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# A model for the geomorphology of the Carolina Bays

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ABSTRACT

Geometrical analysis of the Carolina Bays using Google Earth in combination with LiDAR data makes it possible to postulate that the bays formed as the result of impacts, rather than from eolian and lacustrine processes. The Carolina Bays are elliptical conic sections with width-to-length ratios averaging 0.58 that are radially oriented toward the Great Lakes region. The radial distribution of ejecta is one characteristic of impacts, and the width-to-length ratios of the ellipses correspond to cones inclined at approximately 35°, which is consistent with ballistic trajectories from the point of convergence. These observations, and the fact that these geomorphological features occur only on unconsolidated soil close to the water table, make it plausible to propose that the Carolina Bays are the remodeled remains of oblique conical craters formed on ground liquefied by the seismic shock waves of secondary impacts of glacier ice boulders ejected by an extraterrestrial impact on the Laurentide Ice Sheet. Mathematical analysis using ballistic equations and scaling laws relating yield energy to crater size provide clues about the magnitude of the extraterrestrial event. An experimental model elucidates the remodeling mechanisms and provides an explanation for the morphology and the diverse dates of the bays.


## 1. Introduction

The Carolina Bays are shallow elliptical depressions with raised rims that occur on the Atlantic Coastal Plain along the east coast of the United States. The geometrical elliptical shape of the bays and their particular orientation first became apparent from aerial photographic surveys. Because the bays have very regular shapes that are very different from other geological structures, Melton and Schriever (1933) suggested that they had been created by a swarm of oblique meteorite impacts. However, meteorite fragments are not common in the region where the bays are located, and the alignment of the bays varies by latitude instead of being parallel as would have been expected for impacts by extraterrestrial objects. The lack of impact evidence led to hypotheses of geological mechanisms that could have produced the bays, such as the modification of karst-like depressions by the action of water and wind (Johnson, 1942). In 1975, Eyton and Parkhurst proposed that the Carolina Bays could have formed by air blasts from explosions of fragments of a disintegrating comet. Dating studies of the bays have concluded that the bays were formed over an extended period of time during the Late Pleistocene starting approximately 140,000 years ago (Brooks et al., 2010), thus precluding the possibility that all the bays formed at the same time.

Zanner and Kuzila (2001) reported that Nebraska's Rainwater Basins, which they characterized as eolian blowouts, had many characteristics in common with the Carolina Bays, except that they were oriented from northeast to southwest instead of from northwest to southeast. The Nebraska Rainwater Basins are not as well known as the Carolina Bays but their elliptical shape is so similar that it is necessary to consider that they formed contemporaneously with the Carolina Bays by the same mechanisms. Firestone et al. (2007) proposed that an extraterrestrial object exploding over North America 12,900 years ago contributed to the megafaunal extinctions in North America and partially destabilized the Laurentide Ice Sheet and the thermohaline circulation in the northern Atlantic, thus triggering the Younger Dryas cooling event. The date of the event has been updated to 12,800 cal. BP by Kennett et al. (2015). In a subsequent paper with images of the Carolina Bays and the Nebraska Rainwater Basins, Firestone (2009) stated that the strikingly regular orientation of the bays was consistent with their formation by a shockwave coming from the Great Lakes. Firestone (2009), Firestone et al. (2010) also reported that impact material was found throughout the Carolina Bay sediments whereas these markers were found only in a thin layer elsewhere at the Younger Dryas Boundary; this can be interpreted as an indication that the bays are impact related. Pinter et al. (2011) wrote a “requiem” paper about the Younger Dryas Impact Hypothesis concluding that the evidence for an extraterrestrial impact could not be corroborated and that terrestrial mechanisms could account for the geological formations.

## 2. New impact evidence

The question of whether an extraterrestrial impact occurred at the onset of the Younger Dryas has been a contentious issue because the microspherules, nanodiamonds and other materials that Firestone

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proposed as indicators of an impact have not been recognized as definitive evidence of an impact. Some of the accepted markers of an extraterrestrial event are impact craters with raised rims, meteorite fragments, shocked minerals with planar deformation features caused by the high pressure of a hyperspeed impact, and siderophile elements, such as iridium, that are more common in extraterrestrial objects than in the minerals found in the Earth. Nevertheless, additional reports of microspherules attributed to an extraterrestrial impact at the Younger Dryas Boundary have been reported (Israde-Alcántara et al., 2012; LeCompte et al., 2012).

The support for an extraterrestrial impact was strengthened when analysis of the Greenland Ice Sheet Project 2 (GISP2) ice core by Petaev et al. (2013) found a large platinum anomaly at the Younger Dryas Boundary. The increased platinum was not accompanied by a prominent iridium anomaly, and the ratio of platinum to iridium exceeded those of known terrestrial and extraterrestrial materials. Petaev and his colleagues concluded that the results hinted at an extraterrestrial source of platinum, possibly from an iron meteorite of low iridium content that would be unlikely to result in the airburst proposed by Firestone. An iron meteorite could have survived the passage through the atmosphere, making it possible to consider that material ejected from the primary impact site would have produced secondary impacts.

## 3. Greater availability of good quality imagery

The study of the shapes of the Carolina Bays was limited to photographic aerial surveys prior to the development of LiDAR. The Carolina Bays are obscured by a patchwork of farmed fields and vegetation in aerial and satellite images. Digital Elevation Maps (DEMs) using LiDAR-derived data accentuate the visual representation of these shallow basins. A survey of Carolina Bays by Davias and Gilbride (2011) used a wide range of resources, including 1/9 arc-second elevation data from the USGS Seamless Server, NOAA Digital Coast, South Carolina Department of Natural Resources (DNR), Nebraska DNR, and Virginia's College of William and Mary. The data was processed with the Global Mapper commercial GIS program to visualize the terrain as HSV-shaded images saved as Keyhole Markup Language (KML) tiled data files. The KML files can be directly imported into Google Earth to align the images on a virtual globe from which it is possible to capture geospatial metrics. The Carolina Bay survey now contains data for approximately 45,000 bays (Davias and Harris, 2015).

LiDAR has revealed very clear images of the bays without interference from vegetation, and it is evident that the terrain consisting of unconsolidated material is completely covered with bays, and that many bays overlap while maintaining their elliptical shape. The only places without bays are the streambeds where water erosion has washed away evidence of their existence (Fig. 1).

## 4. Bay orientations

Early studies of the Carolina Bays using aerial images revealed that the bay orientations differ by latitude. Johnson (1942) used photographs from Fairchild Aerial Surveys, Inc., the U.S. Department of Agriculture, the Agricultural Adjustment Administration and the U.S. Geological Survey. The scarcity and inaccuracy of topographic maps for North Carolina, South Carolina and Georgia constrained Johnson to select only 381 bays that could be used to determine axial direction. Johnson found that the northernmost bays were oriented primarily toward the northwest, whereas the southernmost bays were oriented more toward the north. A separate study by Eyton and Parkhurst (1975) of 358 bays in Virginia, North Carolina, South Carolina and Georgia concluded that the bays display radial alignment with an apparent focus in either southern Ohio or Indiana.

Davias and Gilbride (2010, 2011) established a survey of thousands of Carolina Bays and Nebraska Rainwater Basins using LiDAR data and

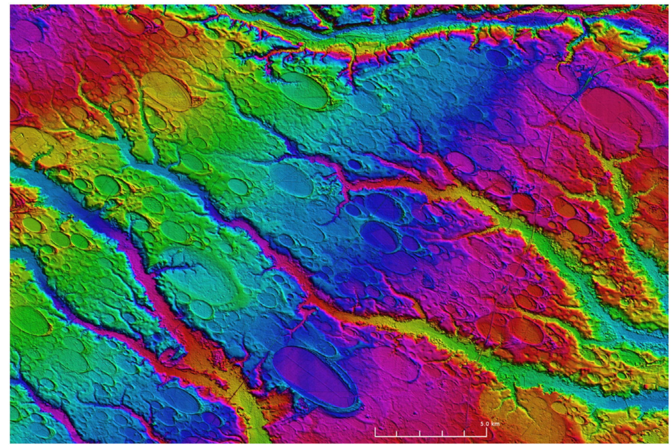

**Fig. 1.** Carolina Bays, 25 km southwest from Fayetteville, NC (Lat. 34.88, Lon. −79.05). The image covers an area of ~550 km$^2$ with an elevation of 76 m above sea level in the upper left and 16 m in the lower right. The image was prepared with the Global Mapper GIS application using 1/9 arc-second LiDAR from the USGS National Elevation Dataset (NED). A color gradient can be used to visualize the terrain elevation.

Google Earth. Using great circle trajectories adjusted for the Coriolis Effect, Davias and Gilbride identified Saginaw Bay in Michigan as the intersection point of the projections of the major axes of the bays. In a subsequent paper, Davias and Harris (2015) provided a trigonometric equation that can predict the azimuthal orientation of 45,000 bays in Nebraska and the East Coast of the USA based only on their geographical coordinates. Davias and Harris (2015) also noted that the equidistance between the Carolina Bays and the Nebraska Rainwater Basins from the proposed impact point in Saginaw Bay suggests that an extraterrestrial impact at a low angle created an oval-shaped crater and a butterfly ejecta pattern. This butterfly pattern could merely be a peculiarity due to the lack of terrain suitable for the formation of elliptical bays between Nebraska and the East Coast.

Before the availability of Google Earth, researchers had not been able to find a point of convergence for the Carolina Bays because they worked with flat maps, and they did not take into consideration the Coriolis Effect corresponding to the time of flight of the ejecta. The axial orientation of the Nebraska Rainwater Basins was also important for determining the point of convergence.

## 5. Bay geometry

Aerial photographs from the 20th century showed the remarkable elliptical symmetry of many Carolina Bays, but interference from vegetation and the patchwork of farmed fields made it difficult to appreciate the extent of this regularity. Consequently, the elliptical shapes of the bays were assumed to be atypical features that formed fortuitously by variable lacustrine and eolian mechanisms (Johnson, 1942).

The consistent shape and orientation of the Carolina Bays was what first attracted the attention of geologists. However, the description of the bays in the published literature seems to be biased according to the hypothesis of formation favored by the authors. Proponents of impact hypotheses (Melton and Schriever, 1933; Prouty, 1952) generally describe the bays as elliptical; they provide graphs of the ellipticity of the bays and relate the shape of the bays to the angle of impact based on conic sections. Ellipticity is defined as the length minus the width, divided by the length. Proponents of eolian and lacustrine processes, on the other hand, characterize the Carolina Bays as oval and do not attribute significance to their consistent shape (Johnson, 1942) or they do not mention the geometric shape of the bays at all (Brooks et al., 2010). Zanner and Kuzila (2001) described the remarkable similarity of the Nebraska Rainwater Basins to the Carolina Bays, and characterized the Nebraska features as oval shaped blowouts.

This dichotomy in the description of the bays brings up the question of whether the Carolina Bays and the Nebraska Rainwater Basins are just ovals with indeterminate curvature or whether they are true ellipses in the mathematical sense. Fortunately, this question can be settled by comparing the geometry of the bays to mathematical ellipses.

The method for testing whether a Carolina Bay is elliptical consists of three steps: 1) measure the width and the length of the proposed Carolina Bay, 2) create an ellipse with the same width-to-length ratio as the target bay, and 3) scale and rotate the ellipse to try to match the bay as precisely as possible. For this testing procedure, the rims are considered to be external to the presumed conical cavity corresponding to the bay, and they are not included in the measurement of the bay or the fitting of the ellipse. The matching depends on the size, placement and orientation of the ellipse. The goodness of fit can be made visually or by quantitative measures such as least squares fitting once the margins of the bay have been identified accurately.

Problems related to measuring the bays and fitting the ellipses arise from irregularities in the shapes of the bays due to distortions caused by bay overlaps, geological surface deformations, water erosion and encroachment of the bays by eolian deposits. The determination of the bay boundaries can be subject to interpretation, as pointed out by Johnson (1942). Even under ideal conditions, the identification of craters is difficult. A project to map Moon craters by overlaying them with circles found 10–35% dispersion among experts in the number of craters found, even though the experts were more consistent than volunteers in identifying craters (Robbins et al., 2014). The fitting of ellipses for the Carolina Bays is even more difficult because it requires the extra step of determining the axial orientation. In spite of this, it is possible to conclude that the prototypical shape of the Carolina Bays is elliptical. An examination of a sample of Carolina Bays and Nebraska Rainwater Basins with clearly defined rims showed that they have average width-to-length ratios of $0.58 \pm 0.05$, and that the aspect ratios of the bays in the Carolinas and Nebraska are statistically indistinguishable (Zamora, 2015). The width-to-length ratio of 0.58 corresponds to the average ellipticity reported by Prouty (1952) for large bays in Marion and Darlington counties, South Carolina. Each bay can be precisely fitted with an ellipse whose ratio of minor to major axis corresponds to the dimensions of the bay as illustrated in Figs. 2 and 3. The large bays are much bigger than Meteor Crater in Arizona, which has a diameter of 1.2 km.

Ellipses are mathematical conic sections formed by the intersection of a plane and a cone. The elliptical geomorphology of the Carolina Bays and the Nebraska Rainwater Basins can be explained if the bays originated from slanted conical cavities that were later remodeled into shallow depressions by geological processes. A width-to-length ratio

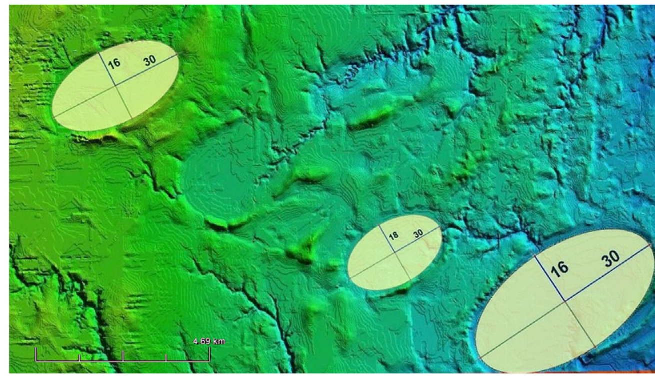


**Fig. 3.** Nebraska Rainwater Basins fitted with ellipses. (Lat. 40.545, Lon. −98.107) The center of the image is on farmland 5 km northwest of Clay Center, Nebraska. The small bay in the center has a length of 3.1 km and no smaller bays are visible.

of 0.58 corresponds to a cone inclined at 35° using the relationship $\sin(\theta) = W/L$. The proposed conical cavities could have been made by impacts of material ejected at approximately 35° in ballistic trajectories from the point of convergence in the Great Lakes Region. The small variations of the width-to-length ratio correspond to slightly different angles that are consistent with possible ballistic trajectories.

The LiDAR images also reveal that some terrains do not have elliptical bays. Davias and Harris (2015) describe six archetype bay shapes that may be determined by the geological characteristics of the terrain. The thickness of the layer of unconsolidated material required to produce an elliptical bay can be estimated by the formula $\tan(\theta) \times L/2$, where L is the length of the major axis and $\theta$ is the angle of inclination. A conical cavity inclined at 35° corresponding to a bay with a major axis of 400 m would require a layer of unconsolidated material with a depth of approximately 140 m.

In general, bays that are not elliptical today may have started as elliptical features that were modified after their formation by erosion or ground movement. Fig. 2 shows many small bays in North Carolina that are on the verge of disappearing due to erosion. The small bays that look like dimples are generally on farmland that gets plowed every year. This ground will eventually be leveled by the frequent human activities of tilling and irrigating the soil, bioturbation by crops and fauna, and by natural environmental erosive processes of rainfall and wind. Fig. 3 shows Nebraska Rainwater Basins that were recognized as analogous to the Carolina Bays by Zanner and Kuzila (2001). The main geological difference noted by these researchers was that cores from Nebraska indicated a sandy landscape buried by loess. If the Carolina Bays and Nebraska Rainwater Basins formed contemporaneously, the lack of small bays and the extensive modification of the large bays in Nebraska indicate that the Nebraska features were subjected to more vigorous erosive processes than the Carolina Bays. The preservation of the Carolina Bays may be due in part to highly permeable ground that allows water to pass quickly below the surface and then flows through underground aquifers. The Nebraska Rainwater Basins are on abandoned Platte River fluvial sand situated on topologically irregular terrain that is more likely to channel water along the surface thus causing greater erosion. Non-elliptical bays are likely to occur in terrain that was unsuitable for the formation of conical cavities due to insufficient depth of unconsolidated sediment or because the water table was too deep for the ground to be liquefied. Fig. 4 shows Carolina Bays on the Delmarva Peninsula that are approximately circular, as would be expected for impacts on a surface with insufficient depth of unconsolidated material.

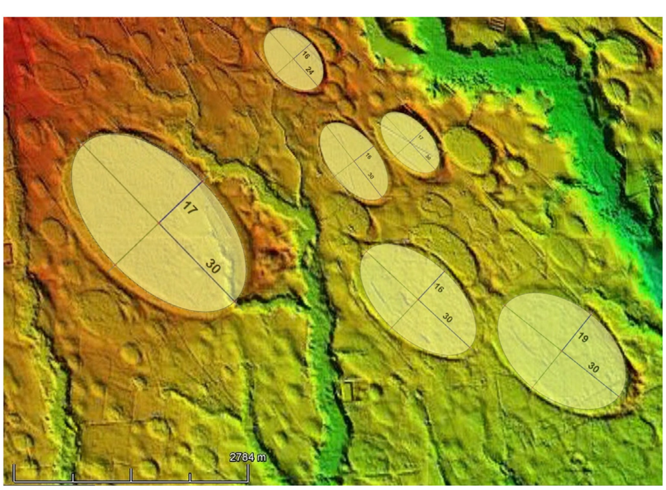


**Fig. 2.** Carolina Bays fitted with ellipses. (Lat. 34.833, Lon. −79.225) The center of the image is 4 km northwest of Red Springs, North Carolina. Small bays with lengths of 100 to 200 m appear as dimples with indistinct rims.

## 6. The Glacier Ice Impact Hypothesis

The Carolina Bays have no evidence of meteorites, petrographic shock metamorphism or enrichment by siderophile elements, so they

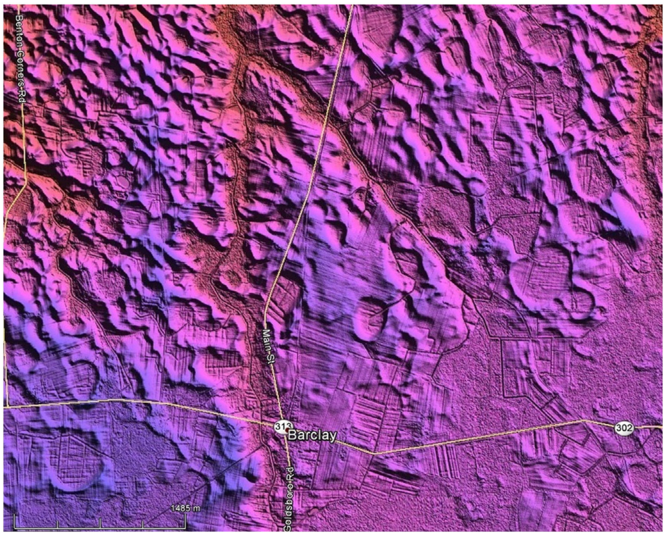


**Fig. 4.** Bays near Barclay, MD on the Delmarva peninsula. (Lat. 39.15933, Lon. −75.85541) The circular shape of the bays may be due to insufficient depth of unconsolidated material that prevented the formation of conical cavities. Circular bays are also found further south in the peninsula near Mappsville, VA.

were definitely not formed by impacts of extraterrestrial objects. However, the bays have raised rims, which is a characteristic of impacts. Unlike karst processes that produce cavities by dissolution, impact cratering displaces material laterally by horizontal compressive forces and ejects debris ballistically to produce stratigraphically uplifted rims around the cavity (Melosh, 1989). The objective of the Glacier Ice Impact Hypothesis is to examine the characteristics of the Carolina Bays and Nebraska Rainwater Basins to determine whether these geomorphological features could have been created by secondary impacts from terrestrial material, such as glacier ice, ejected by an extraterrestrial impact.

The Laurentide Ice Sheet covered the convergence point determined by Davias and Harris (2015) in Saginaw Bay with a thickness of approximately 1500 to 2000 m of ice during the Pleistocene (Dyke et al., 2002). An impact by a meteorite at this location would have ejected chunks of ice in ballistic trajectories, and the heat of the impact would have melted some ice to produce water and steam. The Glacier Ice Impact Hypothesis describes four processes that must have occurred in a specific sequence for the creation of the Carolina Bays.

### *6.1. Extraterrestrial impact ejects glacier ice boulders in ballistic trajectories*

Experiments of high-speed impacts on ice sheets using NASA"s Ames Vertical Gun demonstrate that ice shatters when a projectile hits it. Pieces of ice are ejected radiating from the impact site in ballistic trajectories and the icy layer reduces the extent of subsurface damage (Stickle and Schultz, 2012). If the Carolina Bays were created by secondary impacts of glacier ice ejected by an extraterrestrial impact on the Laurentide sheet, the velocity needed to launch the ice projectiles can be calculated using the ballistic equation $D = (v^2/g)\sin(2\theta)$, where g is the acceleration of gravity. An ice boulder ejected at an angle $\theta$ of 35° from Michigan to the South Carolina seashore would require a launch speed v of approximately 3.6 km/s to cover the distance D of 1220 km.

Substituting distances between 1000 and 1500 km, and angles between 35 and 45° in the formula yields launch speeds of the ejected glacier ice boulders in the range of 3 to 4 km per second. The time of flight T and the maximum height H of the trajectories are given by the equations $T = (2v/g)\sin(\theta)$ and $H = v^2\sin^2(\theta)/2\,g$. Using the same range of distances and launch angles, the times of flight would vary from approximately 6 to 9 min, and all the ballistic trajectories would be suborbital space flights with maximum heights from 150 to 370 km above the surface of the Earth. The atmosphere only extends to 100 km above sea level, so a substantial portion of the trajectory of the ice boulders would have been in the vacuum of space. Some of the projectiles would have broken up during re-entry and produced multiple impacts. Since some Carolina Bays have been found as far south as the Georgia-Florida border, the distal ejecta of the extraterrestrial impact covered approximately an area with a radius of 1500 km from the impact point. The bombardment by the ejected ice boulders lasted for about 9 min after the extraterrestrial impact.

Kennett et al. (2015) and Firestone et al. (2007), Firestone (2009), Firestone et al. (2010) have reported evidence of widespread biomass burning and the emplacement of a black mat at the Younger Dryas boundary. Firestone et al. (2007) stated that an impact by single or multiple objects could have created fireballs that would have ignited a forest in seconds. Could the extraterrestrial impact being considered here have caused a major burning event? A comet at a speed of 50 km/s would traverse the atmosphere vertically in 2 s generating a very intense flash. An asteroid at a speed of 17 km/s would generate a somewhat less intense flash lasting approximately 6 s. An oblique approach by the extraterrestrial projectile would substantially increase the time of intense radiation capable of carbonizing organic material. Any fauna in the line of sight of the incandescent projectile would be burned or disabled, contributing to an extinction event. Some of the fires started by the passage of the projectile would be extinguished by the air blast of its shockwave. The biomass burning would have occurred during the passage of the projectile through the atmosphere and its initial contact with the Laurentide ice sheet. The greatest charring would be under the path of the fireball.

How could the ejected ice boulders survive ablation during their transit? A numerical model indicates that an impact by a kilometer-size projectile would have moved the atmosphere, as well as the mass of ejecta to the rarefied upper atmosphere where even fine ejecta move more or less ballistically (Shuvalov and Dypvik, 2013). The ballistic trajectories of the ice boulders were all suborbital space flights with a significant portion of the flight in the vacuum of space where ice would not be subject to ablation. However, during re-entry, the ice boulders would have experienced ablation, collisions, fragmentation and atmospheric drag causing the smaller projectiles to impact at more vertical angles than the larger projectiles (Melosh, 1989). Considering that the Carolina Bays were produced by a saturation bombardment of glacier ice projectiles, the close proximity of the projectiles as they re-entered the atmosphere could have decreased ablation for the projectiles that traveled behind others. Drafting or slipstreaming occurs when moving objects align in a close group thereby reducing the overall effect of drag by exploiting the lead object's slipstream. The effect of atmospheric drag was reported by Melton and Schriever (1933) and Prouty (1952) in their graphs plotting ellipticity vs. bay length.

Why did the ice boulders travel such long distances? There are three reasons: 1) ice has about one third the density of rock, 2) the ballistic trajectories carried the ice projectiles above the atmosphere where there is no atmospheric drag, and 3) the speed of the ice ejecta was boosted by a rapidly expanding plume of steam from the extraterrestrial impact site. Using the equation for kinetic energy, we can calculate that a rock with three times the density of ice would only have about 0.6 the velocity of ice, and the denser rock at the lower speed could only travel one third as far as the ice. In addition, rocky ejecta would travel within the atmosphere where friction would reduce the speed further.

### *6.2. Secondary impacts liquefy unconsolidated soil*

The size of the glacier ice projectiles can be determined from their speed and the size of the bays using yield-scaling laws that correlate energy with crater size (Melosh, 1989). In addition, the energy of the extraterrestrial impact can be estimated by adding the energy required to form all the bays or by multiplying the energy of a typical bay by

500,000, which is the estimated number of bays reported in the literature (Prouty, 1952).

The equations from Melosh calculate that a crater with a diameter of 1 km, which corresponds to a Carolina Bay of intermediate size, can be made by a spherical ice boulder with a diameter of 180 m traveling at a speed of 3 km/s when impacting sandy terrain at an angle of 45°. The energy of the impact would be approximately $1.27 \times 10^{16}$ J or 3.03 megatons of TNT explosive force. Such an impact would be the equivalent of a magnitude 7.54 earthquake. A smaller bay with a diameter of 220 m would correspond to an impact made by a 28-m ice boulder with energy of 13 kt of TNT, which is about the same energy as a 6.0 magnitude earthquake. By comparison, the bomb dropped on Hiroshima had an approximate yield of 15 kt of TNT. The LiDAR images of adjacent and overlapping bays, such as Fig. 1, indicate that the Carolina Bays could have been created by a powerful saturation bombardment of glacier ice chunks that would have killed fauna and destroyed their habitat.

Soil liquefaction is a phenomenon in which saturated soil loses strength in response to applied stress causing it to behave like a liquid. Liquefaction is frequently associated with earthquakes (Youd et al., 2001). The earthquake in Christchurch, New Zealand in February 2011 had a magnitude of 6.3 and produced seismic shock waves that shook the ground and turned sandy soils into quicksand that swallowed cars and displaced roads. Even smaller aftershocks of magnitude 5.7 liquefied the soil. In general, seismic events of magnitude 6.0 and higher cause sufficient vibration to liquefy saturated soil.

In North Carolina, the water table is within 1.5 m below the sandy soil where the bays are found (Eimers et al., 2001). This ground would have been liquefied by the barrage of ice projectiles with energies of 13 kt to 3 MT of TNT. Even if the initial impacts had encountered solid unconsolidated ground, the impacts occurring shortly thereafter would have struck soil liquefied by the seismic vibrations of the preceding impacts.

The characteristics of the extraterrestrial object can be calculated by considering that if there are 500,000 Carolina Bays and each one was formed by an energy of $1.27 \times 10^{16}$ J, then the total energy of the impacts was approximately $6.35 \times 10^{21}$ J. This total energy provides a rough estimate of the kinetic energy transferred to the ejecta by the extraterrestrial impact. Additional energy would have been converted to heat, seismic energy and fracturing of the target and projectile. The kinetic energy of $6.35 \times 10^{21}$ J corresponds to an asteroid with a diameter of approximately 3 km traveling at a speed of 17 km/s.

### 6.3. Oblique impacts on liquefied soil create slanted conical cavities

Conical impact cavities have not received much attention in the scientific literature because they are usually transient and disappear in fractions of a second. Conical shock waves of objects passing through a fluid are usually visualized using schlieren photography or high-speed photography. Cavities made by the conical shock waves of a projectile can remain stable for a relatively long time if the target material is viscous and not elastic (Zamora, 2015). If the target material is too hard, the projectile will shatter and release its energy explosively sending a hemispherical shock wave that creates a typical bowl-shaped crater. If the material is too elastic, the conical cavity made by the passing projectile will immediately collapse leaving only a tubular trail. Conical cavities can only be made when a projectile travels through a viscous medium without disintegrating and the medium has a consistency thick enough to retain the shape of the shock wave. The projectile loses energy as it parts the viscous medium, and it eventually stops at the vertex of a conical cavity. The creation of a conical cavity is a plastic deformation that can be partially reversed by the elastic properties of the medium or by the force of gravity.

The formation of a conical cavity on a viscous target creates a new surface, which is the interior of the cone. This new surface is exposed to light, but the subsoil beneath the new surface remains unexposed to light when the cavity is formed and when the depth of the cavity is subsequently reduced by viscous relaxation. The penetration of the liquefied soil by the projectile does not create turbulent mixing that would expose any of the subsoil to light during the formation of the conical cavity. This means that dating the subsoil by Optically Stimulated Luminescence (OSL), which determines the time elapsed since some mineral crystals were exposed to light, can only provide the date of the terrain, but not the date of formation of the conical cavity.

Would it be possible to use OSL to date the ejecta that formed the bays? OSL works for gradualistic depositional processes for which the dose of radiation can be ascertained for the terrain where the test material is collected. The luminescence signal increases in proportion to the time the material is buried, and it is reset by exposure to sunlight or intense heat (>150 °C) for an extended period of time (USGS, 2016). The ejecta from the extraterrestrial impact on the Laurentide Ice Sheet would have been mostly ice. Ice boulders ejected from the bottom of the glacier close to the glacial bed could have had significant amounts of quartz grains or other material datable by OSL, but ice chunks ejected from the upper layers of the one- to two-kilometer thick glacier would consist mostly of ice. Let us suppose that the ejected glacier ice chunks were exposed to sunlight during their suborbital space flights. Would sunlight be able to penetrate through 20 m or more of ice to reset the luminescence signal of the imbedded mineral crystals? Probably not because the transmission of light is reduced substantially even by a few centimeters of ice (Little et al., 1972). The imbedded crystals would also be undatable by OSL if the extraterrestrial impact occurred at night and the ice boulders traveled in darkness. After the ice melted following the creation of the conical cavities by the secondary impacts, where would the mineral crystals imbedded within the ice end up? Most likely, the mineral particles from the meltwater of the glacier projectiles would disperse at the apex of the conical cavities in the target terrain, and they would quickly be covered up during viscous relaxation making it impossible to isolate them or date them. Large clasts carried within the glacier chunks might still be retrievable from deep within the bays, but their dates would not be able to confirm the time of formation of the Carolina Bays.

The shallow elliptical Carolina Bays have not been successfully explained as impacts by projectiles striking the soil at grazing angles (Johnson, 1942). However, if seismic shock waves from the impacts liquefy the soil, it is possible to consider that oblique impacts on the liquefied soil can create inclined conical cavities that are remodeled into elliptical bays. The glacier ice boulders ejected from the Laurentide Ice Sheet by the meteorite impact would have traveled in ballistic trajectories. The launch angles would be approximately the same as the impact angles. Taking into consideration that the width-to-length ratio of an ellipse is the sine of the impact angle and that the Carolina Bays have width-to-length ratios of $0.58 \pm 0.05$, we can deduce that the impact angles of the ice projectiles would have had an inclination between 32 and 39°. These oblique impacts would have created slanted conical cavities on liquefied soil.

Ice is brittle and fractures easily upon impact (Schulson, 1999). Glacier ice projectiles with speed of 3 to 4 km/s crashing upon dense solid ground or rocky terrain would have shattered and then melted without leaving any lasting evidence. However, the chunks of glacier ice that survived atmospheric re-entry would have had enough energy to liquefy unconsolidated soil close to the water table and sufficient structural integrity to create conical cavities on liquefied soil.

### 6.4. Viscous relaxation converts conical cavities into shallow elliptical bays

Extraterrestrial impact sites usually have a lens of brecciated and molten material at the bottom of the crater. One of the arguments used against the impact origin of the Carolina Bays is that the stratigraphy beneath the bays is not distorted (Preston and Brown, 1964; Thom, 1970). However, impacts by chunks of glacier ice at speeds of 3 to 4 km/s on liquefied ground are not explosive events like those produced by hypervelocity impacts. A projectile traveling through a viscous medium is slowed down in proportion to its cross-sectional area and drag coefficient. Ablation during transit reduces the projectile mass, which also slows down the projectile (Melosh, 1989). Projectiles impacting a viscous surface penetrate the medium and part it in a plastic deformation that can be partially reversed by viscous relaxation.

Viscous relaxation is a deformation process driven by gravity that tends to smooth out geological features by making hills less prominent and valleys less deep (Melosh, 1989). The process is generally slow, but it can be speeded up by reducing friction within the medium. For saturated soil, this can be accomplished by vibrations that promote liquefaction. A cavity created by an impact in a viscous surface is filled by flow of the material surrounding the deepest part of the cavity. Pressure increases with depth and this creates a velocity gradient that promotes faster centripetal lateral flow at the bottom of a cavity. Viscous relaxation fills an impact cavity in the reverse order in which it was created, starting from the bottom up and restoring the original stratigraphy layer by layer until friction stops the centripetal flow of material and only a shallow bay remains.

**Fig. 5.** Impacts by ice projectiles create conical cavities on a viscous surface.

## 7. Experimental impact model

The eolian and lacustrine hypotheses for the formation of the Carolina Bays cannot be tested meaningfully. There is no way of verifying how the wind was blowing when the bays were created. Some authors state that the bays are aligned with the prevailing wind (Raisz, 1934; Melosh, 2011), while others claim that the bays are elongated perpendicular to the wind direction (Zanner and Kuzila, 2001; Brooks et al., 2010). No weather phenomenon has been confirmed as being capable of forming elliptical bays, but the eolian hypotheses only consider the prevailing winds rather than whirlwinds, tornadoes or hurricanes with variable wind conditions. Furthermore, there is no known eolian or lacustrine mechanism that can consistently create shallow elliptical features with the 0.58 width-to-length ratios observed for the Carolina Bays and Nebraska Rainwater Basins. It is not possible to design an experiment to test the terrestrial hypotheses without knowing how the specific aspect ratios are achieved and maintained over a large geographical area.

By contrast, the Glacier Ice Impact Hypothesis proposes four mechanisms that can be tested with a combination of mathematical and experimental tools. Ballistic equations, scaling laws relating crater size to impact energy, geometrical analysis and statistical analysis provide a mathematical foundation for explaining the shape of the bays and their origin from secondary impacts of glacier ice ejected from the Laurentide Ice Sheet that covered Michigan. From geometry, we know that ellipses with the aspect ratios of the Carolina Bays correspond to conic sections inclined at 35°. It is relatively easy to design experiments to study the formation of slanted conical cavities by oblique impacts of ice projectiles and the process of viscous relaxation. The results of these physical models provide insights about the geomorphology of the Carolina Bays.

The following images show some experiments conducted on a mixture of equal amounts of pottery clay and sand mixed with enough water to have the consistency of bricklayer's mortar. A thin layer of colored sand on the surface enhances visualization. A slingshot was used to fire the ice projectiles that made the impact cavities.

Fig. 5 shows inclined conical cavities made by oblique impacts. The ice projectiles part the soil and stop at the apex of the conical cavity. The penetration of the surface by the projectile creates flanges around the cavity and pushes some material in the direction of travel.

Viscous relaxation reduces the depth of the inclined conical cavities and transforms their flanges into overturned flaps that produce raised rims around the shallow elliptical depressions (Fig. 6). Shaking the experimental container speeds up viscous relaxation. After the ice melts, there is no trace of the projectile. The same would be expected for the glacier ice impacts that created the Carolina Bays. No trace of the projectile would remain in the Carolina Bays, except for some clasts that might have been carried within the glacier ice. It is not known to what depth the extraterrestrial projectile penetrated the glacier, but the projectile would have had to go through the supraglacial and englacial segments to reach the glacial bed in order to bring up clasts. This is something that could be verified by geological exploration of the bays, although not every bay would have such clasts. It is worth noting that the raised rims are overturned flaps with inverted stratigraphy. Finding glacier clasts within the bays or inverted stratigraphy in the rims would provide verification of the Glacier Ice Impact Hypothesis.

Carolina Bays that overlap without affecting the shape of adjacent bays are common. Two examples of bays that overlap can be seen in Fig. 2. The eolian and lacustrine gyroscopic theories that have been proposed for the formation of the Carolina Bays fail to predict the aspect ratios of the bays, their orientations, and the creation of overlapping bays (Melton, 1956). Impact experiments provide an explanation of how the overlapping bays with similar aspect ratios can be created.

Fig. 7 demonstrates that impacts on liquefied ground can create conical cavities adjacent to previous impacts without affecting the shape of the previous bays. The aspect ratio of the resulting bay is determined by the angle of impact.

Viscous relaxation of adjacent conical cavities on liquefied soil produces overlapping bays (Fig. 8). Bay formation follows the principle of superposition. A bay that overlaps another one was created later in time. This makes it possible to determine the relative time of emplacement of overlapping Carolina Bays.

In addition to the experiments illustrated here, the physical model can be used to demonstrate that viscous relaxation, which decreases the depth of an impact cavity by centripetal flow from the bottom up,

**Fig. 6.** Viscous relaxation converts conical cavities into shallow bays with raised rims.

**Fig. 7.** New impacts make conical cavities without disturbing adjacent bays.

restores the stratigraphy and prevents exposure to light of the soil beneath the new conical surface created by the impact (Zamora, 2015). These experiments are important because they provide information about why the subsoil of the Carolina Bays appears undisturbed, and why the dates of the bays are so diverse. The conical cavities are formed by a plastic deformation that prevents light from penetrating below the surface of the new conical cavity thereby making OSL dating inapplicable. OSL has been very successful for dating sedimentary processes, but its use for dating material that may not have been reset by sunlight at the time of formation of the Carolina Bays would be inappropriate. Carbon-14 dating of the Carolina Bays has also been difficult due to the vertical transport of carbon in sedimentary sequences (Kennett et al., 2015). Analysis of charcoal and carbon spherules found within the sediments of some bays have unusual radiocarbon dates that are inconsistent with the age inferred by their stratigraphy and suggest that the spherules are enriched in $^{14}C$ (Firestone, 2009).

Can these experiments scale to the kilometer-size proportions of the Carolina Bays? One advantage of physical models over computer hydrocode simulations is that they integrate all the material interactions of the system being tested. Small-scale physical models were used by Stickle and Schultz (2012) to study impacts on ice, and Prouty (1952) used a high-powered rifle to test the creation of shallow elliptical cavities. It would be possible to design impact experiments to model more closely the scenario proposed by the Glacier Ice Impact Hypothesis by using soil samples from the Atlantic Seaboard on a shaking table that promotes liquefaction. However, it is reasonable to expect that the experiments presented here will scale up as the projectile size increases, although certain attributes of the impact structures, such as rim width relative to cavity size, will be different. The physical models may provide the fundamental parameters for developing computational models to simulate multi-kiloton impacts.

**Fig. 8.** Viscous relaxation of adjacent conical cavities creates overlapping bays.

## 8. Conclusion

The radial orientation of the Carolina Bays and Nebraska Rainwater Basins toward a convergence point in Michigan (Davias and Harris, 2015) and the elliptical shapes of the bays with specific width-to-length ratios can be better explained by impact mechanisms than by terrestrial wind and water processes. The Glacier Ice Impact Hypothesis proposes a sequence of four mechanisms that could have produced the Carolina Bays by secondary impacts of glacier ice ejected from a primary extraterrestrial impact on the Laurentide Ice Sheet. The hypothesis has been supplemented with an experimental model demonstrating that oblique impacts on viscous surfaces can reproducibly create inclined conical cavities that are remodeled into shallow elliptical depressions by viscous relaxation. This makes it possible to model the Carolina Bays and Nebraska Rainwater Basins as conic sections whose width-to-length ratio can be explained by the angle of impact. Unlike the eolian and lacustrine hypotheses of bay formation that cannot be tested, the impact hypothesis uses mathematics and a physical model that can be used to demonstrate stratigraphic restoration by viscous relaxation and the remodeling of conical impact cavities on viscous media.

The great diversity of dates obtained by Optically Stimulated Luminescence (OSL) has been one of the greatest barriers for the acceptance of an impact hypothesis. The use of OSL has assumed that the subsurface of the Carolina Bays was exposed to light at the time of bay formation, but the experimental model shows that impacts on viscous surfaces are plastic deformations that do not expose the subsurface to light. Therefore, OSL can only determine the date of the terrain, but not the date of formation of the bays. If all the Carolina Bays and Nebraska Rainwater Basins formed contemporaneously, it will be necessary to find a different way of dating them.

The Glacier Ice Impact Hypothesis explains all the features of the Carolina Bays and Nebraska Rainwater Basins, including their elliptical shape, radial orientation, raised rims, undisturbed stratigraphy, absence of shock metamorphism, overlapping bays, and the occurrence of bays only in unconsolidated ground. In addition, the Glacier Ice Impact Hypothesis predicts that the raised rims of the Carolina Bays will have inverted stratigraphy characteristic of impacts, and that clasts carried by the glacier ice projectiles might be found at the bottom of some bays where the ice boulders stopped.

If the Carolina Bays were indeed made by impacts of ejected glacier ice, the great surface density of the bays indicates that they were created by a catastrophic saturation bombing with impacts of 13 kt to 3 MT that would have caused a mass extinction in an area with a radius of 1500 km from the extraterrestrial impact in Michigan. This paper has considered mainly the ice boulders ejected by an extraterrestrial impact on the Laurentide Ice Sheet during the Pleistocene, but the impact would also have ejected water and produced steam. Taking into consideration the thermodynamic properties of water, any liquid water ejected above the atmosphere would have transformed into a fog of ice crystals that would have blocked the light of the sun (Zamora, 2015). Thus, the time of formation of the Carolina Bays and Nebraska Rainwater Basins must coincide with an extinction event in the eastern half of the United States and the onset of a period of global cooling. This combination of conditions is best met by the disappearance of the North American megafauna, the end of the Clovis culture and the onset of the Younger Dryas cooling event at 12,800 cal. BP. The report of a platinum anomaly typical of extraterrestrial impacts at the Younger Dryas Boundary by Petaev et al. (2013) supports this scenario. Further study of the Carolina Bays may provide detailed insights about the late Pleistocene and reveal information about near-Earth objects that could destroy our civilization.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.geomorph.2017.01.019. This data include the Google maps of the most important areas described in this article.

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