and Dolan, 1977.)

Scaling the Effects of Blast Waves to Meteor Crater

The effects of blast waves were previously studied in association with multiple surface and atmospheric nuclear explosions. Glasstone and Dolan (1977) derived analytical and empirical relationships between peak overpressure, dynamic pressure, wind velocity, and the resulting damage caused by these phenomena. In general, the radial distance (r) over which damage is produced by an explosion is proportional to the cube root of the yield (E), $r \propto E^{1/3}$, or, in terms of the area (A) affected by the blast, $A \propto E^{2/3}$. The amount of damage is also a function of the height of the explosion. As nuclear bomb tests demonstrated, the most damaging blasts occur above the ground at an "optimum" blast height, which is a function of the energy of the blast. Explosions above or below this height (including surface explosions) produce less damage. The Tunguska impact event of 1908 occurred at an altitude of 6 to 9 km (Turco *et al.*, 1982), near the optimum blast height for a 10 to 20 megaton (MT) blast. In general, for a surface explosion like Meteor Crater, the radial extent of damage on the ground is a factor of two less than that produced by an explosion of the same yield at the optimum blast height (Glasstone and Dolan, 1977). Also, depending on the type of explosion involved (nuclear, chemical, or impact), the fraction of energy partitioned into the shock wave may be different. But for our purposes, the scaling factors determined for nuclear explosions at low altitudes and the surface are good approximations. (For very large impact events, like Chicxulub, or impact events that explode high in the atmosphere, a smaller fraction of the total energy will be partitioned into the shock wave and will affect, directly, plants and animals on the surface. Indeed, if an impact explosion occurs ~2¾× higher in the atmosphere than the optimum altitude, no ground damage is expected (Hills and Goda, 1993)).

TABLE 1. Peak overpressures, peak dynamic pressures, and maximum wind velocities for the Meteor Crater impact event, assuming a yield of 20 to 40 MT, as a function of distance.*

			20 MT		40 MT	
Peak Overpressure (psi)	Peak Dynamic Pressure (psi)	Maximum Wind Velocity (km/h)	Distance (km)	Distance (crater radii)	Distance (km)	Distance (crater radii)
100	123	2277	2.8	4.7	3.6	5.9
50	41	1503	3.8	6.3	4.8	8.0
30	17	1077	4.9	8.2	6.2	10
20	8.1	808	5.9	9.8	7.4	12
10	2.2	473	8.5	14	11	18
5	0.6	262	12	21	16	26
2	0.1	113	21	35	27	44
1	0.02	58	32	53	40	67

Crater radii = 0.6 km.

*These distances were calculated for standard atmospheric conditions at sea level. Meteor Crater is at an elevation of ~5500 ft. (1680 m), so the distances could, ideally, be 5 to 10% larger. Wind velocities would also be subtly larger. For example, an overpressure of 1 psi might produce a 68 km/h wind velocity rather than a 58 km/h wind velocity. However, this falls within the level of uncertainty one would have to assign to the scaling methods and to our knowledge of the temperature and pressure conditions at the time of impact (*e.g.*, did the impact occur during the day or night, and what was the weather like?).

Comparisons with deeply buried nuclear blasts would also be inappropriate, because in those cases, the air blast is created after the shock wave has been transmitted through the ground to the surface where it imparts an upward velocity on the air, rather than being created from the release of high-pressure gases produced by the explosion (Glasstone and Dolan, 1977, p. 231). A small impact event is better described as a near-surface explosive event rather than a deeply buried explosive event, so the air blast should be produced in a manner more like that associated with surface explosions even though it may also be influenced by the ground shock. Consequently, scaling factors determined for nuclear explosions at the surface are good approximations for our purposes, although it may eventually be useful to precisely determine the equivalent depth of burial for a nuclear device that best mimics the Meteor Crater impact event (*e.g.*, Holsapple, 1980) or to devise a detailed computational simulation of the impact event.

The scaling methods devised by Glasstone and Dolan (1977) are both analytical and graphical. To calculate the dynamic pressure (q) as a function of peak overpressure (p) behind the shock front, one uses the following expression (Glasstone and Dolan, 1977, p. 97):

$$q = \frac{5}{2}\left(\frac{p^2}{7P_0 + p}\right)$$

where P_0 is the ambient pressure (ahead of the shock front) and the ratio of specific heats of air is assumed to be 1.4. To calculate the maximum wind velocity (u) as a function of peak overpressure, one uses the following expression (Glasstone and Dolan, 1977, p. 97):

$$u = \frac{5p}{7P_0}\left(\frac{c_0}{\left(1+\frac{6p}{7P_0}\right)^{1/2}}\right)$$

where c_0 is the ambient speed of sound (ahead of the shock front). To determine the distances over which the peak overpressures, dynamic pressures, and maximum wind velocities can produce significant damage, one needs to then utilize graphical scaling methods, which are functions of the altitude and energy of the blast (Glasstone and Dolan, 1977, pp. 108–123 and 222–223). In the case of the Meteor Crater impact event, which was a surface explosion event at an elevation of 1680 m, the effective altitude is zero. (If the elevation was any higher, additional equations would be needed to account for variable temperatures and pressures in the atmosphere; see Table 1 and Glasstone and Dolan, 1977, pp. 102–105 for more details.) The energy of the Meteor Crater event is less certain than the impact's effective altitude. Estimates have varied from ~2 MT (Shoemaker, 1960) to ranges of 10 to 60 MT (Schmidt, 1980). Current estimates based on the latest calculations suggest that the explosive energy of the Meteor Crater event was 20 to 40 MT (Roddy and Shoemaker, 1995). For the purposes of this paper, values of 20 and 40 MT will be used to encompass, hopefully, the range of effects produced by the Meteor Crater impact event.

Based on these scaling relationships, maximum wind velocities for several values of peak pressure have been calculated and are listed in Table 1. Also, the distances from the point of impact that these peak pressures and maximum wind velocities occur are listed, assuming 20 and 40 MT explosions (Table 1, Fig. 3). These results indicate, for example, that at a distance of ~5 crater radii (3 km) from the point of impact, the maximum wind velocity exceeded 2000 km/h and that hurricane force winds occurred as far away as 20 to 40 km from the point of impact. These winds, while tremendous, should be thought of as severe gusts, because they rapidly dissipated after the shock wave passed. Nonetheless, the damage they may have imposed is immense. If an impact of this magnitude occurred within a coniferous forest, 90% of the trees would be flattened over a radial distance of 14.4 to 18.9 km or an area of 650 to 1120 km^2 (Table 2). Moderate damage, in which ~30% of the trees are felled and the remainder have branches blown off, would extend another 3.5 to 4.7 km or an additional 350 to 530 km^2. The destruction of timber would occur nearly instantaneously, because the time required for the blast wave to reach the perimeter of this damaged area is only ~1½ s (Fig. 4).

In addition to the effects of the blast wave, damage would have been produced by a ballistic shock wave that was created when the iron asteroid plowed through the atmosphere. In the case of Tunguska, the ballistic shock wave altered the radially symmetric pattern of damage expected for a point source blast wave and produced instead a butterfly pattern of damage that encompassed a larger area. In front of the Tunguska explosion, the flattened timber extends 15 km (Zotkin and Tsikulin, 1966). However, in two rearward lobes that trail like a boat's wake, the effects extend 38 km, while the effects along the azimuth of the trajectory extend 27 km behind the explosion (Zotkin and Tsikulin, 1966). It is difficult to determine the extent and orientation of similar ballistic shock wave effects around Meteor Crater without knowing its trajectory. While several attempts have been made to estimate the trajectory of the iron asteroid, there is no consensus. Shoemaker argues that the asteroid was moving to the north-northwest, while others argue it was moving in the opposite direction (Roddy and Shoemaker, 1995; Roddy, 1978 and references therein). Depending on which of these orientations is correct, the effects of the ballistic shock wave may have extended ~2× farther than the effects of the blast wave in some directions around Meteor Crater.

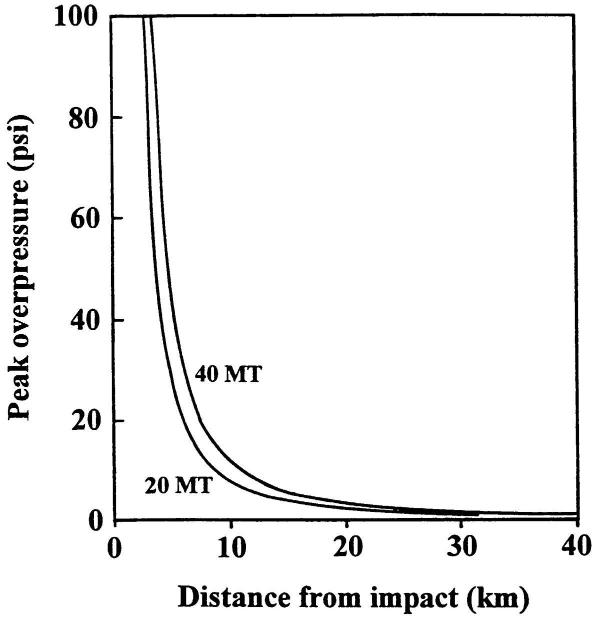

FIG. 3. The peak overpressure as a function of distance from the impact site for 20 and 40 MT blasts.

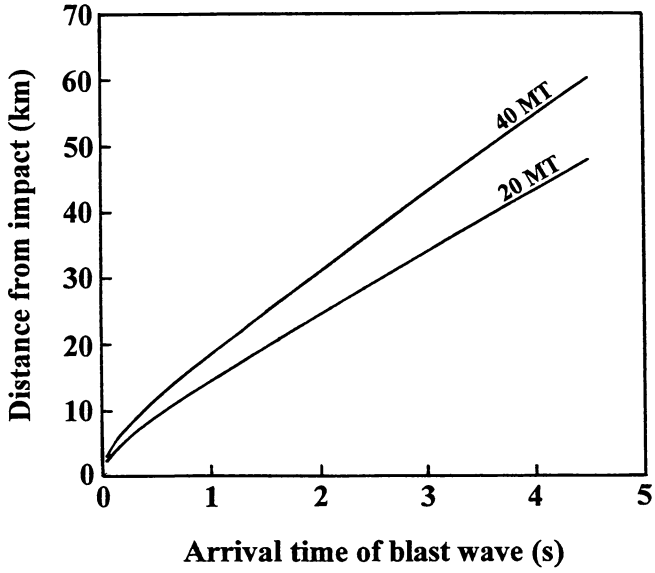

FIG. 4. Arrival time of the blast wave as a function of distance from the point of impact, assuming the Meteor Crater impact event had a yield of 20 MT (lower curve) to 40 MT (upper curve). The calculations are based on the scaling relationships derived by Glasstone and Dolan (1977, pp. 120–121).

THE COLORADO PLATEAU ENVIRONMENT 50 000 YEARS AGO

To provide an estimate of how the blast wave may have damaged the surrounding environment, it is necessary to first determine if the topography could have modified the propagation of the blast wave. It is also necessary to determine what types of plants and animals existed in the region at the time of impact. Fortunately, the time of the impact is well known. Thermoluminescence techniques indicate that Meteor Crater was produced 49 000 ± 3000 years ago (Sutton, 1985), cosmogenic ^{36}Cl techniques indicate that it was produced 49 700 ± 850 years ago (Phillips *et al.*, 1991), and exposure ages based on *in situ* production of ^{10}Be and ^{26}Al indicate a minimum age of 49 200 ± 1700 years (Nishiizumi *et al.*, 1991). These ages are concordant and indicate that the impact occurred ~50 000 years ago. This late Pleistocene age occurs within the Pinedale interstadial, so climatic conditions were relatively warm even though it was within the Wisconsin period of glaciation (Fig. 5). The conditions at that time, based on current geologic and paleontologic evidence, are reconstructed below.

Topography

Meteor Crater is in a relatively low-relief portion of the Colorado Plateau and was produced at an elevation of ~1680 m. The site is underlain by a flat lying sequence of Permian and Triassic sediments in a gentle monoclinal fold (Shoemaker, 1960). The topography in the immediate vicinity of Meteor Crater is dominated by erosion of the very fine-grained sandstone and fissile siltstone sequence of the red Moenkopi formation. On the plains around Meteor Crater, the greatest amount of topographic relief is ~15 m and occurs ~0.3 km beyond the northwest flap of overturned ejecta (Roddy, 1978). The dominant topographically negative feature is Canyon Diablo, which is a sinuous canyon ~18 to 25 m deep. It is part of a drainage system that flows towards the northeast and the Little Colorado River. It is believed that this drainage system had already been established by the time of the impact event (Shoemaker, 1960).

At the precise location of the impact site, the topography was subdued. This can be determined because part of the topography at the time of the impact event has been preserved by and buried beneath the overturned sequence of ejected sediments. The area of buried topography extends from the rim of the crater to distances of ~0.6 to 1.2 km beyond the rim. The U. S. Geological Survey drilled 116 holes through the ejecta in the early 1970s and found that the

TABLE 2. The range and area over which hypothetical forests may have been damaged around the Meteor Crater impact site, based on the scaling relationships of Glasstone and Dolan (1977).

	20 MT		40 MT	
	Distance (km)	Area (km^2)	Distance (km)	Area (km^2)
Coniferous forest				
Severe damage	14.4 ± 2.9	651 ± 261	18.9 ± 3.8	1122 ± 449
Moderate damage	17.9 ± 3.6	1007 ± 403	23.6 ± 4.7	1750 ± 700
Deciduous forest				
Severe damage	18.9 ± 3.8	1122 ± 449	24.8 ± 5.0	1932 ± 773
Moderate damage	21.1 ± 4.2	1399 ± 559	27.6 ± 5.5	2393 ± 957

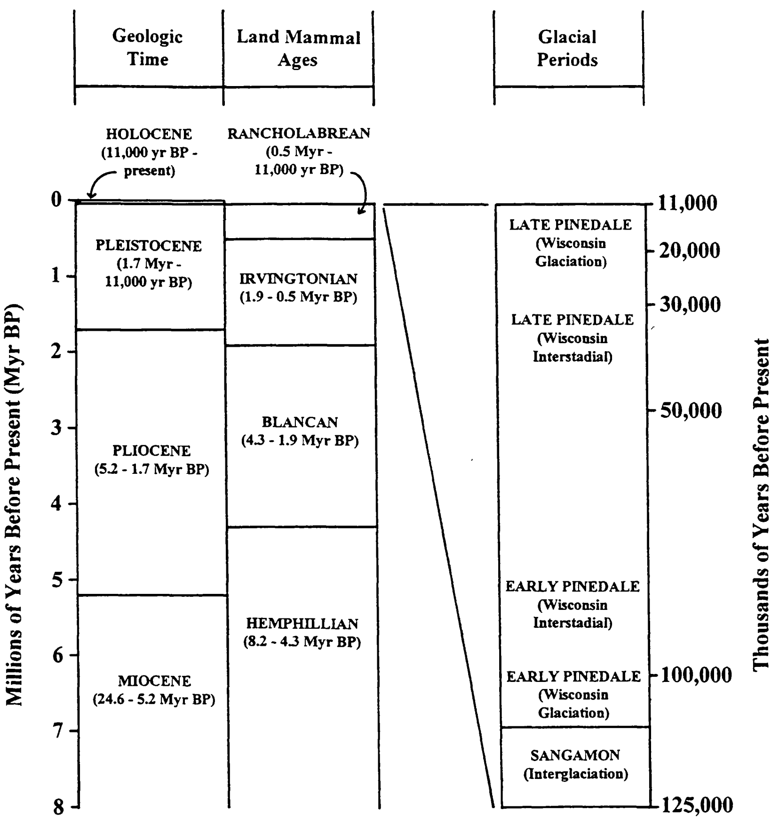

FIG. 5. The relationship between geologic time, land mammal ages, and glacial periods. The time scale is based on divisions assigned by Lindsay (1984) and Elias (1996).

terrain was relatively flat at the time of the impact event (Roddy *et al.*, 1975). The average slope of the terrain was small, ~0.5°, and dipped to the northeast (Roddy, 1978). The few hills or ridges that existed had an average relief of ~5 to 10 m over distances of ~0.25 to 1.0 km (Roddy *et al.*, 1975; Roddy, 1978), which produced a slightly knobby to slightly rolling landscape. The greatest amount of relief was ~20 m (Roddy *et al.*, 1975; Roddy, 1978), ~0.4 km beyond the southwest rim of the crater. This feature has a maximum average slope of 7° on its southwest side and 6° on its northeast side (Roddy, 1978). Similar amounts of preimpact topographic relief, from 9 to 15 m, were measured in the walls of the crater (Shoemaker, 1960). The principal difference between this buried topography and what is seen today may be the slopes of the small ridges, which were not quite as steep then as they are today; the average slope is now ~10° and locally slopes are as high as 45° (Roddy, 1978).

Basaltic cinder cones and lava flows that erupted during the late Tertiary and Quaternary lie ~11 to 29 km to the south, west, and northwest of the crater (Shoemaker, 1974; Fig. 6). The two closest features are West Sunset Mountain and East Sunset Mountain, which are composed of basalts and rise 335 to 410 m above the plain 12 and 21 km, respectively, south-southeast from the center of the crater. To the west, the land rises gently ~300 m until it reaches the base of Anderson Mesa ~29 km from the crater. This mesa is ~150 m high and composed of several lava flows. Farther to the northwest, the San Francisco volcanic field dominates the skyline and reaches a peak elevation of 3851 m.

Most of these volcanic features were present at the time of impact. The age of the basalts in Anderson Mesa range from 5.88 ± 0.30 to 6.39 ± 0.30 Ma (Reynolds *et al.*, 1986). The age of the basalts at West Sunset Mountain and East Sunset Mountain have not been determined radiometrically, but based on the extent of erosion, they appear to be older than 50 000 years. The ages of the volcanic rocks in the San Francisco volcanic field range from 6.13 Ma to ~1000 years (Reynolds *et al.*, 1986), with only a single event being definitely younger than Meteor Crater. This involved the eruption of Sunset Crater in 1064–1065 A.D. (Smiley, 1958), whose ash is now found near the top of the sediment sequence that partially fills Meteor Crater (Shoemaker and Kieffer, 1974). Two other young ages are comparable to the age of Meteor Crater. These reflect the eruption of basaltic andesites at the Strawberry Crater (51 000 ± 46 000 years; 61 km from Meteor Crater) and the O'Neil Crater (56 000 ± 14 000 years; 47 km from Meteor Crater) (Reynolds *et al.*, 1986). Consequently, with the exception of Sunset Crater and possibly the latter two cinder cones, all of the topographic features seen today were present 50 000 years ago.

Because the topography in the immediate vicinity of the impact site 50 000 years ago was so flat, it is not likely to have dramatically affected the course of the air blast wave. In contrast, the slightly more distant features, like West Sunset Mountain, East Sunset Mountain, and Anderson Mesa, may have slightly affected the blast wave because they existed within or near the perimeter of the blast zone (Table 1). For example, when the blast wave hit the base of West Sunset Mountain, the peak overpressure should have increased momentarily (because of partial reflection of the blast wave by the mountain) but then should have decreased as the blast wave moved up and over the mountain. The increase of peak overpressure could have been as much as a factor of two, so the nominal peak overpressure of 5 psi at the distance of West Sunset Mountain (12 km; Table 1) could have been as high as 10 psi on the slope facing the impact site.

Flora

Several types of biotic communities currently exist near Meteor Crater. Palynological studies of lake sediments and packrat middens on the Colorado Plateau indicate that vegetation patterns have shifted several times during the Holocene and Pleistocene since the time of the Meteor Crater impact event but that the same plant genera (and often species) have always been involved. Consequently, before describing the possible vegetation pattern 50 000 years ago, I will first introduce the relevant genera and species as they exist today around Meteor Crater, incorporating regional studies from the literature and as well as new field work designed to augment those past studies with details of the flora in the immediate vicinity of Meteor Crater.

Currently, the vegetation around Meteor Crater is dominated by what is known as a Plains-Great Basin Grassland community (Fig. 7) (Brown, 1994b). Although it is called a grassland, it consists mostly of shrubs like sagebrush (*Artemisia*), snakeweed (*Gutierrezia*), rabbitbrush (*Chrysothamnus*), groundsel (*Senecio*), and, near small Moenkopi mesas, cliffrose (*Cowania*) (Fig. 8a). This does not represent, however, wild conditions; rather, the dearth of grass around the crater is probably the result of cattle grazing during the last 100 years. A few kilometers east of Meteor Crater, near Winslow, the grassland community is better preserved (Brown, 1994b). It is a short-grass variety, dominated by Blue Grama (*Bouteloua gracilis*), Galleta Grass

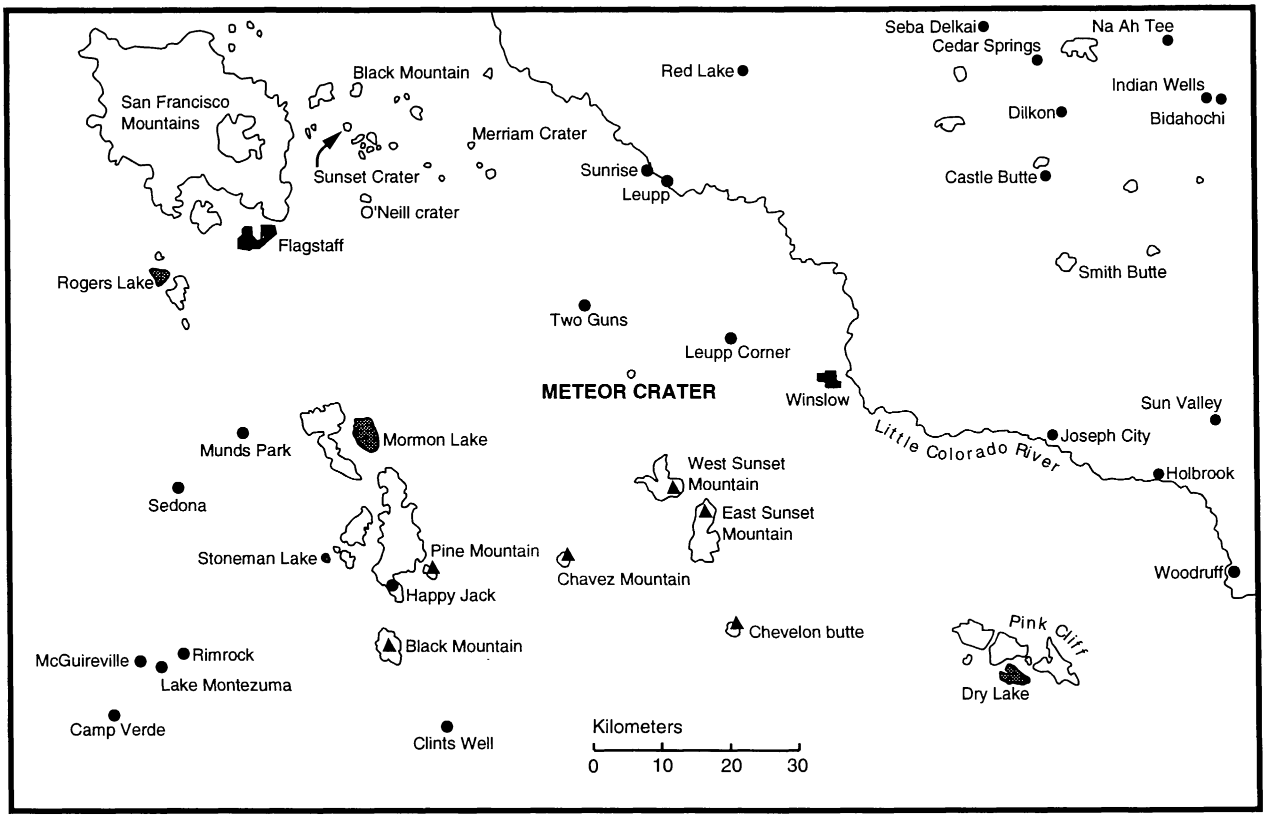

FIG. 6. Map showing the locations of geographic features in the area around Meteor Crater.

(*Hilaria jamesii*), and Indian Rice Grass (*Oryzopsis hymenoides*). The principal shrub is Fourwing Saltbush (*Atriplex canescens*), which is accompanied by lesser amounts of Soapweed Yucca (*Yucca glauca*) (Brown, 1994b).

Junipers (*Juniperus*), locally called cedars, occur inside and on the south rim of the crater (Fig. 8b) and in a bosque on the plain ~7 km south-southeast of the crater. These areas are small patches of what is called the Great Basin Conifer Woodland (Brown, 1994a), which dominates areas west and southwest of the crater at elevations that are ~150 m higher than the Meteor Crater impact site. These communities are open-spaced woodlands of juniper and pinyon (*Pinus*) that rarely exceed heights of 12 m (Brown, 1994a). Understory components usually consist of grasses and shrubs like those in the neighboring Plains-Great Basin Grassland community. For example, near West Sunset Mountain and East Sunset Mountain, the woodland is composed of Rocky Mountain Juniper (*Juniperus scopulorum*), One-seed Juniper (*Juniperus monosperma*), Fourwing Saltbush (*Atriplex canescens*), joint-fir (*Ephedra*), pricklypear (*Opuntia*), and a variety of grasses (Fig. 8c). Apparently, this type of woodland has been invading the Plains-Great Basin Grassland in the vicinity of Meteor Crater during the past 100 years (Brown, 1994b).

Other nearby biotic zones, at higher elevations, include the Rocky Mountain Montane Conifer Forest (Fig. 8d), Rocky Mountain Subalpine Conifer Forest, and Alpine Tundra. The Rocky Mountain Montane Conifer Forest is dominated by Ponderosa Pine (*Pinus ponderosa*) at lower elevations and a mixture of Douglas-fir (*Pseudotsuga menziesii*), White-fir (*Abies concolor*), Limber Pine, and Aspen (*Populus tremoloides*) at higher elevations. The understory in the Ponderosa Pine zone (which is nearest Meteor Crater today) is thin. Where present, however, the understory may consist of shrubs and/or grasses and sedges. Currently, the Rocky Mountain Montane Conifer Forest begins at an elevation between 1980 and 2130 m, ~35 km to the west and southwest of Meteor Crater. Rocky Mountain Subalpine Conifer Forests and Alpine Tundra only occur on the San Francisco Peaks, ~60 to 70 km northwest of the crater.

To the northeast of Meteor Crater, where the elevation decreases towards the Little Colorado River, the flora changes to a Great Basin Desertscrub community, which is also sometimes called the Painted Desert community (Turner, 1994). The vegetation is dominated by either sagebrush (*Artemisia*) or Shadescale (*Astriplex confertifolia*; a saltbush). In the Little Colorado River drainage system, the sagebrush is usually Bigelow Sagebrush (*Artemisia bigelovii*). Other shrubs in this community include Winterfat (*Ceratoides lanata*), rabbitbrush (*Chrysothamnus*), blackbrush (*Coleogyne ramosissima*), Greasewood (*Sarcobatus vermiculatus*), Broom Snakeweed (*Gutierrezia sarothrae*), hopsage (*Grayia*), and horsebrush (*Tetradymia*) (Turner, 1994). A few cacti (*Opuntia* and *Echinocereus*) are also usually present. This community, however, is very young. It appears to have evolved in the last 5000 to 12 000 years (Butler, 1976; Stutz, 1976) and was not likely to have been present at the time of the Meteor Crater impact. That is, this community is probably a consequence of the increasingly dryer conditions that followed the Wisconsin glacial period, conditions which did not exist 50 000 years ago during the middle Wisconsin period.

To determine if the remaining biotic zones existed 50 000 years ago and whether they may have shifted elevation, one needs to study the palynological records in lake sediments and packrat middens of that age. Along the southern edge of the Colorado Plateau, sediments from several lakes have been cored. However, only one of these cores was drilled deep enough to sample sediments deposited ~50 000 years

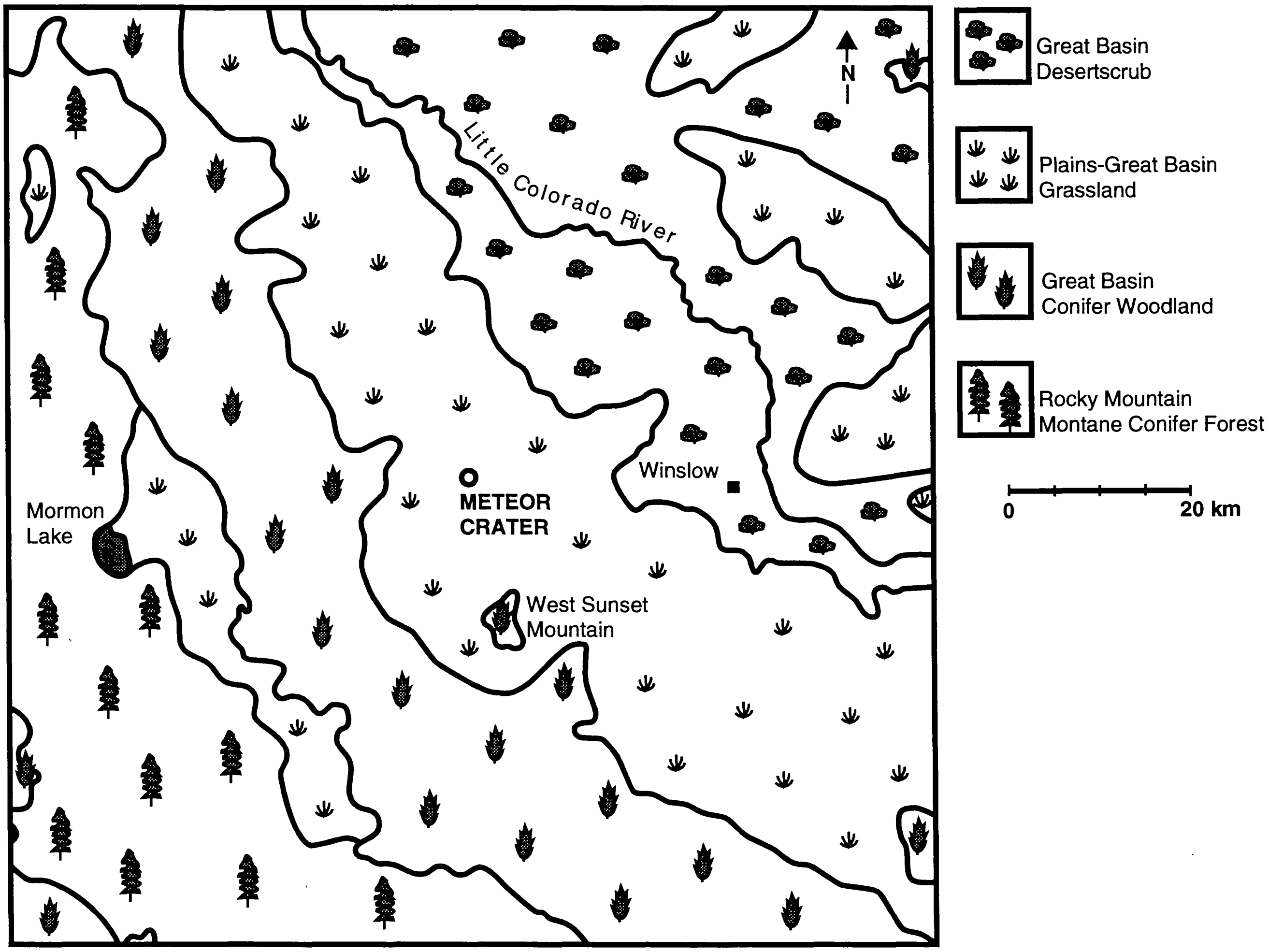

FIG. 7. Map showing the distribution of biotic communities in the area around Meteor Crater. The divisions between the desertscrub, grassland, woodland, and forest zones were extracted from a map of the biotic communities throughout the southwest by Brown and Lowe (1980).

ago. This core comes from Walker Lake, which is a small lake in a volcanic crater in the San Francisco volcanic field (Hevly, 1985). The lake is ~76 km northwest of Meteor Crater and at a higher elevation (2700 m *vs.* 1680 m). Hevly (1985) interprets the pollen record at Walker Lake to mean that conditions 45 000 to 50 000 years ago were quite mesic and that some middle to higher altitude plant species may have been displaced to lower elevations. Displacements on the order of 100 m are suspected (Owen Davis, pers. comm., 1996). (To put this in perspective, vegetation zones moved ~900 to 1200 m downslope during the subsequent full glacial period (Mehringer, 1965; Betancourt, 1990).)

This type of displacement is consistent with an analysis of sediments from Hay Lake, 187 km southeast of Meteor Crater. The lowermost portion of a core from that lake has an estimated age of 45 000 years, based on four radiocarbon ages of younger portions of the core and assumptions of sedimentation and compaction (Jacobs, 1985). In this section of the core, spruce (*Picea*), which is indicative of a subalpine forest, occurs where today ponderosa pine and other trees indicative of a Rocky Mountain Montane Conifer Forest dominate, which indicates that the vegetation zones were displaced downward 45 000 years ago compared to today. If this downward displacement of vegetation zones occurred in the mountains west of Meteor Crater and this displacement also pushed the forests onto the plains, then a juniper and pinyon woodland or possibly a ponderosa pine woodland may have existed where the Meteor Crater impact occurred. However, whether or not downslope displacment of the forests in the mountains pushes woodlands out onto the plains in the basins is controversial. Some investigators believe woodlands were pushed out into the basins during the Pleistocene (Betancourt, 1990), while others do not (Owen Davis, pers. comm., 1996). Consequently, it is unclear whether the biotic community at the site of the Meteor Crater impact 50 000 years ago would have been similar to that of today, a grassland or possibly an open juniper-pinyon woodland, or whether it would have been a juniper-pinyon woodland that was possibly transitional to a conifer forest.

The only other sample of palynological material close in age to the Meteor Crater impact event was found in the Eleana Range at the Nevada Test Site. Two packrat midden samples with a radiocarbon age of 45 000 ± 900 years were collected at an elevation of 1800 m (Spaulding, 1985), which is a little more than 100 m above the elevation of the Meteor Crater impact site. While the pattern of vegetation in the Eleana Range is different from that around Meteor Crater, for that area, the vegetation 45 000 years ago was similar to what is seen today at the same elevation. Thus, in contrast to the interpretation of data from Walker Lake and Hay Lake, there does not appear to be any evidence of a downslope shift of vegetation zones.

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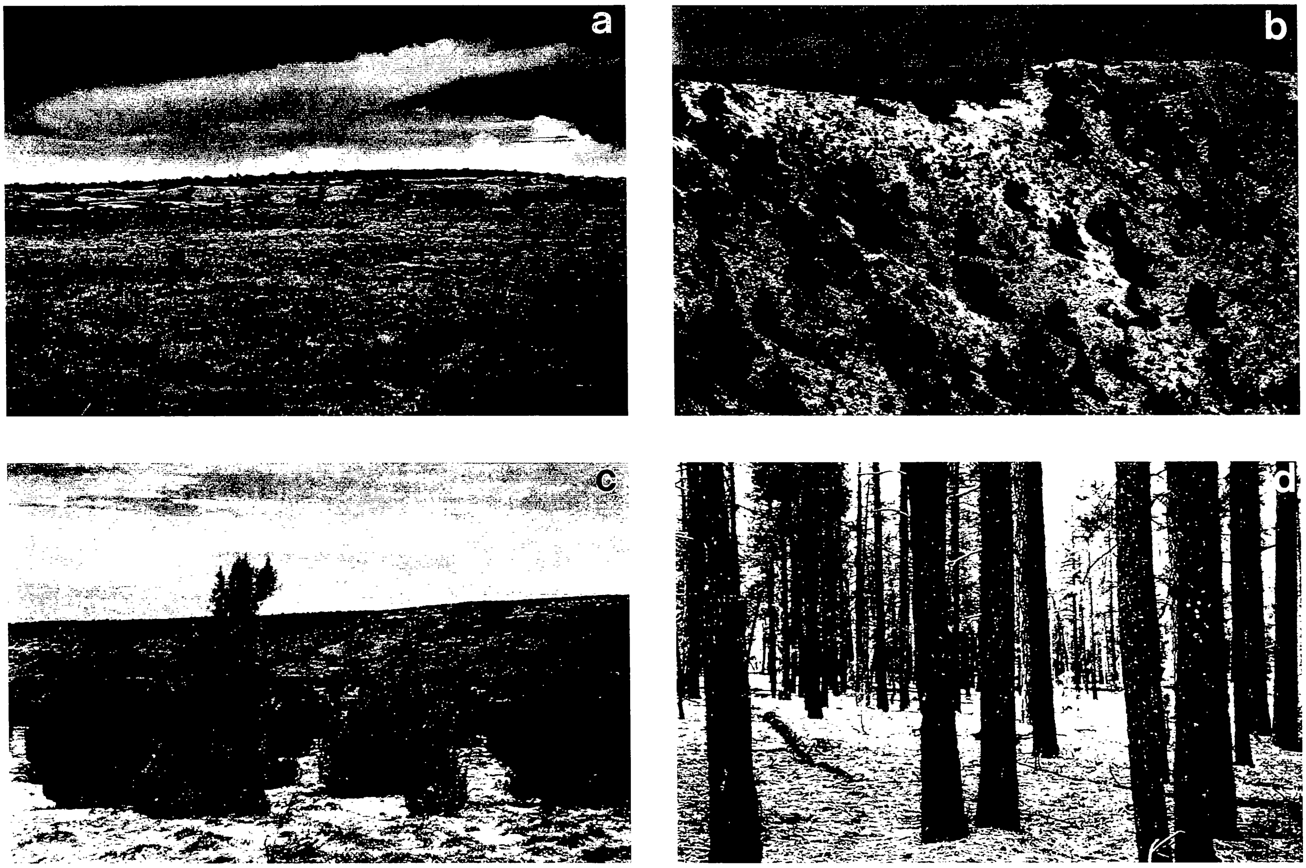

FIG. 8. Photographs of the vegetation as it currently exists in the area of Meteor Crater. (a) The Plains-Great Basin Grassland community immediately north of Meteor Crater. (b) Junipers along the south-southeast rim of Meteor Crater. (c) The Great Basin Conifer Woodland community between West Sunset Mountain and East Sunset Mountain. (d) The Rocky Mountain Montane Conifer Forest ~35 km west-southwest of Meteor Crater.

Based on the relative abundances of pollen taxa, Spaulding (1985) estimates that precipitation was the same then as it is today in that area, although more of the precipitation may have fallen during the summer months than it does today.

The next oldest pollen sample was found in the Sheep Range, which is also in southern Nevada but outside the Nevada Test Site. This sample has an age of 43 700 ± 2300 years and was collected at an elevation of ~1500 m (Spaulding, 1985). This site indicates that a juniper woodland existed where a desertscrub community currently exists. Taken at face value, this would seem to suggest, in contrast to the Eleana Range site, that the woodlands had moved downslope. However, other mesic species were not found at the site, so Spaulding (1985) argues that the vegetation is different, not because of a downslope shift but because a single species, the Utah juniper, no longer exists in the area for nonclimatic reasons.

Based on these four sites, it is unclear whether vegetation shifted downslope or whether it was the same 50 000 years ago as it is today. Because of this uncertainty, it is important to collect additional pollen samples from 50 000 years ago, particularly in the vicinity of Meteor Crater. In the meantime, however, the ramifications of the Meteor Crater impact will be discussed below for two cases: one in which the vegetation 50 000 years ago at the site of the impact was the same as it is today, and one in which there was a downslope shift of woodlands that also extended out onto the plain around Meteor Crater. In either case, there was probably more moisture in the area than currently exists. This is likely because the study of pollen at Walker Lake indicates that conditions were very mesic 50 000 years ago. In addition, lake sediments deposited within Meteor Crater soon after the impact event indicate the water table in the area was 30 m higher than it is today (Shoemaker and Kieffer, 1974; Roddy, 1978), which also implies more mesic conditions.

Megafauna

While the species of flora have remained approximately the same during the last 50 000 years, there has been dramatic turnover in megafauna. In Arizona, the late Pleistocene is a period known for mammoths (*Mammuthus columbi*), mastodons (*Mammut americanum*), large ground sloths (*Nothrotheriops shastensis* and *Glossotherium harlani*), tapirs (*Tapirus merriami*), bison (*Bison bison*), camels (*Camelops hesternus* and *Titanotylopus nebraskensis*), mountain goats (*Oreamnos harringtoni*), and horses (*Equus*). Unfortunately, a description of the megafauna exactly 50 000 years ago does not exist, in part because fossils are so rare, and also because radiometric ^{14}C techniques cannot always be used to reliably correlate fossil sites that are older than ~40 000 years. (Other dating techniques exist that could identify 50 000-year-old ages, namely, the uranium series technique, but they have not been as widely applied.) Thus far, available age determinations suggest that mammoths, sloths, and bison were probably on the Colorado Plateau at the time of impact and that mastodons, mountain goats, camels, horses, and tapirs also may have been on the Colorado Plateau.

Mammoths, in the form of *Mammuthus meridionalis*, first appeared in North America ~1.7 Ma ago and a variety of species seem to have been present up until the terminal Pleistocene extinction (Agenbroad, 1984). The late Pleistocene species that could potentially have been in the vicinity of Meteor Crater is the Columbian mammoth (*Mammuthus columbi*), which was 3.5 to 4 m tall, had a shoulder height of 3.2 to 3.4 m, and weighed more than 9000 kg (Anderson, 1984; Nelson, 1990). Many specimens of the Columbian mammoth have been collected in the Little Colorado River drainage system, including a site only a few kilometers east of the crater near Winslow. The mammoth found near Winslow is 22 360 ± 500 years old and two others in the area are 23 370 ± 1720 and 30 800 ± 1700 years old (Agenbroad and Mead, 1989). All of the other fossil sites are simply constrained to be from the Rancholabrean Age (~500 000 to 11 000 years ago; Fig. 5). If mammoths were present 50 000 years ago, then they most likely would have been living in the grassland community around Meteor Crater because dung samples indicate that they grazed mostly on grass (Gramineae; *e.g.*, *Sporobolus*), sedge (*Carex*), or reed (*Phragmites*), and, to a lesser extent, sagebrush (*Artemisia*), saltbush (*Artiplex*), birch (*Betula*), rose (*Rosa*), and cactus (*Cactaceae*) (Agenbroad and Mead, 1989). In some cases, aquatic species (sedge and reed) dominated the mammoth's diet, which indicates that they also grazed near streams that cut through grassland communities (Davis *et al.*, 1985). Smaller amounts of blue spruce (*Picea pungens*), wolfberry (*Symphoricarpos*), and red-osier dogwood (*Cornus stolonifera*) in dung (Davis *et al.*, 1985) also suggest that the mammoths may have occasionally moved into forest communities.

Mastodons arrived in North America in the middle Miocene and one species, *Mammut americanum*, was present in the Rancholabrean until its extinction ~11 000 years ago (Anderson, 1984). A fossil mastodon has been found near the Little Colorado River drainage system, only a few tens of kilometers north of Meteor Crater, although the age of this particular site is unknown (Nelson, 1990). These animals stood ~2.7 to 3.0 m high at the shoulder and had a total body length of 4.5 m (Anderson, 1984). Where their diet has been studied, mastodons seem to have favored open spruce woodlands, spruce forests, and open pine woodlands where they could feed on twigs and cones of conifers, leaves, coarse grasses, and swamp plants (Anderson, 1984). This diet suggests that mastadons preferred forests and woodlands, which, if woodlands existed where today there is a grassland community, indicates that they may have been present at the impact site 50 000 years ago. Even if the impact site was composed of grasslands, it is still possible that the mastodons were present as indicated by the fossil mastodon found on the plains north of the crater.

Two types of ground sloths lived in the Colorado Plateau region. The Shasta ground sloth (*Nothrotheriops shastensis*) arrived in the region some time before 40 000 years ago based on minimum ages of their dung (Hansen, 1978). A brief report of a 51 000-year-old site has also been published (Nelson, 1990), so it seems likely that Shasta ground sloths were present on the Colorado Plateau at the time of the Meteor Crater impact. (Late Irvington Age fossils have been documented elsewhere in North America (Anderson, 1984), which indicates a possible presence as early as 1.9 Ma ago.) Adult Shasta sloths were ~2.75 m long and weighed between 135–180 kg and 250 kg (Anderson, 1984; Hansen, 1978). They lived in juniper woodlands and montane conifer communities (Thompson *et al.*, 1980) where they browsed and grazed. In one locality, their diet was dominated by desert globemallow (*Sphaeralcea ambigua*), Nevada mormontea (*Ephedra nevadensis*), saltbushes (*Atriplex*), catclaw acacia (*Acacia greggii*), cactus (*Cactaceae*), common reed (*Phragmites communis*), and yucca (*Yucca*) (Hansen, 1978). In general, however, they preferred grazing on fescue (*Festuca*), drop seed grass (*Sporobolus*), reed (*Phragmites*), wheatgrass (*Agropyron*), and sedge (*Carex*), while they browsed conifer (*Pseudotsuga*), globe mallow (*Sphaeralcea*), acacia (*Acacia*), saltbush (*Atriplex*), serviceberry (*Amelanchier*), agave (*Agave*), rose (*Rosa*), and sagebrush (*Artemisia*) (Mead and Agenbroad, 1989).

The Harlan ground sloth (*Glossotherium harlani*) weighed about twice as much as the Shasta sloth and was 3.5 m tall when standing upright to strip leaves from trees (Nelson, 1990). It was present in North America from the Late Blancan through the Late Rancholabrean (Anderson, 1984), or from ~3 Ma to 11 ka ago. Two fossil sites have been found on the Colorado Plateau in northeastern Arizona and a third was found in southern Utah. This sloth is thought to have fed on tree leaves (Nelson, 1990), although specific tree species have not yet been identified.

Bison (*Bison bison*) is the indicator fauna of the Rancholabrean Age (Anderson, 1984), so it was probably present on the Colorado Plateau 50 000 years ago and, like modern bison, lived in large herds. One of the fossil localities of bison is along the Little Colorado River (Nelson, 1990), a few tens of kilometers north of Meteor Crater, but the age of this site is not known. Male and female bison weighed up to 900 kg and 545 kg, respectively, although they diminished in size through the Pleistocene and were, thus, bigger than modern bison (Anderson, 1984; Nelson, 1990). Bison were predominantly grazers but would usually also have some browsing activity in their diet. Drop seed grass (*Sporobolus*) was their favorite grazing material, but brome (*Bromus*), sedge (*Carex*), needlegrass (*Stipa*), ricegrass (*Oryzopsis*), horsetail (*Equisetum*), and wheatgrass (*Agropyron*) were also consumed (Mead and Agenbroad, 1989).

Mountain goats (*Oreamnos harringtoni*) arrived on the Colorado Plateau more than 40 000 years ago (Mead *et al.*, 1987) and were probably present at the time of the Meteor Crater impact event. They lived in a wide range of environments: boreal forests, steep canyons, and open juniper woodlands with desert elements, the latter of which may have included the terrain around Meteor Crater 50 000 years ago. The goats' diet varied seasonally and included both grazing and browsing components. Like modern goats (*Oreamnos americanus*), they had a very diverse diet, although their grazing material was dominated by three-awn (*Aristida*), drop seed grass (*Sporobolus*), fescue (*Festuca*), brome (*Bromis*), sedge (*Carex*), and wheatgrass (*Agropyron*), while their browsing material was dominated by bark, baccharis (*Baccharis*), mountain-mahogany (*Cercocarpus*), a conifer (*Pseudotsuga*), and limber pine (*Pinus flexilis*) (Mead *et al.*, 1987; Mead and Agenbroad, 1989).

It is not clear when camels (*Camelops hesternus* and, less commonly, *Titanotylopus nebraskensis*) evolved or moved into the Plateau region, although fossils as early as Blancan Age (4.3 to 1.9 Ma; Fig. 5) have been found in North America (Anderson, 1984). Their remains have been found at several sites on the Colorado Plateau and elsewhere in Arizona. It appears that they existed in the area until the end of the Pleistocene ~11 000 years ago (Nelson, 1990). *Camelops*, commonly called Yesterday's camel, was just a little larger than the present-day single-humped camels of eastern Asia and North Africa (Webb, 1965), although the *Titanotylopus* was a giant with a shoulder height of ~4.2 m (Nelson, 1990). A detailed study of their diet has not yet been done, but *Camelops* appear to have been browsers and grazers (Webb, 1965). Dung tentatively thought to be

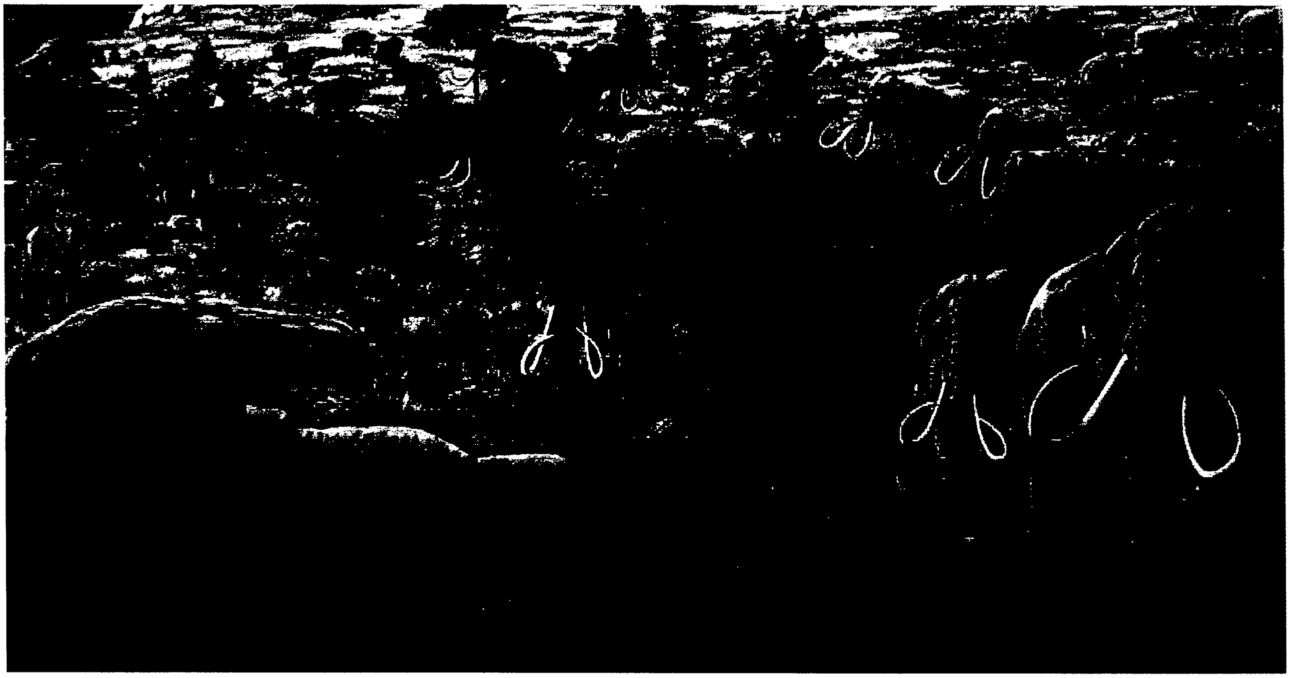

FIG. 9. Painting showing the megafauna that may have existed in a grassland community on the Colorado Plateau 50 000 years ago. From left to right are camels (*Camelops hesternus*), giant short-faced bear (*Arctodus simus*), bison (*Bison bison*), mastodons (*Mammut americanum*), Harlan's ground sloth (*Glossotherium harlani*), and mammoths (*Mammuthus columbi*). Painting by Denny Carley, based on research by Larry Agenbroad and Jim Mead.

from *Camelops* has been collected (Mead and Agenbroad, 1986), but it has not yet been studied. Generally, though, *Camelops* probably inhabited both woodland and grassland communities, and was thus a likely visitor to, or resident in, the area of the impact site.

Horses (*Equus*) and possibly tapirs (*Tapirus merriami*) may have also been present on the Colorado Plateau 50 000 years ago (Nelson, 1990), although much less is known about their distribution and diets. Presumably, smaller fauna like packrats also lived in the area.

THE ENVIRONMENTAL EFFECTS OF THE METEOR CRATER BLAST WAVE

Despite the palynological samples, fossil megafauna, and dietary information in preserved dung described above, there is still a lot we do not know about the flora and fauna on the Colorado Plateau 50 000 years ago. Consequently, any reconstruction of the environment at that time is necessarily uncertain and should be considered tentative. However, with that caveat, the above data seem to suggest that there was a grassland community, like that depicted in Fig. 9, or a juniper-pinyon woodland community in the vicinity of the Meteor Crater impact site 50 000 years ago. The topography was similar but not identical to that seen today. It would have been slightly more rolling and, instead of being cut by steep-walled canyons like Canyon Diablo, the area was probably drained by shallow streams flowing towards the Little Colorado River a few kilometers to the northeast. These streams may have been perennial since there appears to have been a greater amount of moisture at the time. Any mammoths, sloths, bison, and camels in the area may have been grazing on the grass and sedge, or, alternatively, with mastodons, browsing on bushes and woodland trees. In the distant San Francisco Peaks, glaciers may still have been present (*e.g.*, Sharp, 1942), but, if so, they had probably retreated to the high icy ramparts of their source cirques during the interstadial period.

At some point, we do not know if it was day or night, this scene was disrupted by an ~50 m (Roddy and Shoemaker, 1995) iron asteroid hurtling through the sky. Within 30 s, it passed through the entire atmosphere of Earth and slammed into the Colorado Plateau, producing a 20 to 40 MT blast. The plants and animals at ground zero, even the underlying bedrock and most of the asteroid, were vaporized. Bedrock below and around the vaporized zone was then ejected and overturned, burying the topography and anything not already swept away by the air blast out to a distance of 1 to 2 km. As calculated above (Table 1), the air blast would have produced winds in excess of 1000 km/h within 3 to 5 km of the point of impact. These winds likely scoured the surface of loose debris, plants, animals, and soil. At larger distances, the peak overpressure, dynamic pressure, and wind velocity would have gradually diminished, although they would have remained fairly large for distances approaching 20 to 40 km. In some directions, these effects would have been compounded by the effects of the ballistic shock wave.

If a grassland community occupied the impact site, the grass (and possibly soil) would have been stripped away near the crater by the >1000 km/h winds. If the impact site was instead composed of a woodland community, then juniper and pinyon trees would have been flattened over a radial distance of ~14 to 19 km by the blast wave, assuming that these trees have the same drag as an average coniferous forest (Table 2). Because these trees, particularly the junipers, are denser than many coniferous trees, the drag on them may be intermediate between average coniferous forest and deciduous forest. In this case, the range over which trees were largely flattened may have been ~16 to 22 km (Fig. 10). Lesser damage, corresponding to 30% tree fall, would have then extended to ~18 to 26 km. Again, damage at greater distances was probably produced by the ballistic shock wave, but since the trajectory of the iron asteroid is not known, the direction of this damage cannot be estimated.

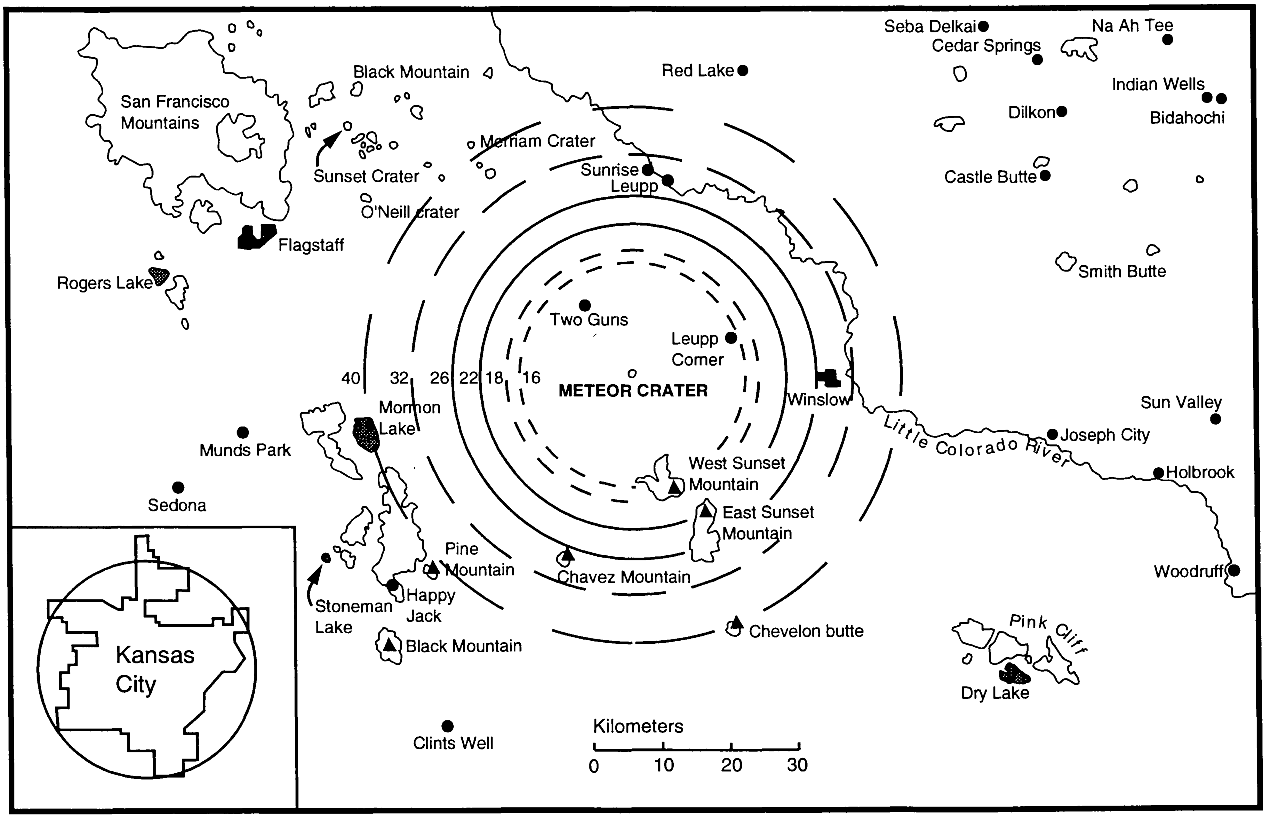

FIG. 10. Map of the Meteor Crater region, illustrating the areas of severe and moderate damage to vegetation. The inner dashed circles represent the diameter of severe (32 km) and moderate (36 km) damage to a woodland assuming a 20 MT blast. The solid circles represent the diameter of severe (44 km) and moderate (52 km) damage to a woodland assuming a 40 MT blast. The outermost dashed circles represent the 64 and 80 km diameter limits of >1 psi peak overpressures for 20 and 40 MT blasts, respectively. For comparison, the area of the Kansas City metropolitan area is shown in the inset with a 40 km diameter circle for scale, corresponding roughly to the mean range of severe to moderate woodland damage calculated for 20 and 40 MT blasts.

The effect of the blast on the megafauna is more sensitive to the details of the pressure pulse than is the effect on vegetation. When the impact shock wave reached each animal, their bodies would have had to endure severe compression and tried to respond to different internal and external pressures. Based on previous analyses of blast injuries (White *et al.*, 1971; Glasstone and Dolan, 1977, pp. 548–552), we know that this would have induced rapid pressure oscillations in air-containing organs and that the passage of the shock wave would have damaged areas between tissues of different densities (*e.g.*, near joints). The results include hemorrhaging and edema in the lungs that may have caused suffocation, air emboli that may have obstructed blood vessels in the heart and brain, and fibrin emboli in the blood that may have damaged the brain and other organs. Among those animals affected, death would have occurred within a few minutes.

The severity of damage to animals around the impact site would have depended in part on the rise time of the pressure pulse, because the shorter the rise time, the harder it is for a body to respond to the difference between external and internal pressures. For this reason, it has long been recognized that nuclear explosions, which have very fast rise times, can produce more damage than conventional chemical explosions. The severity of damage is also a function of the duration of the positive phase of the pressure pulse (Fig. 2). Again, in general, injuries produced by nuclear explosions are more severe than those produced by conventional chemical explosions because the former have much longer pulse durations. The duration of the positive phase in nuclear explosions with yields in excess of 10 kT approaches 1 s or more (Glasstone and Dolan, 1977, p. 551). In contrast, the duration of overpressure in impact events is much shorter, ranging from 0.001 to 0.1 s for events produced by 10 m to 1 km diameter projectiles (Melosh, 1989, p. 42). Consequently, the blast injuries among megafauna caused by the Meteor Crater impact event, which involved a ~50 m projectile, will be slightly less than those associated with nuclear explosions.

Another factor to consider is the effective peak overpressure, which could potentially be more important than either the rise time of the pressure pulse or the duration of the positive phase of the blast wave. Previous analyses of blast injuries indicate that when the positive phase of the blast wave is longer than several tens to a few hundred milliseconds, then the injury caused by the blast is largely a function of the effective peak overpressure (Glasstone and Dolan, 1977, p. 551). Consequently, in the case of nuclear explosions with yields in excess of 10 kT and positive phases approaching 1 s or more, the effective peak overpressure is the more important factor. In the case of the Meteor Crater impact event, in which the duration of overpressure was in the range of tens of milliseconds, the effective peak overpressure would have been an important factor although not necessarily the dominant one. (The effective peak overpressure is similar to the peak overpressure but takes into account the orientation of an animal's body with respect to the blast wave and to any nearby surfaces that can reflect the blast wave. For example, a Shasta ground sloth in an alcove of Moenkopi sandstone would have had to endure a much higher effective peak overpressure than a sloth in an open grassy area.)

The effective peak overpressures that produce lung damage or death have been estimated based on injuries to both large and small animals, including steers, burros, sheep, goats, monkeys, swine, dogs, cats, rabbits, chickens, rats, hamsters, and mice (White *et al.*, 1971). In general, large animals can endure higher overpressures than smaller animals. For example, for a 0.005 s pressure pulse, a population of sheep can withstand 4× greater peak overpressure than can mice (White *et al.*, 1971, p. 59). All of the megafauna that existed 50 000 years ago fall into the broad category of large mammals and will be treated similarly here. There is too much uncertainty in the overpressure effects, as well as the physiologies of 50 000-year-old megafauna, to scale them to specific species. Consequently, the overpressures that produce lung damage or death will be based on average values for large mammals, including humans (Glasstone and Dolan, 1977, p. 552). Based on these studies, the threshold for lung damage is 8 to 15 psi, while severe lung damage occurs between 20 and 30 psi. The threshold for death is 30 to 50 psi and increasingly larger fractions of a population will be killed with greater overpressures. Fifty percent of a population will be killed between 50 and 75 psi and 100% of a population will be killed between (or in excess of) 75 to 115 psi. If one scales these figures to radial distances of peak overpressures around the Meteor Crater impact site (Table 1, Fig. 3), they suggest 100% lethality within a radius of 2.7 to 3.2 km and lung damage within a radius of 6.5 to 9.3 km, assuming a 20 MT explosion (Table 3). In the case of a 40 MT explosion, these distances increase to 3.4 to 4.1 km and 8.1 to 11.7 km, respectively. Animals at larger distances could also have been affected if they were near rocky outcrops or other types of reflecting surfaces that would have increased the effective peak overpressure.

In addition to these direct blast injuries, animals also would have been injured when the blast wave hit them, accelerated their bodies to velocities on the order of a few to tens of kilometers per hour, and then slammed them back onto the ground or they collided with other objects. Field tests using animal cadavers of different sizes were once conducted to test the survivability of animals and humans when subjected to these types of displacements (Glasstone and Dolan, 1977, pp. 554 and 558–559). For humans, or animals the size of humans, it is likely that casualties due to displacement would occur within 16 to 24 km of the Meteor Crater impact site, depending on whether the terrain was a grassland community (without obstacles) or a woodland community (with obstacles) (Table 4). A 50% casualty rate would occur between 9 and 14 km. In comparison to humans, mammoths and most other megafauna on the Colorado Plateau 50 000 years ago are larger and, thus, their blast cross sections would have been greater. However, most of these animals also had more inertia, which would have variously offset the influence of their greater cross sections. Consequently, the estimated distances for casualties in Table 4 should be considered estimates whose exact values depend on each type of animal.

TABLE 3. Estimated radial distances and areas over which serious injuries and death among human-sized animals were caused by the direct blast effects of the Meteor Crater impact event.*

		20 MT		40 MT	
Biological Effect	Effective Peak Overpressure (psi)	Radial Distance (km)	Area (km^2)	Radial Distance (km)	Area (km^2)
Lung Damage					
Threshold	8–15	6.5–9.3	130–270	8.1–11.7	210–430
Severe	20–30	4.9–5.9	75–110	6.2–7.4	120–170
Lethality					
Threshold	30–50	3.8–4.9	45–75	4.8–6.2	72–120
50%	50–75	3.2–3.8	32–45	4.1–4.8	52–72
100%	75–115	2.7–3.2	23–32	3.4–4.1	37–52

*Estimates of the effective peak overpressures needed to produce the listed biological effects are strictly for fast-rising, long-duration pressure pulses like those produced by nuclear explosions (Glasstone and Dolan, 1977, p. 552). In an impact event, the duration of the positive phase of the blast is shorter, which means the effective peak overpressures should be considered minima and the corresponding radial distances and areas maxima. On the other hand, the radial distances and areas correspond to peak overpressures, not effective peak overpressures. Consequently, these distances underestimate the range of effects for animals near reflecting surfaces like outcrops of Moenkopi sandstone.

The blast wave would have also picked up broken branches, rocks, and other types of missiles that could impale, lacerate, or traumatize animals. It is much harder to assess the injuries and deaths caused by this blast effect, because the experimental database mostly involves broken glass, which would not have been a factor in a natural setting 50 000 years ago. The results of only a single experiment using stone projectiles have been reported (Glasstone and Dolan, 1977, p. 554). This study indicates that a peak overpressure of 8.5 psi can accelerate stones with a median mass of 0.22 grams (pea-sized or half-centimeter sized pebbles) to a median velocity of 314 km/h. The density of stones carried by this type of blast can be as high as 430 m^{-2}. It is not clear how fast other objects (larger stones, sticks, *etc.*) can be carried, nor have specific injury and casualty rates been estimated. Nonetheless, one can imagine that if a fusilade of ~1500 pea-sized stones hit a standing mammoth at 314 km/h, it could blind, if not kill, the animal. Based on these data and the range of peak overpressures expected around the Meteor Crater impact site (Table 1), it seems that additional injuries may have been caused by missiles over distances of at least 10 to 13 km from the impact site. The distribution of Canyon Diablo meteorites around Meteor Crater (Barringer, 1909; Mason, 1962) indicate that additional iron projectiles rained down within the inner 9.5 km of this area after the blast wave passed.

Finally, it is possible that these direct and indirect blast effects may have been compounded by thermal radiation. In the case of the 1908 Tunguska event, the cambium on the sides of trees facing the

TABLE 4. Estimated casualties for randomly oriented human-sized animals produced by physical displacment following the Meteor Crater impact event.*

	20 MT Radial Distance (km)	40 MT Radial Distance (km)
Grassland community		
1% casualties	15.8	20.8
50% casualties	8.7	11.4
Woodland community		
1% casualties	17.9	23.7
50% casualties	10.9	14.3

*Estimates are scaled from casualty estimates for nuclear blasts (Glasstone and Dolan, 1977, p. 558–559). The estimates for the grassland community correspond to previous estimates for displacements in open terrains, while the estimates for the woodland community correspond to previous estimates for displacements near structures.

explosion were damaged for several kilometers around the epicenter (Florenskiy, 1963). These injuries, sometimes associated with charred branches, are thought to have been produced by intense thermal emission or flash fire (Florenskiy, 1963; Krinov, 1966). In some areas, the thermal emission apparently ignited vegetation, because a forest fire, largely confined to tree tops, burned for several days after the impact event (Florenskiy, 1963). Approximately 200 km^2 of the Siberian taiga were consumed by the fire (Vasilyev, 1996). Similar thermal emissions during the Meteor Crater impact event may have caused range fires or forest fires, although no direct evidence of fire has yet been found.

CONCLUSIONS

If one combines the direct and indirect effects of the blast wave, it seems likely that the vegetation would have been almost completely destroyed over an area of 800 to 1500 km^2 around the Meteor Crater impact site and damaged over an additional area of 200 to 600 km^2 (Fig. 10). Likewise, the megafauna within 3 to 4 km of the impact site (or an area of ~30 to 50 km^2) would have probably been killed. Severe injuries that may have crippled their ability to feed and defend themselves may have affected the megafauna to distances of ~16 to 24 km (or an area of 800 to 1800 km^2). Clearly, the impact would have been devasting to the local population of plants and animals. These effects, however, would not have produced any extinctions and most of the area was probably recolonized within a few to ~100 years. Indeed, new species may have joined the community because of the additional habitat provided by the springs and lake inside the crater.

Several issues still need more attention. First, a better record of the flora that existed in the area before and after the impact 50 000 years ago is needed. There are several lakes on the Colorado Plateau near Meteor Crater and lake sediments within the crater that may contain 50 000-year-old sediment records; hopefully these will eventually be cored and examined. This is particularly important if Meteor Crater is truly going to be used as a baseline for illustrating the cause and effect relationships between 20 to 40 MT impact events and the environment. Second, a better record of the megafauna that existed 50 000 years ago is needed, but this may be difficult to obtain in a region with little sedimentation. Third, to assess the added effects of the ballistic shock wave, we need to determine if the iron asteroid came from the northwest, the southeast, or some other direction. And finally, a model of the thermal emission associated with impact events would provide better estimates of the severity of burn injuries and postimpact fires. These factors will, ideally, be eventually combined in a detailed computational simulation of the impact event which could illustrate more clearly the shock intensities, pulse duration, *etc.* around the impact site.

As shown in Fig. 10, Meteor Crater occurs in an area that now contains several small towns and a small city. If the impact were to occur today in the same location, it would probably produce human casualties. Of course, when compared to other areas of the world, this region of the Colorado Plateau is relatively uninhabited. In a more densely populated area, the effects of an impact this size could be even more catastrophic. For example, if one superimposes the effects of the Meteor Crater impact event on Kansas City (Fig. 10 inset), one sees that the blast wave would have completely destroyed the entire metropolitan area. Almost all of the metropolitan area is within a 40 km diameter region that corresponds roughly to the mean of severe to moderate woodland damage calculated for 20 and 40 MT blasts. The peak overpressures within this region are 4 psi or greater, which would have the capacity to shatter glass windows, shatter corrugated asbestos siding, cause connection failure and buckling of corrugated steel or aluminum paneling, shatter 8 to 12 in thick concrete or cinder-block walls, cause some 8 to 12 in thick brick walls to collapse, and blow out wood siding panels used in house construction (Glasstone and Dolan, 1977, p. 221). Reinforced structures would fair better, but the damage would still be extensive. Tens of thousands to hundreds of thousands of people (even millions in more densely populated areas) could be killed in an impact event of this size if it occurred unexpectedly.

When gauging these effects and the possibility that they may occur in modern times, it is important to recall that Meteor Crater is a relatively small impact event and, thus, the type of event that is relatively common. As described in the introduction, current estimates suggest that an impact event comparable to that which produced Meteor Crater occurs, on average, every 1600 years somewhere on Earth or about every 6000 years in a continental region. This is a time scale that is both meaningful and memorable in terms of human history and should probably be kept in mind when evaluating the hazards of objects in or entering near-Earth space.

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