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Interpreting the Geomorphology of Carolina Bays as Secondary Impact Structures

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ABSTRACT

This study examines the Carolina Bays and Nebraska Rainwater Basins, using high-resolution LiDAR elevation models to analyze their unique shapes. The research reveals that well-preserved Bays exhibit precise elliptical geometry, distinguishing them from various oriented lakes they are often compared to. While the timing of their formation is discussed, the primary goal of this paper is to establish a repeatable method for quantifying the elliptical nature of these dominant geomorphic landforms. By applying the least squares method to points selected along the perimeters of these extraordinary basins, the study confirms their elliptical geometry with an error margin of less than 3%. This rigorous mathematical approach sets a high standard for any hypothesis attempting to explain the origin of these depressions using natural environmental conditions. Notably, the long axes of these elliptical basins converge near the Great Lakes region, and since ellipses can be described as conic sections, this finding supports the plausibility of a cosmic impact origin. The study suggests that these basins may be secondary impact features formed during a past glacial cycle of the Laurentide Ice Sheet. This research establishes a strong mathematical foundation to support future studies on the possible impact origin of the Carolina Bays and Nebraska Rainwater Basins.

Keywords: Carolina Bays; Nebraska Rainwater Basins; Oblique Impacts; Penetration Funnels; Elliptical Basins; Conical Cavities; Thermokarst; LiDAR

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1. Introduction

1.1. Background and Literature Review

Over the past several decades, it has become abundantly clear that the Carolina Bays are the most prevalent geomorphic land features on the Atlantic Coastal Plain. These shallow elliptical basins, with raised sandy rims, uniform geometry, and consistent alignment toward the Great Lakes have grabbed the attention of scientists and advocationalists alike since the early 1930s. After aerial photography first revealed the vastness of these remarkable features, numerous hypotheses have been proposed to explain how they might have formed. These enigmatic basins have been interpreted as meteorite craters [1, 2] or depressions made by comet airbursts [3]. However, after an extensive search for direct evidence of meteorite fragments yielded no solid results, the research shifted to a more gradual causation for the Carolina Bays. More recently, these elliptical depressions have been hypothesized to be shallow-oriented ponds [4], thermokarst lakes [5], and even thermokarst-related eolian sand dunes [6]. Comparing the Carolina Bays to these similar landforms fails to explain their consistently precise elliptical shapes. The origin of the Carolina Bays remains a mystery and has been the subject of contentious debates over the decades. The following table (**Table 1**) cites the most relevant literature and key arguments published over the past twenty years.

Table 1. Literature review of the limited number of relevant articles on Carolina Bays as secondary impact features published over the last two decades (2005–2025).

Author(s)	Year	Key Arguments
Firestone et al. [7]	2006	The Carolina Bays are secondary impact craters made by ice projectiles ejected by an impact on the Laurentide Ice Sheet.
Firestone et al. [8]	2007	An extraterrestrial impact caused the extinction of the megafauna and the Younger Dryas cooling event 12,900 years ago. Carolina Bay sediments were analyzed for impact proxies.
Pinter et al. [9]	2011	The impact origin of the Carolina Bays is unlikely. The dating of rim sediment indicated a significant amount of time for formation.
Zamora [10]	2017	The Carolina Bays have a mathematically elliptical geometry and are secondary impact craters made by ice projectiles.
Klokočník et al. [11]	2018	The gravity anomaly study of Saginaw Bay, Michigan, provides circumstantial evidence of a Michigan impact event possibly at the Younger Dryas Boundary.
Schaetzl et al. [12]	2019	Prior to 12.9 ka, ice had already receded from the Saginaw Bay area, rendering an impact by a meteorite at that time on an ice sheet in that region impossible.
Swezey [6]	2020	The Carolina Bays are not the product of a single event of limited duration.
Davias & Harris [13]	2022	Postulated that an impact over Michigan created the Carolina Bays and the AA tektites simultaneously ca. 788 ka.
Holliday et al. [14]	2023	The Carolina Bays are not oriented toward the Great Lakes. They are well-documented ice-melt landforms.
Zamora [15]	2025	The orientations of the Carolina Bays can be determined accurately by fitting them with ellipses. The Carolinas did not experience glaciation or widespread permafrost.
Lundine & Trembanis [16]	2025	In favor of aeolian and lacustrine processes for Carolina Bay formation, highlighting field-based and remote sensing data.

1.2. Significance of Satellite and LiDAR Imagery

Satellite images are widely available through various mapping and navigation services. **Figure 1** shows some Carolina Bays about 3 km southeast of Antioch, North Carolina. Three large Bays are in the center of the image, but vegetation, farm fields, and roads hide their outlines.

Figure 1. Satellite image of some Carolina Bays about three km southeast of Antioch, North Carolina.

LiDAR images reveal the details of the terrain surface. **Figure 2** is an image of the same area as **Figure 1**. LiDAR shows three large bays in the center of the picture, and many other smaller bays that are not visible in the satellite image. The LiDAR High-Resolution Topology Model (HRTM) has seamless coverage across the 48 contiguous United States and uses a 10-meter cyclic perceptive color ramp that provides a relative elevation reading for the local terrain, as each color repeats every 10 meters. The rendering adds shading to produce a 3D effect [17,18,19].

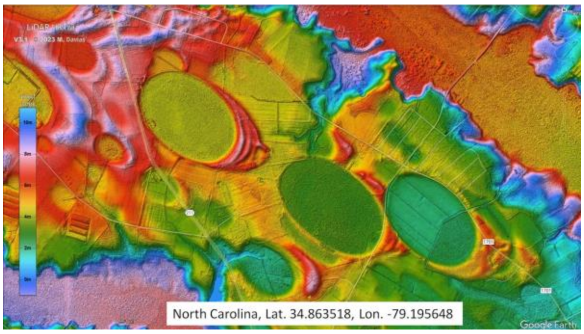


Figure 2. LiDAR image of the same area as **Figure 1** about three km southeast of Antioch, North Carolina. The elevation of the terrain is approximately 65 m above sea level.

The development of LiDAR HRTM has revolutionized the study of the Carolina Bays, revealing tens of thousands of elliptical basins that were previously concealed by vegetation. **Figure 2** shows a landscape where some bays overlap others and allows the determination of the sequence of bay emplacement using the geological law of superposition. When examined using LiDAR, several features of the Carolina Bays and Nebraska Rainwater Basins are readily apparent. The basins have a regular elliptical shape that is consistent between almost every example. As seen in **Figure 3**, the Carolina Bays have raised rims, with the most prominent rim to the southeast, and their long axes are consistently oriented toward the same area of the Great Lakes, regardless of their geographic location or other environmental variables.

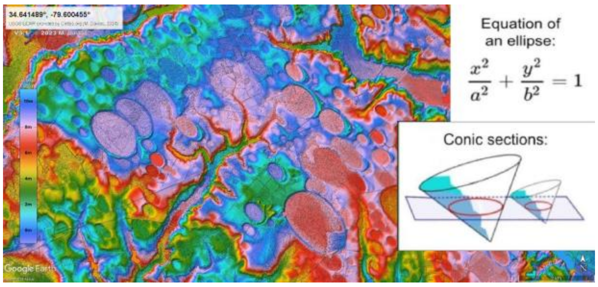


Figure 3. LiDAR image of elliptical depressions surrounding the town of Tatum, SC. An ellipse is one of four cone sections intersecting with a plane.

1.3. Nebraska Rainwater Basins

The comparatively recent discovery from the Midwest shows that Nebraska also has elliptical basins analogous to the Carolina Bays, known as the Nebraska Rainwater Basins [20]. This, along with the LiDAR elevation models, now widely available, has provided a broader perspective on the nature of these unique geological structures. These Nebraska Rainwater Basins are found in abandoned Platte River fluvial sands and gravels. The satellite image of this area (**Figure 4**) reveals a grid of one-square-mile farms, with no visible basins.

Figure 4. The Nebraska Rainwater Basins are well hidden in the landscape imagery without the aid of LiDAR.

Figure 5 shows that when viewed with LiDAR and compared to the Carolina Bays, Nebraska Rainwater Basins are often found on relatively rough terrain, and many have been heavily degraded by natural and agricultural erosion. Notice that the Nebraska Rainwater Basins have a northeast-to-southwest orientation, which is almost perpendicular to the orientation of the Carolina Bays.

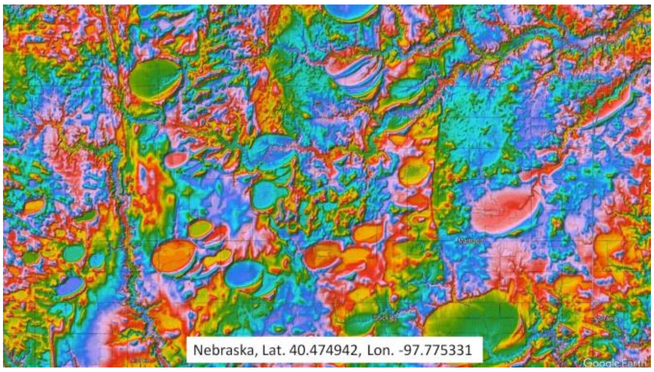


Figure 5. Elliptical basins approximately four km northeast of Ong, Nebraska viewed with LiDAR. The elevation of the terrain is about 510 m above sea level.

1.4. Convergence Point of the Elliptical Basins

After the discovery of the similarity of the Nebraska Rainwater Basins to the Carolina Bays, there were several efforts to compare the convergence point of the basins with that of the Carolina Bays. If the two converged on the same location, this would offer strong evidence that both were formed by the same impact event. Davias and Gilbride [18] showed a triangulation point centered at 43.5° N, 89.5° W. This location is near Portage, Wisconsin, about 140 km from the western shore of Lake Michigan. The solid lines in **Figure 6** show the intersection of the three basins discussed in this study. The intersection is about 55 km south of the convergence point found by Davias and Gilbride. Based on the eastward rotation of the Earth of 0.25 degrees of arc for every minute of flight time, the material that formed these basins would have originated in the middle of Lake Michigan, 160 kilometers to the east of the non-adjusted point, assuming an 8-minute ballistic flight. This is illustrated by the dashed lines in **Figure 6**. Davias and Gilbride heuristically examined various geological depressions east of the convergence point and selected Saginaw Bay in Michigan as the potential impact site.

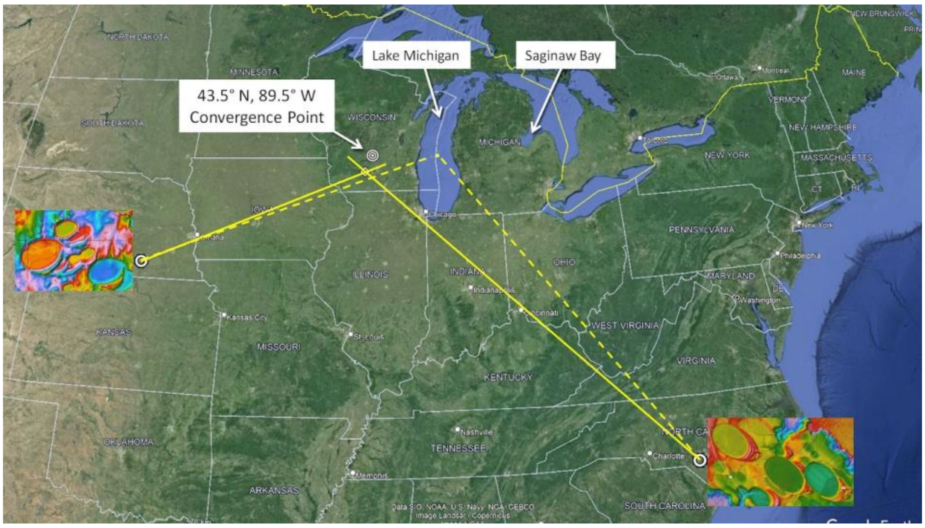


Figure 6. Extending the major axes of the ellipses in Nebraska and on the East Coast reveals a convergence point in Wisconsin by the Great Lakes. The black and white target shows Davias & Gilbride's [18] convergence point. Solid yellow lines indicate the convergence point of the three basins discussed in this study. The dashed yellow lines correspond to the Davias and Gilbride convergence point adjusted for the Coriolis effect.

The convergence of the orientations of the Carolina Bays and the Nebraska Rainwater Basins by the Great Lakes, as well as their unique elliptical geometry, has led to proposals that an extraterrestrial impact onto an ice sheet over North America during a previous glacial cycle could have launched chunks of icy ejecta in ballistic trajectories and whose secondary impacts created the Carolina Bays [7, 10]. The Carolina Bays and Nebraska Rainwater Basins exhibit elliptical geometries that can be characterized as conic sections intersecting a flat plane. By applying the least squares method to quantify these elliptical features, this study aims to establish a baseline of plausibility for the hypothesis, thereby providing a credible foundation to justify and encourage further scientific investigation into these geological formations.

2. Data and Methods

2.1. Study Area and Data Collection

Some researchers supporting a non-impact origin for the Carolina Bays have described the basins as oval without testing the quality of their geometry [21]. To test the geometry of the Bays, a Python program was developed to fit them with ellipses using the least squares method [22]. **Figure 7** shows Basin A, a Carolina Bay whose mathematically elliptical geometry can be confirmed by selecting points along the basin's perimeter and fitting them with an ellipse. The colorized topography helps to differentiate the flat central portion of the Bay from its rims and makes it easier to determine the perimeter. Basin A has a width of 599 meters and a length of 909 meters. An ellipse is an example of a conic section (**Figure 3**), implying that the Bay originated as a penetration funnel or cone inclined at 41.2 degrees. The raised rims on every Carolina Bay are consistent with an impact origin because the penetration of a projectile on a target surface produces overturned flaps that form uplifted rims around the cavity [23].

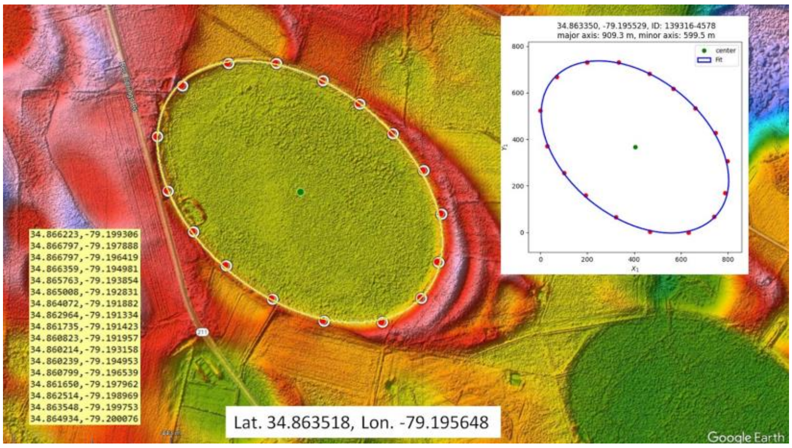


Figure 7. Basin A. Points are selected along the perimeter of the Carolina Bay and fitted with an ellipse. All the points are along the elliptical curve.

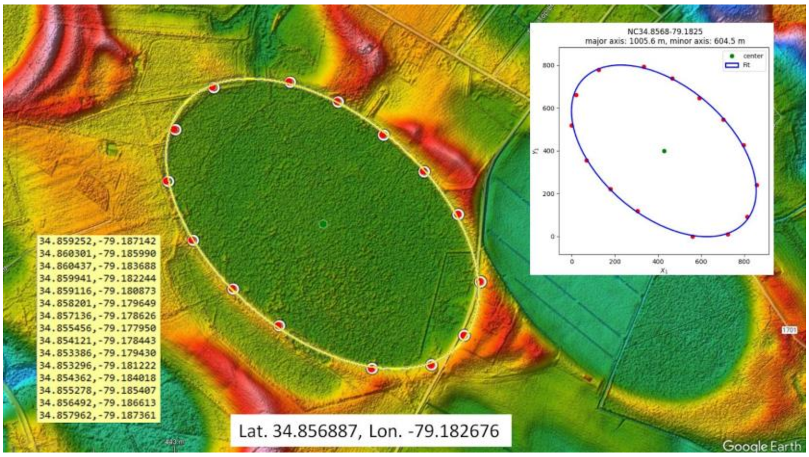


Figure 8. Basin B. The basin adjacent to the previous one also has mathematically elliptical geometry.

Well-preserved Carolina Bays that have not been degraded by erosion, movement of the terrain, or bioturbation have elliptical geometry. **Figure 8** shows Basin B, which is adjacent to Basin A. Basin B has a width of 604 meters and a length of 1005 meters, indicating extreme geometric precision over a distance of more than 1 km. The width-to-length ratio of the ellipse translates to a cone inclined at 36.9 degrees. From an impact perspective, the inclination of the cones is interpreted as the angle of impact that can be used to derive more information using ballistic equations.

These are only two examples of elliptical Carolina Bays, but there are thousands along the Atlantic Coastal Plain whose geometry exhibits precise mathematical definitions consistent with ellipses using the least squares method. The comparison is not just a coincidence. **Figure 9** shows that well-preserved Nebraska Rainwater Basins can be fit with an ellipse to verify their elliptical geometry in precisely the same manner as the Carolina Bays. When selecting the points of the perimeter, it is necessary to avoid the portions that have been washed away by erosion. This Nebraska basin has a width of 1436 meters and a length of 2032 meters, or more than 2 kilometers. The width-to-length ratio of the ellipse corresponds to a cone inclined at 45 degrees.

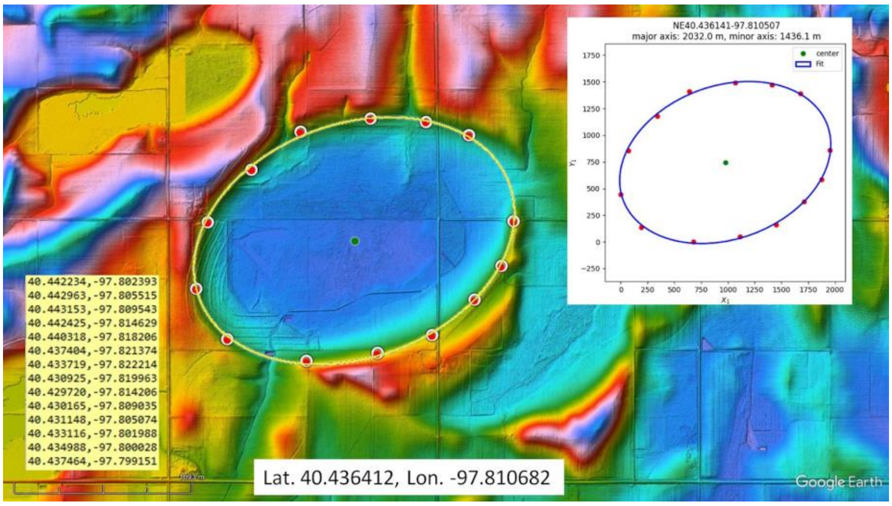


Figure 9. Like the Carolina Bays, Nebraska Rainwater Basins demonstrate elliptical geometry when tested with the least squares method.

Some researchers have criticized claims of widespread geometric regularity, suggesting that Carolina Bays selected for publication in support of such claims were specifically selected for their regularity [21]. While it is true that mathematical analysis of LiDAR images has shown that elliptical geometry is a predominant feature of well-preserved Carolina Bays, not all Carolina Bays exhibit such perfect geometry. Erosion and land movement can affect their geometry. For example, Bays located on inclined terrain show specific deformations caused by the flow of material downhill.

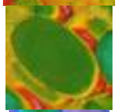
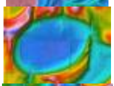
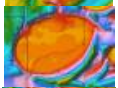
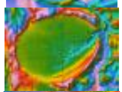
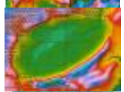
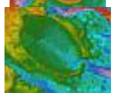
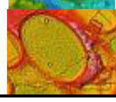
2.2. Applying the Least Squares Method

The Carolina Bays have very low topographic relief, and for this reason, monochromic LiDAR images like the USGS 3DEP Elevation Hillshade Stretched do not provide enough contrast to accurately trace the perimeter of the bays. For this reason, this project used a LiDAR visualization tool for Google Earth [19] that provides a relative elevation color ramp that repeats every 10 meters and uses hill shade exaggerated 20x compared to normal sun shadow. The colorized topography helps to distinguish the transition of the flat portion of the basin to the rim. Basins are tested for ellipticity by selecting points along the perimeter and fitting the points with an ellipse by the least squares method. The open-source Python program [22] can process points from Google Earth's geographical coordinates or a digitized image. The coordinates of each point (comma-separated latitude and longitude) are recorded as separate lines in a text file. No points are selected in portions of the rim that have been degraded by erosion or human activity. The Python program converts the coordinate positions to meters relative to the southernmost and westernmost points of the data set so that the ellipse with the fitted points can be displayed in the first quadrant of a graph. The procedure for converting the coordinates to meters recognizes that one degree of latitude corresponds to 10,000,000 meters for 90 degrees or 111,111 meters per degree. The distance in meters between degrees of longitude depends on the latitude. The distances for longitude are obtained by multiplying the meters per degree by the cosine of the latitude of the coordinate pairs. The Python program uses the algorithm by Halir and Flusser [24] to fit an ellipse to the points. The program also calculates the goodness of fit. Standard measures of fitness, like the Mean Squared Error, do not provide meaningful comparisons for ellipses of different sizes. The error measure needs to be independent of the number of sample points and the size of the ellipse. The program computes the total of all error distances between the observed points and the corresponding points on the ellipse and then divides this sum by the number of points to determine the average error. Next, it calculates the fitting error as a percentage by dividing the average error by the semiminor axis of the ellipse, effectively scaling the average error to the ellipse's size and enabling error comparisons across ellipses of varying dimensions. Well-preserved Carolina Bays, like those near Bowmore, North Carolina, have mathematically elliptical geometry with an average fitting error of 1.59 percent. In general, Carolina Bays have fitting errors of less than 3 percent.

3. Results and Analysis

The Carolina Bays are the most prevalent geological features of the Atlantic Coastal Plain. Each basin is unique due to the characteristics of the terrain on which it is emplaced and the erosive forces that have altered it over millennia. The Nebraska Basins are found on ground that is less flat than the Atlantic Coastal Plain, and they have suffered greater degradation by erosion. **Table 2** shows a sample of 12 basins from the East Coast and the Midwest that have been fitted with ellipses by the least squares method. The procedure is relatively streamlined. Points are selected along the perimeter of a basin and their geographical coordinates in decimal format are saved in a text file. The text file is fed into the ellipse-fitting Python program, which then generates a graph displaying an ellipse matched to the points, along with details about the ellipse such as the lengths of the major and minor axes, the azimuth aligned with the major axis, and the fitting error, which indicates how well the ellipse fits the data.

Table 2. Sample results of fitting ellipses by the least squares method to the Carolina Bays and Nebraska Rainwater Basins. The thumbnails show a LiDAR image of the basin. The fitted ellipse and the list of points are available in the supplemental section.

Ref. No. & Location	Latitude	Longitude	Length	Width	Azimuth	Error (%)	Thumbnail
(01) Antioch, NC	34.8635	–79.1956	909.3	599.5	129.3	1.31	
(02) Antioch, NC	34.8569	–79.1827	1005.6	604.5	131.0	1.69	
(03) Bennettsville, SC	34.6446	–79.6369	1404.4	909.6	137.0	1.29	
(04) Herndon Bay, NC	34.8621	–78.9446	1101.0	672.1	128.3	1.00	
(05) Ong, NE	40.4364	–97.8107	2032.0	1436.1	249.9	1.64	
(06) Ong, NE	40.4450	–97.8537	2311.5	1673.4	244.5	0.94	
(07) Sutton, NE	40.5285	–97.8655	2753.6	1893.8	248.2	2.45	
(08) Inland, NE	40.5671	–98.1684	3567.1	1915.4	247.1	2.82	
(09) Orangeburg, SC	33.4182	–80.6990	1800.1	1249.0	138.4	0.66	
(10) Rennert, NC	34.7934	–79.0656	4246.9	2129.1	130.5	1.44	
(11) Bowmore, NC	34.9172	–79.2786	2561.4	1570.1	130.3	1.39	
(12) Bowmore, NC	34.9094	–79.3092	871.5	566.7	134.8	1.54	

Several examples from **Table 2** are illustrated in more detail elsewhere in this article. Examples 1 and 2 are illustrated in **Figure 7** and **Figure 8**, respectively. Example 5 is illustrated in **Figure 9**. Example 4 is Herndon Bay, which is illustrated in the upcoming Discussion section 1. Example 8 illustrates a Nebraska Rainwater Basin. Zanner and Kuzila [20] recognized the similarity of the Nebraska Basins to the Carolina Bays based on a previous study by Kuzila [25]. Example 9 shows a basin on sloping terrain. The central portion of the basin is at an elevation of 48 meters above sea level, and the northwest rim is at 51 meters above sea level. The southeastern half of the basin has been washed out by erosion. Several types of basin deformations are common on inclined terrain. The average fitting error for these 12 basins is 1.51%. Two of the Nebraska Basins have the greatest error because their poorly defined margins make it difficult to select points. In general, the Carolina Bays and the Nebraska Basins conform closely to an elliptical geometry, but the same cannot be said for the thermokarst lakes illustrated in the Discussion.

4. Discussion

4.1. Eolian-Lacustrine Hypothesis

The eolian-lacustrine hypothesis proposes that the

Carolina Bays are oriented lakes whose shape and sandy rims were created by wind and wave mechanisms over many millennia. Brooks et al. [4] concluded that the bays acquired their characteristic shapes and northwest-southeast orientations due to the influence of robust southwesterly winds, which were stronger than they are today. These winds blew across water trapped in shallow depressions, expanding and shaping the depressions through wave erosion. This process led to the elongation of bays in a direction perpendicular to the wind, along with the formation of sand rims and shorelines on their eastern and southeastern edges.

Kaczorowski [26], while working on his Ph.D. dissertation, tested the eolian-lacustrine hypothesis using experimental methods. He began by digging a circular depression into a tray of sand. The basin was then filled with water, and a fan was set to blow over the pool to simulate the prevailing winds. Kaczorowski then proceeded to change the direction of the fan by 180 degrees every fifteen minutes for four hours. At the end of the experiment, the pool had a pointy shape that was not elliptical and did not resemble a Carolina Bay, but Kaczorowski described the depression as elliptical in the caption of the resulting image (**Figure 10**). No attempt to experimentally recreate elliptical depressions by natural aeolian and lacustrine mechanisms has ever been peer-reviewed.

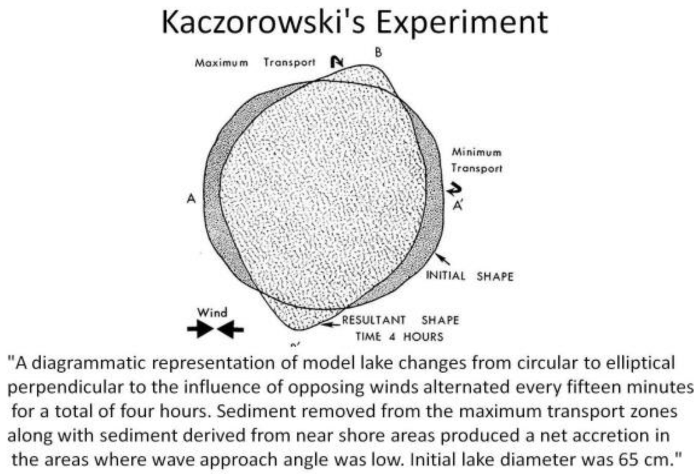


Figure 10. The results of Raymond Kaczorowski's 1977 Carolina Bay eolian-lacustrine modeling experiment [26] (pp. 92–93).

The proponents of the eolian-lacustrine hypothesis generally do not consider the physical constraints necessary for producing mathematically elliptical geological features, and they do not mention the Nebraska Basins whose orientation is different from the Carolina Bays. No wind and water experiments have ever been attempted to create the commonly occurring elliptical overlapping bays.

Carolina Bays with multiple rims have been interpreted as evidence that some bays migrate under the action of the wind, whereas such rims could have been produced by closely overlapping impacts. Moore et al. [27] studied Herndon Bay and proposed a gradual process to explain how the Bays can move against the wind and form multiple rims. Their geological research on Herndon Bay, a Carolina Bay located in North Carolina's Coastal Plain (USA), suggests that during Marine Isotope Stage (MIS) 3 of the late Pleistocene, the basin experienced rapid erosion and shifting. LiDAR data reveal a series of receding sand rims that partially infill older sections of the bay, indicating that the basin shifted to the northwest by over 600 meters.

Like so many others, Herndon Bay is a mathematically defined elliptical basin (**Figure 11**), and the so-called "regressive sequence of sand rims" are the rims of other basins that were overlaid. Only five points are necessary to define an ellipse, and it is possible to reconstruct the complete elliptical shapes for basins that have been partially obscured by others. The mathematical analysis indicates that Herndon Bay would have needed to change sizes as it migrated while leaving remnant rims in its wake, and all the time maintaining its mathematically elliptical geometry. This migration was supposedly driven by the wind, but there is little evidence that neighboring Carolina Bays also migrated. **Figure 11** shows multiple overlapping basins, and overlaps are the simplest explanation for multiple rims.

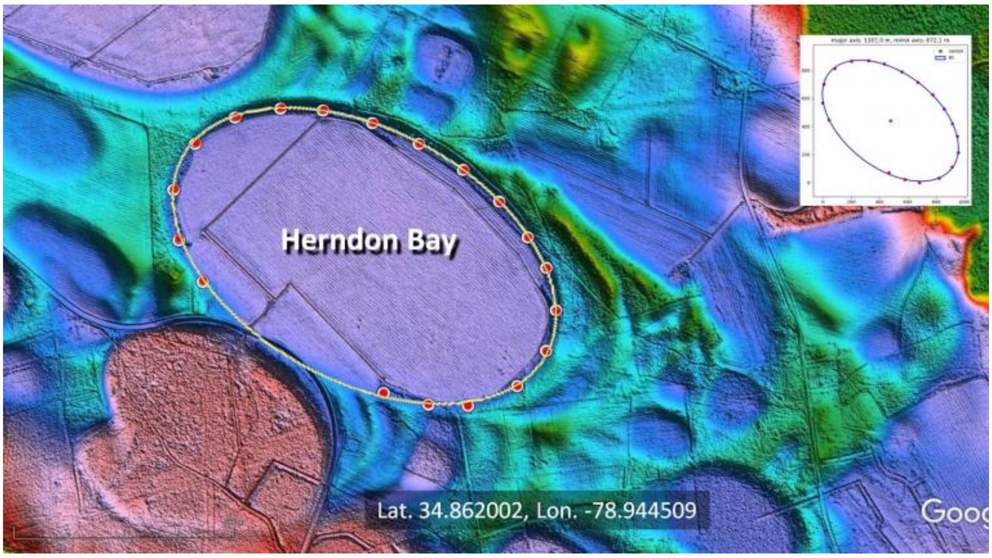


Figure 11. Herndon Bay has a mathematically elliptical geometry, and it is surrounded by many overlapping basins.

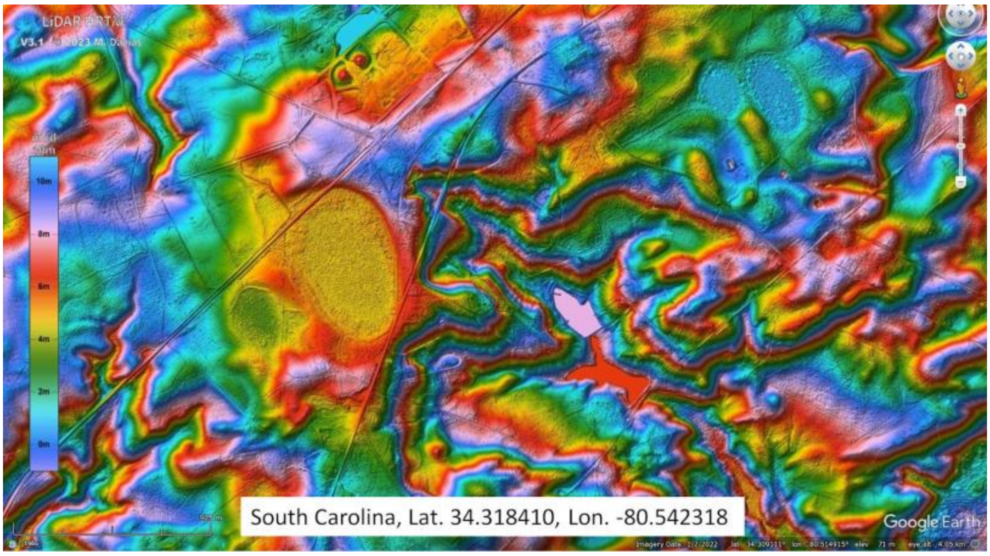


Figure 12. Carolina Bay with a length of 760 meters persists on a flat hilltop at 114 m above sea level 170 km from the Atlantic Ocean. There are no traces of bays on the inclined terrain.

The Carolina Bays consist mainly of unconsolidated soil, so they are highly susceptible to erosion on inclined terrain. However, there are many examples of Bays that have persisted while the rest of the landscape around them has undergone significant erosion, see **Figure 12**. These isolated bays are usually found on relatively flat hilltop terraces where the coastal plain transitions to the Piedmont.

4.2. Thermokarst Hypothesis

The thermokarst hypothesis proposes that the Carolina Bays originated as thermokarst lakes produced by melting permafrost (**Figure 13**). However, the notion that permafrost extended as far south as the Atlantic Coastal Plain in North Carolina and South Carolina during the Last Glacial Maximum is not supported. Permafrost is only known to have extended as far as central Virginia during the LGM [28]. A chapter in a book about eolian dunes and sand sheets of the Atlantic Coastal Plain says: “Although the southern limit of permafrost during the LGM is typically thought to have been located in central or northern Virginia, discontinuous and sporadic permafrost probably extended much farther south.” [6].

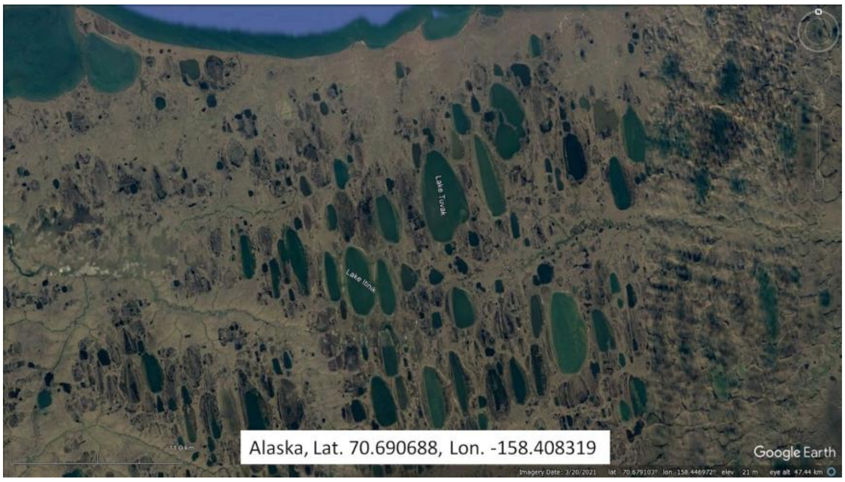


Figure 13. Satellite image in northern Alaska around Lake Tuvak. The thermokarst lakes in this region have been compared to Carolina Bays. Careful inspection can demonstrate that these lakes do not have the mathematically elliptical geometry of the Carolina Bays and Nebraska Rainwater Basins, and many are not even ovoid.

In addition to the precise elliptical geometry and the pronounced raised rims, Carolina Bays differ from thermokarst lakes in their geological characteristics. The suggestion by Swezey that the Coastal Plain of the Carolinas had permafrost and that the Bays originated as thermokarst lakes is disputed by Lundine and Trembanis [29] based on the geomorphology of the bays. These authors say that although the Carolina Bays are often likened to thermokarst or thaw lakes in the Arctic due to their similar physical characteristics (oriented, elliptical depressions), the maximum elevation difference (from rim apex to basin bottom) in thaw lakes typically exceeds 10 meters, which is significantly greater than the maximum reliefs observed in Carolina Bays. Even when the deposits within the Carolina Bay basins are removed, the increase in their relief is only a few meters, which is much less compared to typical thaw lakes. In addition, the existence of permafrost, which is essential for the formation of thermokarst, extending as far south as the coastal plain of Georgia seems improbable, even during past glacial maxima, and it is neither supported by proxy data nor by model predictions of historical permafrost extents. **Figure 14** shows the absence of raised rims in the Alaskan lakes.

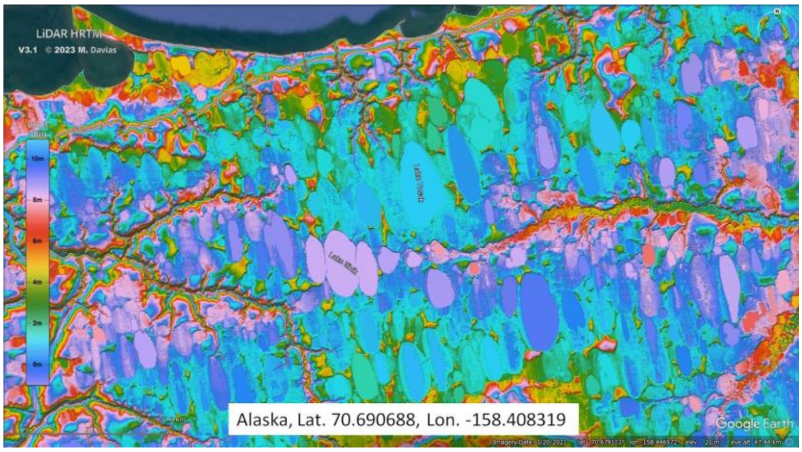


Figure 14. A LiDAR image of the same area as **Figure 13** demonstrates the geomorphological differences between these lakes and the Carolina Bays, including the absence of raised rims.

4.3. Timing of Formation

While the uniform elliptical shape and radial alignments towards the Great Lakes appear to support the idea that the Carolina Bays and Nebraska Rainwater Basins originated as secondary impact structures, the timing of this event remains heavily debated, even among the proponents of this hypothesis. Most of these basins are composed of sandy unconsolidated sediments, which can be modified by erosional events, land movements, and bioturbation over time. In the past, and under the assumption these basins were created by aeolian and lacustrine processes, dating methods such as radiocarbon dating and Optically Stimulated Luminescence (OSL) yielded a wide range of late Pleistocene and early Holocene dates that are often subject to researcher interpretation.

For example, an examination of Big Bay in South Carolina [4] found dates ranging from about 2000 ka to 74,000 ka. The authors of this paper proposed that the wide range of dates recovered was due to the Carolina Bays being subjected to periodic episodes of activity, causing the basin to evolve over tens of thousands of years. Using 45 OSL dates, the authors concluded that active shorelines and eolian deposition happened during marine isotope stage (MIS) 2 to the latter part of MIS 3 (~12 to 50 ka), MIS 4 to the end of MIS 5 (60–80 ka), and late MIS 6 (120–140 ka). These timeframes align with the ages of other eolian formations in the Coastal Plain, such as sand sheets and dunefields, indicating that a climatic threshold was reached during the transition toward stadials, which triggered both bay and dune activity.

Thom [30] studied the Carolina Bays in Horry and Marion counties, South Carolina, and concluded that the exact age when the bay depressions and their elliptical shape formed remains uncertain. There is some evidence, such as the age of basal peat in Pee Dee Islands Bay No. 2, suggesting that organic fill began at least 6600 years ago. If the age of the base of the uppermost organic horizon in the Bladen County Bay lakes has regional significance, the final phase of organic fill might have started about 10,000 years ago. The deeper fill in these lakes, dating over 38,000 years in the lower organic zones, implies that some bay depressions existed in early Wisconsin glaciation. Nevertheless, the bay-fill stratigraphy and preservation of bay morphology across numerous bays on various geomorphic surfaces in Horry and Marion counties suggest that bay development processes likely occurred in one or two periods during the Wisconsin glaciation. Thom concludes that bay initiation and orientation appear to bracket the interval from approximately 7,000 to 40,000 years ago.

Some proponents of the glacial ice impact origin for the Carolina Bays argue that since the bays have a mathematically elliptical geometry, they must have originated as inclined conical cavities, and that viscous relaxation reduced the depth of the cavities to produce shallow elliptical basins. In this scenario, all the bays formed contemporaneously within a few minutes rather than over thousands of years. They hypothesize that if the Carolina Bays are impact structures, their rims would have formed from overturned flaps, which would display inverted stratigraphy. Inverted stratigraphy can be identified by analyzing at least three sections of a core sample taken from the rim. Moving from the top layer downwards, the surface contains the newest material that accumulates through regular eolian and sedimentary processes. Directly beneath this youngest layer, there is an older layer of material that was excavated and overturned during the formation of the raised rim. Below this older material, a layer of base material represents the original terrain surface before the impact cavity was formed. Successively deeper layers consist of progressively older material [15].

Moore et al. [31] reported the dates of a core taken from the rim of Flamingo Bay in South Carolina. The sequence of dates in the core identified inverted stratigraphy, where a layer of older sediments is stratigraphically higher than younger sediments. The authors emphasize the significance of luminescence dating for establishing landform chronology. Specifically, at Flamingo Bay (38AK469), single-grain OSL dates (n = 5) collected in 2009 provided minimum age model estimates consistent with the site's observed archaeostratigraphy. These age estimates range from 5.0 kiloannum (ka) at 35 centimeters below the surface (cmbs) (40 cmbd) to 15.5 ka at 80 cmbs (85 cmbd), located beneath archaeological deposits. Age estimates of 9.2 ka and 11.5 ka, between 50 cmbs (55 cmbd) and 65 cmbs (70 cmbd), bracket Early Archaic occupations at Flamingo Bay. Additionally, a 13.1 ka OSL date at 100 cmbs (105 cmbd) statistically overlaps with the 15.5 ka data, potentially indicating a thicker layer of Younger Dryas-aged sediments within the top meter of the sand rim at Flamingo Bay. However, the uncertainties in the base layer's date of 13.1 ± 1.7 ka and the overturned layer's date of 15.5 ±1.8 ka make it impossible to confirm the inversion.

Analysis of a core taken from the rim of a Carolina Bay near the town of Blackville, South Carolina [32] found an unambiguous case of inverted stratigraphy. The samples for optically stimulated luminescence were taken at 107, 152, and 183 cm below the surface. The dates obtained were 12.96 ±1.19 ka at 183 cmbs, 18.54 ± 1.68 ka at 152 cmbs, and 11.5 ± 1.03 ka at 107 cmbs at 1σ probability. The base layer at 12.96 ka is overlaid with material dated at 18.54 ka. From an impact perspective, this older material could have been excavated by the secondary impact to form the overturned flap. The old material was then overlaid with a younger layer dated at 11.5 ka by material that accumulated after the impact.

Theoretically, the base layer under the inverted stratigraphy of a rim should correspond to the date when the bay formed, because it considers the mechanism of crater formation. This includes the creation of the overturned flaps on top of the base terrain at the moment of impact. The dates of the base layers obtained by Moore and Bunch are in the range of the date determined for the Younger Dryas Boundary as stated by Kennett [33] who wrote: "Bayesian chronological modeling was applied to 354 dates from 23 stratigraphic sections in 12 countries on four continents to establish a modeled YDB age range for this event of 12,835–12,735 Cal B.P. at 95% probability. This range overlaps that of a peak in extraterrestrial platinum in the Greenland Ice Sheet and the earliest age of the Younger Dryas climate episode in six proxy records, suggesting a causal connection between the YDB impact event and the Younger Dryas." Further investigation into other Carolina

Bay rims with possible inverted stratigraphy is worth pursuing, specifically from basins emplaced onto the terrain initially to ensure the most accurate dates.

While these proponents of the glacial ice impact hypothesis highlight the onset of the Younger Dryas cooling event as a possible formation date, others argue that all dates recovered from radiocarbon and OSL dating are indicators of extreme erosional events post-formation, making the basins much older. Researchers advocating a Mid-Pleistocene origin for the Carolina Bays propose that these elliptical depressions on the U.S. Atlantic Coastal Plain formed around 786,000 years ago during the Mid-Pleistocene Transition, a period characterized by the Matuyama-Brunhes geomagnetic reversal and a shift from 41,000 to 100,000-year glacial cycles. Davias and Harris [34] have advanced this hypothesis, suggesting that a cosmic impact into the Laurentide Ice Sheet near Saginaw, Michigan, produced a massive ejecta blanket responsible for the bays. Harris's evidence includes suborbital analysis of Australasian (AA) tektites, dated to 788.1 ± 2.8 ka, indicating a launch from a northern hemisphere site with trajectories aligning with a Michigan Impact. He argues this event fluidized terrestrial sediments, depositing them as a conformal silicate aggregate across Southeast Asia and Australia (the antipode of Michigan), with the Bays manifesting as surface voids. The AA tektites [35] align temporally with MIS 19, and Davias and Harris suggest their high-velocity ejection (10 km/s) from a low-angle impact into thick MIS 20 ice explains both their distribution and the bays' formation, with ice plume dynamics dissipating energy, along with seven subsequent glacial cycles, to obscure a traditional crater.

The Mid-Pleistocene Transition hypothesis for the formation date of the Carolina Bays may be supported by their geomorphic context within Pleistocene Marine Isotope Stages (MIS) and interglacial shoreline features as well. Direct evidence of Carolina Bays being truncated by shorelines from either MIS 11c (409–397 ka) or MIS 5e (125–115 ka), the last two times sea levels were higher than today, is not comprehensively documented in the scientific literature, but geomorphic and stratigraphic relationships provide suggestive clues for both periods. The MIS 11c shoreline, tied to a Mid-Pleistocene interglacial highstand with sea levels up to ~20 meters above present, is marked by scarps and terraces such as the Suffolk Scarp in Virginia and the Penholoway terrace in South Carolina [36]. Similarly, the MIS 5e shoreline, from the Last Interglacial with sea levels ~6–9 meters above present, is represented by features like the Princess Anne terrace and the Waccamaw scarp [37]. Truncation by either shoreline, which preliminary research suggests, would imply that affected Bays predate the respective highstand, with their rims cut or altered by the scarp's formation. While definitive dating remains elusive, the Bays' topographic and stratigraphic relationships with Mid-Pleistocene MIS stages and interglacial shorelines provide robust evidence for a Mid-Pleistocene age, urging further geochronological investigation to refine this timeline.

5. Conclusions

The elliptical depressions of North America found in various geological settings exhibit the same well-defined mathematical precision, suggesting they formed simultaneously during a single event. The uniformity of Carolina Bays and Nebraska Rainwater Basins is their most significant feature, and despite speculation, there are no other analogous landforms elsewhere in the world. The mathematically elliptical geometry is a distinct indication that these oriented basins originated as inclined conical cavities or penetration funnels following a primary glacial impact in the Great Lakes region during a previous glaciation cycle of the Laurentide Ice Sheet. The physical characteristics of the Carolina Bays are not consistent with an origin from eolian and lacustrine mechanisms, with or without the aid of permafrost. This paper has introduced a procedure for fitting ellipses to the Carolina Bays using the least squares method to quantify the elliptical geometry of the Bays to less than 3% error, and for distinguishing them from various oriented lakes around the globe. This repeatable method establishes a baseline of credibility for an impact origin of the Carolina Bays that will allow for future research into the timing and ballistic sedimentation of these astonishing geomorphic land features.

Supplementary Materials

A zip file containing the supplemental data (larger images, plotted points, the output of the ellipse-fitting program, etc.) for **Table 2** can be found here: https://drive.google.com/file/d/1Am2TWAvcYsT4MBz4aLskd7L8J6x_nyNW/view?usp=sharing.

Author Contributions

Conceptualization, C.C. and A.Z.; methodology, A.Z.; software, A.Z.; formal analysis, C.C.; writing—original draft preparation, A.Z. and C.C.; writing—review and editing, C.C. and A.Z; visualization, C.C. and A.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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