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A RE-EVALUATION OF THE EXTRATERRESTRIAL ORIGIN OF THE CAROLINA BAYS

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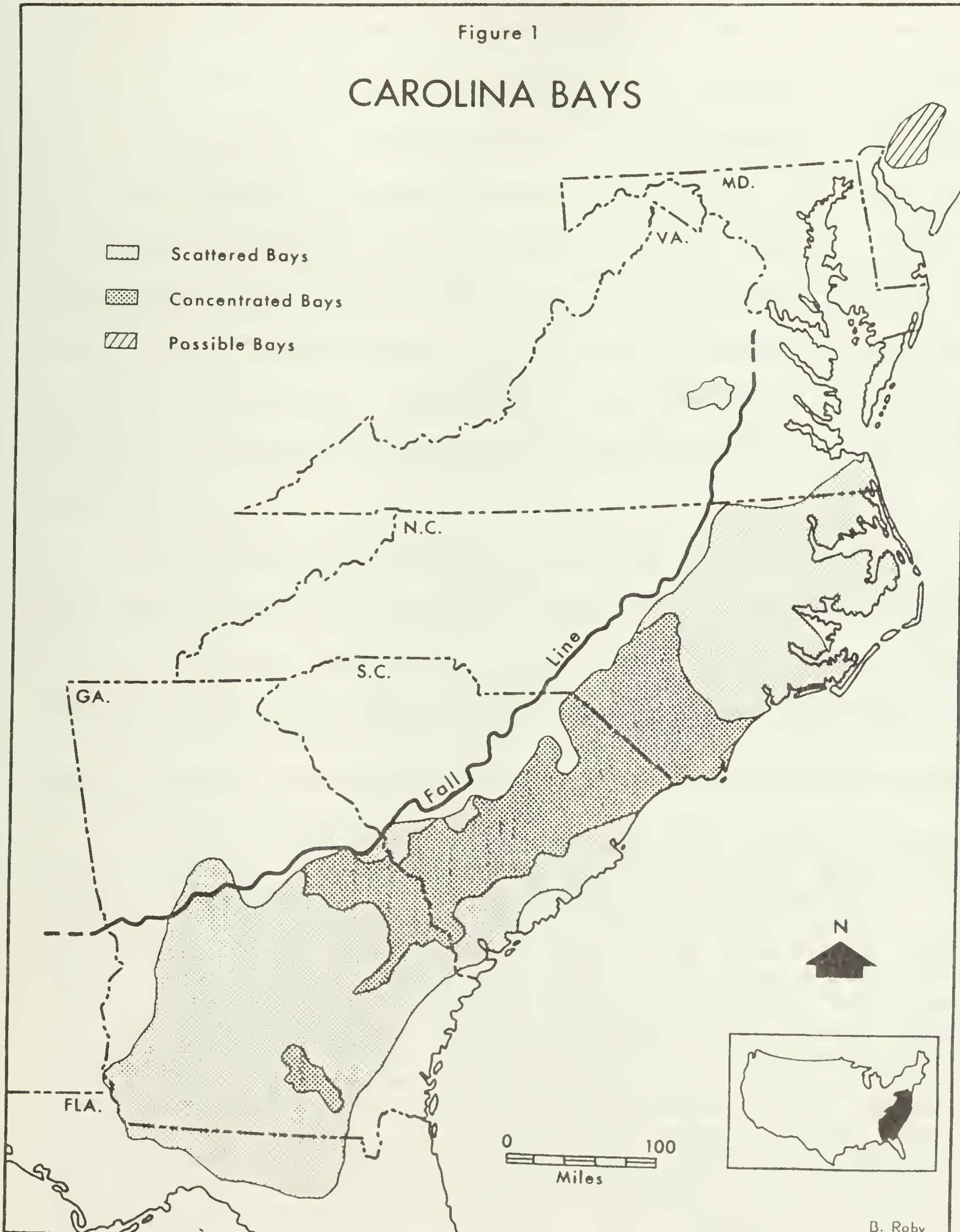
Figure 1
CAROLINA BAYS
Scattered Bays
Concentrated Bays
Possible Bays
MD.
VA.
N.C.
S.C.
GA.
FLA.
Fall Line
N
0
100
Miles
B. Roby

Most hypotheses concerning the origin of the Carolina Bays use either marine or subaerial processes. Some use a single process, others require two or more processes operating simultaneously, whereas still others envision a series of processes operating sequentially. The terrestrial hypotheses have been reviewed elsewhere (Johnson, 1942; Prouty, 1952; Thornbury, 1965; Price, 1968), and some of these theories have been proved mathematically or physically impossible whereas others are considered improbable. Nonetheless, several marine as well as subaerial hypotheses listed below still retain supporters.[1]

Alternative hypotheses to terrestrial processes thus far have been limited to showers of meteorites impacting in the area (Melton and Schriever, 1933; Melton, 1934, 1950; Prouty, 1952; and Well and Boyce, 1953). In this case the Carolina Bays represent scars which have not yet been obliterated by

[1]Marine theories include sand bar dams across drowned valleys (Glenn, 1895); swales in underwater sand dunes (Glenn, 1895); submarine scour by eddies, currents and undertow (Melton, 1934); progressive lagoon segmentation (Cooke, 1934); gyroscopic eddies (Cooke, 1940; 1954); and fish nests created by the simultaneous waving of fish fins in unison over submarine artesian springs (Grant, 1945). Subaerial hypotheses include artesian spring sapping (Toumey, 1848); peat burning by paleo-Indians (Wells and Boyce, 1953); eolian deflation and/or deposition (Raisz, 1934; Price, 1951, 1958, 1968; and Carson and Hussey, 1962); solution (Johnson, 1936; Lobeck, 1939; Le Grand, 1953; and Shockley and others, 1956); periglacial thaw lakes (Wolfe, 1953); wind deflation combined with perched water tables and lake shore erosion at a 90° angle to the prevailing wind (Thom, 1970); artesian spring sapping and eolian deposition (Johnson, 1936); and progressive lagoon segmentation modified by eolian processes stabilized by climatic changes (Price, 1951, 1958, 1968).

terrestrial weathering and erosion. Many people found a meteorite shower to be an appealing explanation because it can explain many attributes of bay morphology and the apparent uniqueness of the Carolina Bays. In addition, the area where Carolina Bays are abundant adjoins a large area from Alabama to Virginia, including much of Tennessee and Kentucky, where meteorites are abundant.

Meteoritic impact is no longer widely regarded as a plausible hypothesis. No meteoritic fragments have been found that are genetically related to the Carolina Bays. No known meteorite falls elsewhere in the world have resulted in approximately half a million depressions over a wide area. Studies of magnetic anomalies associated with individual bays are not conclusive (MacCarthy, 1936; Prouty, 1952). Shatter cones and high pressure changes in quartz grains associated with known impact craters are absent. The heavy mineralogy of sediments within one bay did not differ from sediments beyond the bay rim (Preston and Brown, 1964). The selective confinement of Carolina Bays to one physiographic province has also been cited as evidence against any extraterrestrial hypothesis.

Recent research in Virginia (Goodwin and Johnson, 1970) located depressions similar in alignment and morphology to the Carolina Bays, 345 to 360 feet above sea level, on deeply weathered Piedmont fluvial gravels. If these depressions are truly Carolina Bays, terrestrial hypotheses can no longer

include marine mechanisms, considerably restricting the previous list. No marine terraces are known to be at elevations over 350 feet above sea level along the Atlantic Coastal Plain (Thornbury, 1965). If bays can no longer be restricted to a single physiographic province and the list of potential terrestrial hypotheses is correspondingly reduced to subaerial mechanisms, the extraterrestrial hypothesis gains more credence and warrants additional study.

We do not believe that any existing terrestrial theory fully accounts for all the observed morphologic and stratigraphic characteristics of the Carolina Bays, nor do we believe that extraterrestrial alternatives have been fully explored. The extensive literature on Carolina Bays provides a framework from which we intend to reexamine the extraterrestrial hypothesis. In particular, we propose to examine the physical and orbital characteristics of extraterrestrial objects available for impact, to determine necessary impact parameters which can be met by these bodies, and to assess the correspondence of Carolina Bay morphometry and impact mechanics.

CAROLINA BAY CHARACTERISTICS

Many of the articles mentioned earlier discussed the morphology of the Carolina Bays and several described the stratigraphy of one or more bays. Nonetheless, because the terrestrial or extraterrestrial hypothesis which eventually becomes accepted must account for salient features associated

[illegible]

[illegible]

[illegible]

with the bays, the characteristics are reviewed. Figure 2, a photomosaic of southeastern Cumberland County, North Carolina, illustrates many characteristic morphologic details of the Carolina Bays:

1. The Carolina Bays are ellipses and tend to become more elliptical with increasing size. Many bays, however, lack true bilateral symmetry along either the major or minor axis. The southeast portion of many bays is more pointed than the northwest end and the northeast side bulges slightly more than the southwest side. Known major axis dimensions vary from approximately 200 feet to 7 miles.

2. The Carolina Bays display a marked alignment with northwest-southeast being the preferred orientation. Although there are minor local fluctuations, deviations from the preferred orientation appear to be systematic by latitude (Prouty, 1952).

3. The bays are shallow depressions below the general topographic surface with a maximum depth of about 50 feet. Large bays tend to be deeper than small bays, but the deepest portion of any bay is offset to the southeast from the bay center.

4. Many bays have elevated sandy rims with maximum development to the southeast. Both single and multiple rims occur, and the inner ridge of a multiple rim is less well developed than the outer rim. Rim heights vary from 0 to 23 feet.

5. Carolina Bays frequently overlap other bays without destroying the morphology of either depression. One or more small bays can be completely contained in a larger bay.

6. Some bays contain lakes, some are boggy, others are either naturally or artificially drained and are farmed, and still others are naturally dry.

7. The stratigraphy beneath the bays is not distorted (Preston and Brown, 1964; Thom, 1970).

8. Bays occur only in unconsolidated sediments. Bays in South Carolina are found on relict marine barrier beaches associated with Pleistoncene sea level fluctuations, in dune fields, on stream terraces and sandy portions of backbarrier flats (Thom, 1970). No bays occur on modern river flood

FIGURE 2

CAROLINA BAYS

CUMBERLAND COUNTY,NORTH CAROLINA

scale 0 1 2 miles

The photo displays many attributes common to Carolina Bays, including bays within bays, alignment, and rim development.

plains and beaches. Bays exist on marine terraces as much as 150 feet above sea level in South Carolina but also occur on discontinuous veneers of fluvial gravels on the Piedmont in Virginia (Goodwin and Johnson, 1970).

9. Carolina Bays appear to be equally preserved on terraces of different ages and formational processes.

10. Bays occur in linear arrays, in complex clusters of as many as fourteen bays, as scattered individuals, and in parallel groups aligned along the minor axes (Figure 2).

11. Bays are either filled or partly filled with both organic and inorganic materials. The basal unit in some bays is a silt believed to represent loess deposited in water.

12. No new bays appear to be forming although Thom (1970) and Frey (1954) cite evidence for recent enlargement of existing Carolina Bays. Price (1968) states that most bays appear to be getting smaller by infilling.

13. Bays are underlain by carbonate, clastic and crystalline bedrock overlain by variable thicknesses of unconsolidated sediments in which the bays are found.

14. Ghosts of semi-obliterated Carolina Bays appear to represent former bays which were filled after formation by terrestrial sediments and organic materials.

15. Small bays deviate further from the mean orientation per region than large bays do.

16. No variation in the heavy mineral suite was found along a traverse of the major axis of one South Carolina bay, even though samples were taken from the bay floor, bay rim and the adjacent non-bay terrace (Preston and Brown, 1964).

In summation, the remarkable regularity with which these characteristics recur suggests that further consideration of a unique, causal mechanism is warranted. With rare exceptions, such as the aligned lakes of the Arctic Coastal Plain (Carson and Hussey, 1962), terrestrial processes do not create widespread, elliptical, aligned landforms. Whereas morphology and alignment are not conclusive proof of an extraterrestrial

hypothesis, and although we recognize valid weaknesses in the existing meteoritic swarm or shower hypothesis, we believe that most of these objections should not serve as a deterrent for a re-examination of additional extraterrestrial alternatives.

OPPOSING EXPLANATIONS OF BAY CHARACTERISTICS

Early researchers, notably Melton and Schriever (1933) and Prouty (1952), inferred an extraterrestrial causal mechanism primarily from the regularity with which elements of bay morphology repeated themselves in the Carolina Bays. They concluded that the list of characteristics was best explained by impact of a meteorite shower (Melton and Schriever, 1933) or its shock wave (Prouty, 1935; 1952; MacCarthy, 1936). They speculated that the meteorite shower or swarm might be related to a degenerate comet perturbed into a low angle, northwest trajectory. This hypotheses accounts for such morphologic characteristics as maximum rim development offset to the southeast end of many bays, variable rim height, bay overlap, bays contained within bays, maximum depth offset southeast from the bay center, variability in bay size, and equal degree of preservation on surfaces of different ages. Because a single meteorite shower could not readily explain ghost bays, Melton (1950) subsequently modified his original impact hypothesis to include aperiodic meteorite showers, possibly beginning during the Cretaceous.

Critics of the extraterrestrial hypothesis have also used bay morphology and morphometry to refute an astronomical origin for the Carolina Bays (Johnson, 1942; Price, 1968). The bays lack the elevated structural rims associated with known meteorite impact craters; craters tend to be deep and round whereas the bays are shallow ellipses; known meteor crater clusters, such as those at Campo del Cielo, Argentina (Cassidy and others, 1965), do not result in thousands of depressions across a wide area; and, as noted previously, no known meteorites are genetically related to bays. Thornbury (1965, p. 43) added that aperiodic Mesozoic and Cenozoic meteorite showers are "difficult to visualize in view of the fact that the bays are present on terrace surfaces that are generally considered to be of Pleistocene age."

The only additional bay characteristic to receive considerable attention has been bay alignment, although a few stratigraphic, mineralogic, or ecologic characteristics have also been studied for individual bays (Frey, 1951; 1954; Preston and Brown, 1964; Thom, 1970). Working in a localized area in South Carolina, Melton and Schriever (1933) found an apparent parallel orientation for the major axes of the bays. They assumed that all bays would display similar orientation because the meteorites in the shower would maintain roughly the same trajectory. Prouty, using a much larger sample of bays with greater areal extent, recognized the radial pattern in bay alignment.

> The average local orientation of the bays varies from about south 55° east in the northwestern portion of the area to about south 15° east in the southwestern area. There is thus a divergence of about 40° in the elongation direction of the bays in the two extreme areas. . . . This divergence is due to the fanning-out effect of a group of bodies, the meteorites, passing through the resisting gaseous medium of the atmosphere (Prouty, 1952, p. 186).

Prouty added that variance from the mean orientation for bays in a particular location was caused either by the effects of a "partial vacuum in the air pressure cone accompanying the fall of tandem meteorites" (p. 187) or "mild" explosions of meteorites caused by atmospheric resistance. He suggested that small meteorites would be more affected by this phenomenon than large ones, causing small meteorites to deviate further from the original trajectory.

While some opponents of extraterrestrial hypotheses did not consider bay alignment, others ascribed orientation to a variety of terrestrial causes. For example, Cooke (1934) said that a unidirectional wind had generated near-shore currents which created parallel landforms, accounting for bay alignment and elongation. Johnson (1942) suggested that elongation and parallelism were caused by joint controlled artesian springs along the southeasterly regional dip of the strata. Thom (1970) postulated that southwest winds blowing across preexisting lakes generated currents which eroded the southeast and northwest segments of each lake, creating parallel elliptical landforms. Furthermore, based on evidence from northeast South Carolina,

Thom concluded that mean orientations and standard deviations of Carolina Bays differed from beach ridges, dune fields, river terraces, and back barrier flats. Whether this relationship between geomorphology and orientation would remain consistent on a regional level is not known. The degree to which this apparent alignment is a function either of sampling or of bay size per geomorphic setting is also unknown. Small bays do differ more widely in their orientations than large bays do.

EXTRATERRESTRIAL BAY FORMING MECHANISMS

With the exception of MacCarthy (1936), who discussed the effects of the shock wave accompanying infall of meteorites, research on the Carolina Bays has been concentrated on terrestrial characteristics. No one has discussed the orbital characteristics of potential impacting bodies, the extraterrestrial mass required to produce half a million bays, the availability of extraterrestrial materials, the bay forming energies available related to different impact velocities and masses, and whether impact morphometry corresponds to Carolina Bay morphology.

Because the probability of inclusion of any body outside the solar system is extremely small, the solar system is commonly regarded as a closed system. If impact of an extraterrestrial body did form the Carolina Bays, the body or bodies must be contained within the solar system. Only three minor

members of the solar system can possibly impact on earth: asteroids, comets, and meteoriods. If the Carolina Bays are the result of a singular extraterrestrial event, then bay forming impacts could have been caused by any one of these objects. Examination of the physical and orbital characteristics of these bodies, then, provides one method for selecting from extraterrestrial alternatives the most likely bay-forming mechanism.

Orbital Characteristics

Tables 1, 2, and 3 indicate salient characteristics for the three extraterrestrial alternatives. Of the three, asteroids (Table 1) appear to be the most predictable with respect to their physical and orbital characteristics. They have more regular orbits than either comets or meteoroids, albeit a few asteroids such as Icarus and Hidalgo have highly eccentric orbits and Hermes passed within 500,000 miles of Earth in 1937. Although it is difficult to determine the actual number of close encounters that have taken place, Wyatt (1966) assumed one impact per 60,000 years to be a crude estimate of the probability of impact by an asteroid one mile or less in diameter. Comets (Table 2), on the other hand, have either parabolic or elliptical orbits, depending on whether or not they have been perturbed and whether the perturbation resulted in short or long period orbits. It is not possible to estimate the probability of impact for comets with parabolic orbits, but the

TABLE 1

ASTEROIDAL CHARACTERISTICS[1]

Characteristic	Descriptions	
Size - Frequency	Diameter (miles)	Frequency
	> 200	3
	100 - 200	15
	50 - 100	50
	25 - 50	400
	12½ - 25	2500
	< 12½	> 1000's
Orbits	location	dominantly between Mars and Jupiter
	motion	direct
	inclination	typically up to 30°
	eccentricities	range is .1 to .3
Physical Attributes	shape	most small asteroids have elongated or irregular shapes
	material	colorimetric observations indicate material properties similar to the moon
	other	polametric studies indicate intricate micro-fracturing and possible dust mantles
Possible Origin	The planetessimal forming process was interrupted from perturbations by the planet Jupiter. The larger asteroids are thought to be remainders of the original planetessimals. Smaller asteroids are the fragmented remains of earlier collisions.	

[1]after Wyatt, 1966; Hartmann, 1973.

TABLE 2

COMET CHARACTERISTICS[1]

Characteristic		Descriptions	
Orbit - Frequency		Short Period	Long Period
	total observations	94	472
	prograde #	87	227
	retrograde #	7	245
	typical inclination	15°	random
	typical orbit	elliptical	290 (parabolic) 182 (elliptical)
	aphelion	5 A.U.[2]	infinity for parabolic orbits up to 2 light years for ellipses
Physical Attributes (Nucleus)	density	$1.00 - 1.3 g/cm^3$	
	mass	$10^{15} - 10^{19} g$	
	diameter	<1 - 10 km	
	composition	OH, [OI], CH, CH_2, NH, NH_2, CN, C_2, C_3, H_2O (spectrophotometer emission bands)	
Possible Origin	Comets may be the result of planetessimal formations at the outer edge of the solar system which were perturbed out of the solar system by the gas giant planets. The residing location of comets is called Oorts cloud, a reservoir of cometary material from which a comet by chance is perturbed towards the sun. Some of these comets may undergo further perturbation by Jupiter and become short period comets.		

[1]after Hawkins, 1964; Wyatt, 1966; and Hartmann, 1973.

[2]Astronomical Units

TABLE 3

METEOROID CHARACTERISTICS[1]

Characteristic	Descriptions		
Types	Sporadic	Shower	Fireball
	meteorites are possible	meteors only	low velocity have inclinations from 0 - 30° with aphelions under 5 A.U.
	prograde orbits	either prograde or retrograde orbits	high velocity have higher inclinations and much greater aphelions
	aphelion near asteroid belt	aphelions range up to 100's A.U.	
Physical Attributes	density		type
	$1.0 g/cm^3$		shower
	$1.0 g/cm^3$ to $8.0 g/cm^3$		sporadic meteorites
	$.4 g/cm^3$ to $1.2 g/cm^3$		fireballs
Meteoritic Finds	class		frequency
	stones (Aerolites)		92.8%
	stony-irons (Siderolites)		1.5%
	irons (Siderites)		5.7%
Possible Origin	Most shower meteors are thought to be the non-volatile remains of degenerate short period comets. Meteorites are probably asteroidal fragments while fireballs are most likely to be small cometary nuclei or fragments of a cometary nucleus.		

[1]after Hartmann, 1973.

probability is small based on the number of comets known to have parabolic orbits. Meteoroids (Table 3), the mechanism most commonly invoked to explain the Carolina Bays (Melton and Schriever, 1933; Melton, 1934, 1950; Prouty, 1952; and Wells and Boyce, 1953), consist of three types but have orbital characteristics similar to those of either asteroids or comets. Those meteoroids which create meteor showers but produce no finds are believed to be the remains of degenerate short period comets. Although they may be large in numbers with observed rates of 50 per hour, their mass is insufficient to survive atmospheric passage. Sporadic meteoroids which can survive atmospheric passage as stones or irons are probably fragments of asteroids, and fireballs, the remaining class, may be nuclei of small comets.

Meteoroids are the least regular in physical character and origin of the three extraterrestrial alternatives, yet they have been hypothesized as the extraterrestrial causal mechanism responsible for the formation of the Carolina Bays. The authors strongly believe that meteoroids are the least likely among the extraterrestrial alternatives. Although the shower hypothesis (Melton and Schriever, 1933; Melton, 1934, 1950; Prouty, 1952; and Wells and Boyce, 1953) may account for a sufficient number of objects to form half a million bays, it is doubtful that there was sufficient mass to survive atmospheric passage. No finds have been recorded from the meteoroid

streams and swarms which are responsible for meteor showers. The larger sporadic meteoroids which probably originated as asteroidal fragments may survive passage through the atmosphere, as attested to by the number of finds. Although they may travel in small groups or may break up into several dozen pieces in the atmosphere, it is unlikely that they existed in sufficient numbers to create half a million Carolina bays. In addition, the orbits of the sporadic meteoroids suggests that their impact on Earth is an individual random process very unlike the impingement of the shower meteoroids.

Only two classes of extraterrestrial alternatives remain. Based solely upon the characteristics previously discussed, Carolina Bays could be the result of either prograde asteroidal bodies perturbed out of orbit, or they could have been formed by collision with a relatively young comet nucleus moving either in prograde or retrograde motion. The probabilities of collision with a retrograde object are somewhat higher than the prograde or directly moving object, because an object perturbed out of a direct orbit will, when crossing planetary orbits, spend more time in the vicinity of the planets which are moving in the same general direction as the perturbed body. Further perturbations are likely and the object will most probably end up in orbit about the sun.

Velocities

In addition to the previous physical and orbital characteristics, a discussion of the impact velocities on Earth is

necessary to complete the picture. The minimum and maximum velocity range is easy to determine. Prograde motion, objects which just barely "catch up" to the Earth, will result in impacts on the surface of the Earth at escape velocity (≈11km/sec). This is the minimum velocity expected for any impacting body. Objects which have come from the farthest reaches of our solar system may reasonably be expected to have velocities near the escape velocity of the solar system (≈42km/sec). If the object exhibits retrograde motion, the impact velocity on Earth will be additive, equal to the velocity of that body plus the velocity of the Earth as it moves in orbit about the sun (30km/sec). For objects such as comets which have retrograde motion, a parabolic orbit and velocities near the escape velocity of the solar system, the maximum impact velocity would then be 30 + 42 = 72km/sec. A comet with a prograde orbit would then impact at 42 - 30 = 12km/sec. Meteoroids would impact at velocities ranging from the minimum (11km/sec) to a maximum (72km/sec). This range is confirmed by observation of meteor velocities. A reasonable impact value for asteroids perturbed out of orbit in direct motion is 16km/sec.

Impact Mechanics

If the Carolina Bays are the result of impact of a fragmenting comet or asteroid, aspects of impact mechanics may lead to further conclusions concerning the likelihood of such an event. The basis for these impact studies are found in the

energy relationships for terrestrial craters, both from impact and from nuclear explosion, and are well documented by Baldwin (1963). The results of these experiments can be stated as a simple cube scaling law where crater diameters are proportional to the cube root of the energy of the explosion.[1] For one such explosion (Teapot-Ess) a 300 foot crater was produced by a 1.2 kiloton nuclear device. The relationship for this blast is:

$$D = kW^{1/3}, \tag{1}$$

where:

D = diameter of the crater in feet
k = proportionality constant
W = energy of blast in ergs (1 ton TNT = 4.16×10^{16})

Solving for the proportionality constant:

$$300' = k \sqrt[3]{(1.2 \times 10^{3})(4.16 \times 10^{16})}$$

$$k = 8.1 \times 10^{-5} \quad .$$

This relationship ($D = 8.1 \times 10^{-5} \times W^{1/3}$) has been used for impact craters and for craters produced by other nuclear devices and appears to be legitimate. This expression, then, can be applied to the Carolina Bays to determine the size of object necessary to produce one average bay and the size of object required to produce all bays, assuming fragmentation. The energy, W, can be calculated by assuming all the kinetic energy to be available for the blast. The cube scaling law then becomes:

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[1]More exact relationships can be found using exponents other than 3.00 (Baldwin, 1963). The authors feel, however, that simple cube scaling will suffice for a first approximation.

$$D = k(1/2MV^2)^{1/3}, \tag{2}$$

where:

$$1/2MV^2 = \text{kinetic energy.}$$

If assumptions are made concerning the velocity of impact (V) needed to form a particular size crater (D), then the mass can be determined from equation 2 or rewriting as 3:

$$M = \frac{2D^3}{k^3V^2} \quad . \tag{3}$$

Further assumptions can be made as to the density of the material, and the size of the object represented as a sphere can be determined from equation 4 shown below:

$$R = \frac{1.5D^3}{\rho\pi k^3V^2} \quad , \tag{4}$$

where:

D = diameter of crater in feet
ρ = density of impacting material g/cm^3
k = proportionality constant of cube scaling
F = velocity of impacting body in cm/sec.

This model was used to determine the size of a single fragment necessary to create a Carolina Bay one-half mile in diameter and the original dimensions of the body needed to create 500,000 bays of the same size. This was done as a small computer program (Appendix A) in which different velocities, densities, exponents and proportionality constants for cube scaling could be changed. The results for impacting asteroids and comets are shown in Table 4. Only the values from the computer output for the upper and lower limits of the impact

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

velocity are included. The resulting size range appears to fit the range of expected diameters for either comets or asteroids.

TABLE 4

IMPACT MECHANICS[1] FOR HIGH AND LOW VELOCITY ASTEROIDS AND COMETS

Impacting Body	Impact mps	Velocity (km/sec)	Density g/cm^3	Single Fragment[2] Mass lbs (kgm)	Single Fragment[2] Diameter ft (m)	Entire Body[3] Mass T (MT)	Entire Body[3] Diameter mile (km)
Asteroid	7	(11)	3.00	$.118\text{X}10^6$ ($.536\text{X}10^8$)	106.4 (32.43)	$.608\text{X}10^{10}$ ($.268\text{X}10^{11}$)	1.6 (2.57)
Asteroid	10	(16)	3.00	$.579\text{X}10^5$ ($.263\text{X}10^8$)	83.89 (25.57)	$.298\text{X}10^{10}$ ($.131\text{X}10^{11}$)	1.26 (2.03)
Comet	7	(11)	1.30	$.118\text{X}10^6$ ($.536\text{X}10^8$)	140.6 (42.86)	$.608\text{X}10^{10}$ ($.268\text{X}10^{11}$)	2.1 (3.4)
Comet	45	(72)	1.30	$.286\text{X}10^4$ ($.130\text{X}10^7$)	40.67 (12.40)	$.147\text{X}10^9$ ($.649\text{X}10^9$)	.61 (.98)

[1]Cube scaling = 3.00, energy available for impact = 100%
[2]Mean diameter of crater = 2640.0 ft (1/2 mile)
[3]Total number craters = 500,000

Other constraints on the fall and impact process can restrict the model. A limit can be set on the mass of an object which will pass through the Earth's atmosphere without retardation of velocity. Objects with masses of one ton or less will be decelerated until the original impact velocity has reached zero and the object will continue to fall at terminal velocity in the atmosphere. Objects greater than 1000

tons will not significantly decrease in velocity (Hawkins, 1964, p. 90-91).

Further complications exist if the body breaks into fragments as required for bay formation. The mass of the objects (Table 4) are appreciably greater than 1000 tons and will, on entering the atmosphere, maintain their original approach velocity. After fragmenting, the individual particles range in size from approximately one ton for a fast moving comet to fifty tons for a slow moving asteroid. If fragmentation occurs at a fairly high altitude, then considerable deceleration and loss of mass through ablation will probably occur. Fragmentation at lower altitudes would reduce ablation and deceleration considerably. Both instantaneous and continual fragmentation has been observed in meteor falls. It is expected that the higher velocity objects impinging on the Earth's atmosphere are more apt to break up (Hartmann, 1973, p. 180).

Although the characteristics of fragmentation favors a cometary impact, the general impact model appears to satisfy the requirements for either a comet or an asteroid collision. Examination of the morphometric characteristics of the Carolina Bays may permit further differentiation as to the possible source of the impacting body.

Crater Morphometry and the Carolina Bays

The majority of lunar craters and known terrestrial cryptoexplosion features such as Gosses Bluff, Australia (Milton

and others, 1972), and the Arizona Meteorite Crater are commonly recognized as impact structures. Such features, similar in form to craters produced by chemical or nuclear devices, result from the release of energy at or below ground level caused by impact of a rapidly moving mass. These energies override the chemical bonds in the rock, causing severe deformation and brecciation plus formation of high-density SiO_2 polymorphs and shattercones (Baldwin, 1965). If the velocity of the mass is sufficient (over 6 miles per second), the impact results in a violent explosion, vaporizing some or all of the impacting particles.

Because impact craters are analogous to chemical and nuclear explosions, much crater research has concentrated on these more readily available, if smaller sized forms (see Baldwin, 1963; 1965). Various morphometric crater characteristics have a fundamental relationship -- expected logarithmic relationships between crater depth (D) and crater diameter (d), between rim height (RH) and diameter, and between crater rim width (RW) and diameter. Impact craters ranging from several inches to hundreds of miles in diameter are plotted in Figure 3a. While Baldwin plotted both cubic and linear solutions, the shallow cubic relationship deviated only slightly from the linear solution (Baldwin, 1965, p. 68-72). Therefore, only the straight line approximations are included in Figure 3a.

For a Carolina Bay with a major axis of one mile to be regarded as an impact crater, the expected depth should be

Figure 3a: Logarithmic Depth (d), Rim Width (RW), Rim Height (RH) vs. Logarithmic Diameter (D) for Impact Craters

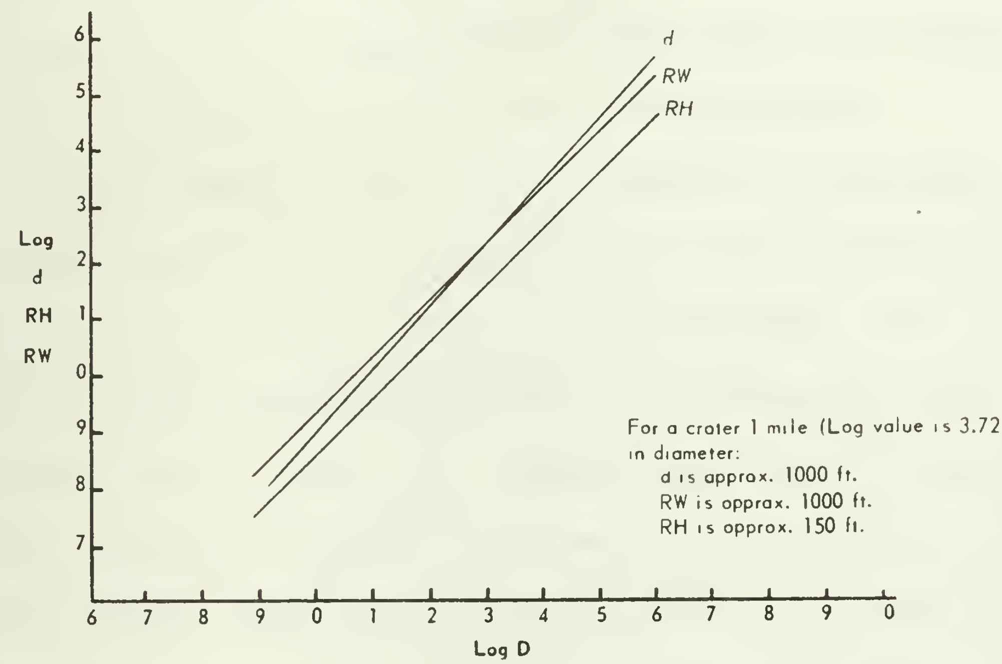
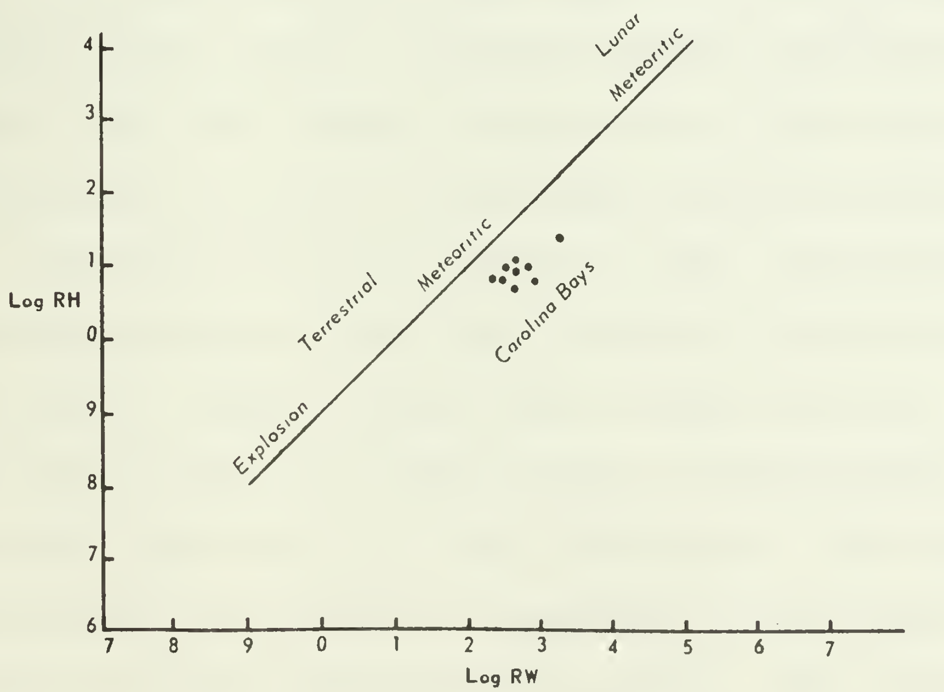


Figure 3b: Logarithmic Rim Height (RH) vs. Logarithmic Rim Width (RW)



approximately 1,000 feet, the rim height 150 feet and the rim width 1,000 feet. There are few field data available on the depths of Carolina Bays. However, from descriptions of bays with a major axis of approximately one mile, the depth is less than 1,000 feet by several orders of magnitude.

Actual measured data on any aspect or Carolina Bay morphometry are scarce. Measurements are confined to rim heights and rim widths for nine bays (Prouty, 1952, p. 179-183) with bay length determined either from Prouty's text of U.S.G.S. topographic maps (Table 5). Those bays such as Junkyard and St. Luke's Church, which are close to one mile in length along the major axis, have rim heights of less than ten feet, whereas the expected rim heights derived from Baldwin approximate 150 feet. The rim widths, on the other hand, are somewhat closer to the expected values. Baldwin's model predicted widths of almost 1,000 feet whereas Junkyard has a mean rim width of 575 feet and St. Luke's Church has a mean rim width of 300 feet.

According to Prouty (1952, p. 183), the maximum rim width for Junkyard Bay is 1,200 feet, whereas the maximum cited rim width for St. Luke's Church Bay is only 350 feet. In both cases the maximum rim widths occur at the southeast end of the bays wher rims tend to be best developed. Observed rim width maxima sometimes exceed and sometimes do not approach the predicted rim widths from Baldwin's model. Part of this variation may represent field measurement error: the rim heights are low,

TABLE 5

BAY MORPHOMETRY

Bay Name	Location	$\bar{x}$ RH (feet)	$\bar{x}$ RW (feet)	Major Axis (feet)
Lake Waccamaw	Columbus Co., N.C.	23.0	2000	32,366
Junkyard	Clarendon Co., S.C.	7.4	575	6,660
Polk Swamp	Orangeburg Co., S.C.	7.4	378	13,590
St. Luke's Church	S.C. (county unknown)	5.25	300	6,300
Grassy	Allendale Co., S.C.	5.25	272	7,286
Big Horsepen	S.C. (county unknown)	7.25	525	7,804
Bowman	(location unknown)	6.0	750	10,230
Little Sister	Marion Co., S.C.	4.5	350	10,560
Swallow Savanna	Alendale Co., S.C.	7.8	523	3,150

after Prouty, 1952, pp. 179-183

the rim width slopes are quite gentle, and the outside perimeter of the rim is irregular, almost scalloped, causing wide fluctuations in rim widths over short distances.

Carolina Bays do not even closely approximate impact crater morphometric characteristics. The rim widths appear to be the only measure which even falls within the range predicted by the impact model. In an attempt to examine this phenomenon, a curve relating rim height and rim width was derived from Baldwin's curves and the values for the bays in Table 5 were

plotted (Figure 3b). For an impact crater to have a rim height of 7.5 feet, it should have a rim width of 100 feet. Junkyard Bay has a mean rim width of 575 feet with a mean rim height of only 7.4 feet. In all nine bays, rim width is considerably greater with respect to rim height than the model predicts. As impact structures, the Carolina Bays exhibit crater depths that are much too shallow for their diameter, rim heights that are too low for their diameter, and rim widths that are too narrow for their diameter. The rim widths are considerably wider than is expected with respect to the actual rim heights. Clearly, the bays are not impact phenomena of the type that created the lunar and terrestrial craters. Additional terrestrial Carolina Bay characteristics such as the absence of coesite and stishovite (SiO_2 polymorphs), the lack of any meteorites genetically related to bays, and the elliptical, rather than circular form of the bays, also do not support any traditional type of extraterrestrial impact bay formation model.

A COMET AS THE BAY FORMING MECHANISM

One other aspect peculiar to comets may be important to the genesis of the Carolina Bays. Because of the volatile content in a comet nucleus, a collision trajectory may not result in actual impact. Observations of meteors and fireballs indicate that some of these objects break up as they enter the Earth's atmosphere and sometimes explode in the air.

The 1908 Tunguska fall in Siberia is commonly regarded as the explosion of a very small comet nucleus. Hartmann (1973, p. 146) said that the explosion, estimated to be 10^{21} to 10^{23} ergs, knocked a man off his porch 38 miles away. Trees as much as nine miles from the impact site were felled radially outward by the shock wave, whereas trees at ground zero were merely denuded of their branches and left in growth position. Baldwin (1963, p. 37) added that trees in protected locations such as deep valleys remained standing and in some cases were still alive. According to Hartmann (p. 146), by 1928 when trained observers first visited the site, they found the impact site to be pockmarked with a series of shallow, funnel-shaped depressions of variable width but not more than four or five meters in depth. No meteorites were discovered. Baldwin (1963, p. 37) noted that in 1928 the original forest vegetation was replaced with tundra except in the craters where swampy vegetation was already well established.

Hartmann (1973, pp. 146-147) summarized the evidence supporting a cometary origin for the 1908 fall:

> 1. The object evidently exploded in the air, since trees at "ground zero" stood upright but were stripped of branches. A loosely consolidated ice comet nucleus would be expected to volatilize and explode before it hit the ground.
>
> 2. The lack of meteorite fragments is consistent with our picture of a predominantly icy nucleus.
>
> 3. A 1961 expedition recovered soil samples that contained small spherules believed to be part of the object. The spherules would be consistent

[illegible]

with the idea of an admixture of small grains of non-icy "dirt" in the dirty iceberg and their spherical shape could be the result of sudden melting during the explosion.

4. Observations of the motion of the object across the sky indicated that it was traveling toward the earth probably in retrograde motion at a very high velocity, perhaps 50 km/sec, which would be typical of a comet but not of ordinary meteorites. . . .

5. For weeks afterward, the night sky in Europe and Russia was anomalously bright. This may have been due in part to atmospheric interaction with tail and coma material (although the comet was too small to have been noticed prior to the collision, being on the order 10^{10} to 10^{11}g in mass instead of about 10^{18}g, typical of observed comets).

Multiple shallow craters of variable widths, a climax vegetation destroyed except where topographically protected, the absence of meteoritic finds, a high velocity but low angle trajectory, plus a shock wave felt at least 38 miles and heard 620 miles from the impact site suggest a cometary explosion before actual impact. Hartmann stated that the Tunguska fall was a small comet nucleus. If such a singular event happened once, it could happen at least once more.[1]

Available Cometary Energy

In a discussion of the energies needed to produce craters by nuclear explosions, Baldwin (1963, pp. 41-42) indicated that:

---

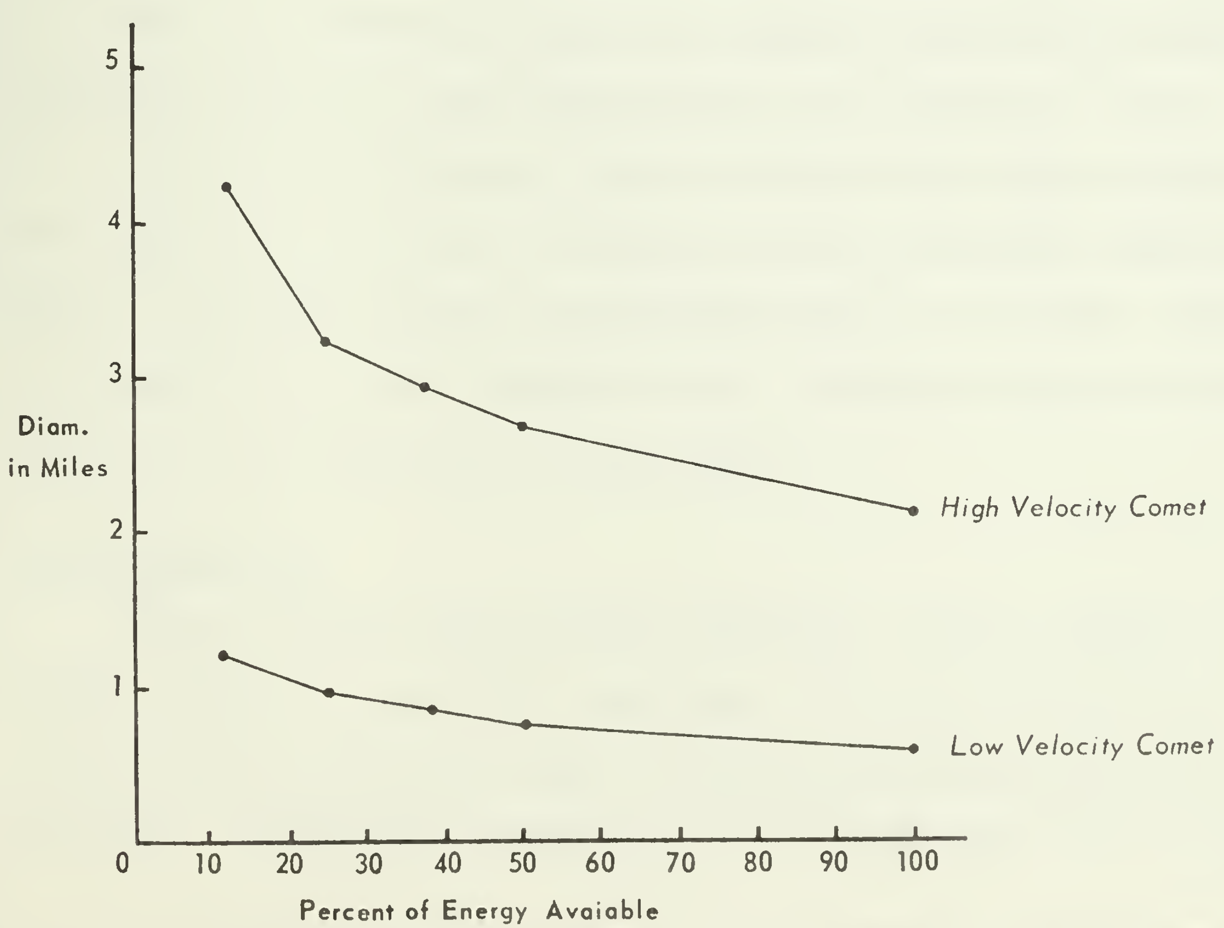
[1]While a heading in the article concerning the original extraterrestrial hypothesis mentions the possibility of a cometary impact (Melton and Schriever, 1933, p. 63), the article never explores such a mechanism as an alternative to meteoritic showers.

> As the transition is made from an air burst to a surface burst to a subsurface burst, the energies which go to produce the crater become an increasing percentage of the total energy and the attenuation of the shock waves in the air becomes marked. The maximum blast effect of a 20 KT bomb are greatest for a height of [air] burst of about 1,850 feet.

Baldwin reports that calculations of the energy in the Tunguska air blast could be the equivalent of a 23.9 KT bomb.

In an attempt to see how a reduction of energy because of an air blast would affect the impact model, we re-ran the model using decreasing amounts of energy available for impact (Figure 4). The diameter for the comet nucleus is within an acceptable range of sizes of available cometary material.

Figure 4: Comet Diameter vs. Energy Available for Impact



Impact of a shock wave caused by an air blast has considerable portent for structure of the bays. The shock wave would be extended for the duration of time each particle volatized and exploded. This could account for the elliptical structure of the bays. The elliptical structure would also be more pronounced if the trajectory of the comet as it approached the earth's surface was low. We have not been able to ascertain what the specific shape of the Tunguska craters were. Presumably, since descriptions refer to diameters, the depressions are probably rounded or sub-rounded rather than elliptical. However, the Campo del Cielo meteorite which fragmented in the atmosphere over Chile and Argentina produced individual craters which are elliptical to sub-rounded (Cassidy and others, 1965, p. 1058), so ellipticity, per se, cannot rule out an extraterrestrial origin as was suggested by Price (1968, p. 104).

A shallow trajectory and air blast could also account for the apparent piling up of material on the southeast rims of the bays. Although a fairly speculative model at present, there is the precedence of the Tunguska fall. Further support can be found in the orientation of the bays.

Bay Orientation

Many scholars (Melton and Schriever, 1933; Johnson, 1942; Prouty, 1952; Price, 1968; and Thom, 1970) have variously interpreted the northwest-southeast orientation of the major axes of the bays. Melton and Schriever (p. 63) said that the alignment

is and should be parallel, because bays formed by a meteoritic shower of particles were on a common trajectory. Johnson, using mean orientation of 75 bays scattered from North Carolina to Georgia, said that the azimuthal standard deviation was too large for alignment to be a significant bay attribute. Later, when Prouty measured the orientation of Carolina Bays, he recognized a radial alignment with southern locations having orientations slightly west of north and northerly bays oriented almost due west.

We measured the azimuths of a 358 bay sample including fourteen counties from Georgia north to Virginia (Table 6). The mean azimuths vary from 344.2° in southern South Carolina and 342.6° in southern Georgia to a mean azimuth of 294.9° in Virginia. In general these results appear to verify those of Prouty who stated that there was a systematic latitudinal variation in orientation. Systematic locational variation may have led Johnson to conclude that the overall standard deviation was too large to be meaningful.

While our mean azimuth (342.6°) for Atkinson County, Georgia, is similar to Prouty's 345° for the same county, measurement error is a very real possibility. Measuring the precise orientation of an ellipse where overlap occurs is difficult. Although we omitted bays where we thought the orientation was too indistinct, some subjectivity in the actual alignment certainly occurred. Relatively small sample sizes,

particularly in counties with wide azimuthal fluctuations, also affects the results. Nonetheless, a wide scatter in bay orientations in a localized area has a possible significance.

TABLE 6

CAROLINA BAY ORIENTATION

State	County	Number Measured Bays	$\overline{X}$ Azimuth	S_x	± 1 S_x in Degrees
Ga.	Atkinson	27	342.6°	16.5	359.1 - 326.1
S.C.	Allendale	10	341.4°	7.8	349.2 - 333.6
S.C.	Barnwell	30	344.2°	5.1	349.3 - 339.1
S.C.	Florence	2*	322.0°	---	-------------
S.C.	Georgetown	9	328.4°	6.5	334.9 - 321.9
S.C.	Horry	38	312.3	6.1	318.4 - 306.2
S.C.	Lee	2*	319.5°	---	-------------
S.C.	Marion	8	316.5°	6.7	323.2 - 309.8
S.C.	Sumter	3*	342.0°	---	-------------
N.C.	Bladen	98	311.4°	4.7	316.1 - 306.7
N.C.	Carteret	9	300.4°	6.3	306.7 - 294.1
N.C.	Cumberland	15	311.6°	8.5	320.1 - 303.1
N.C.	Robeson	90	311.2°	5.8	317.0 - 305.4
Va.	Powhatan	17	294.9°	20.3	315.2 - 274.6

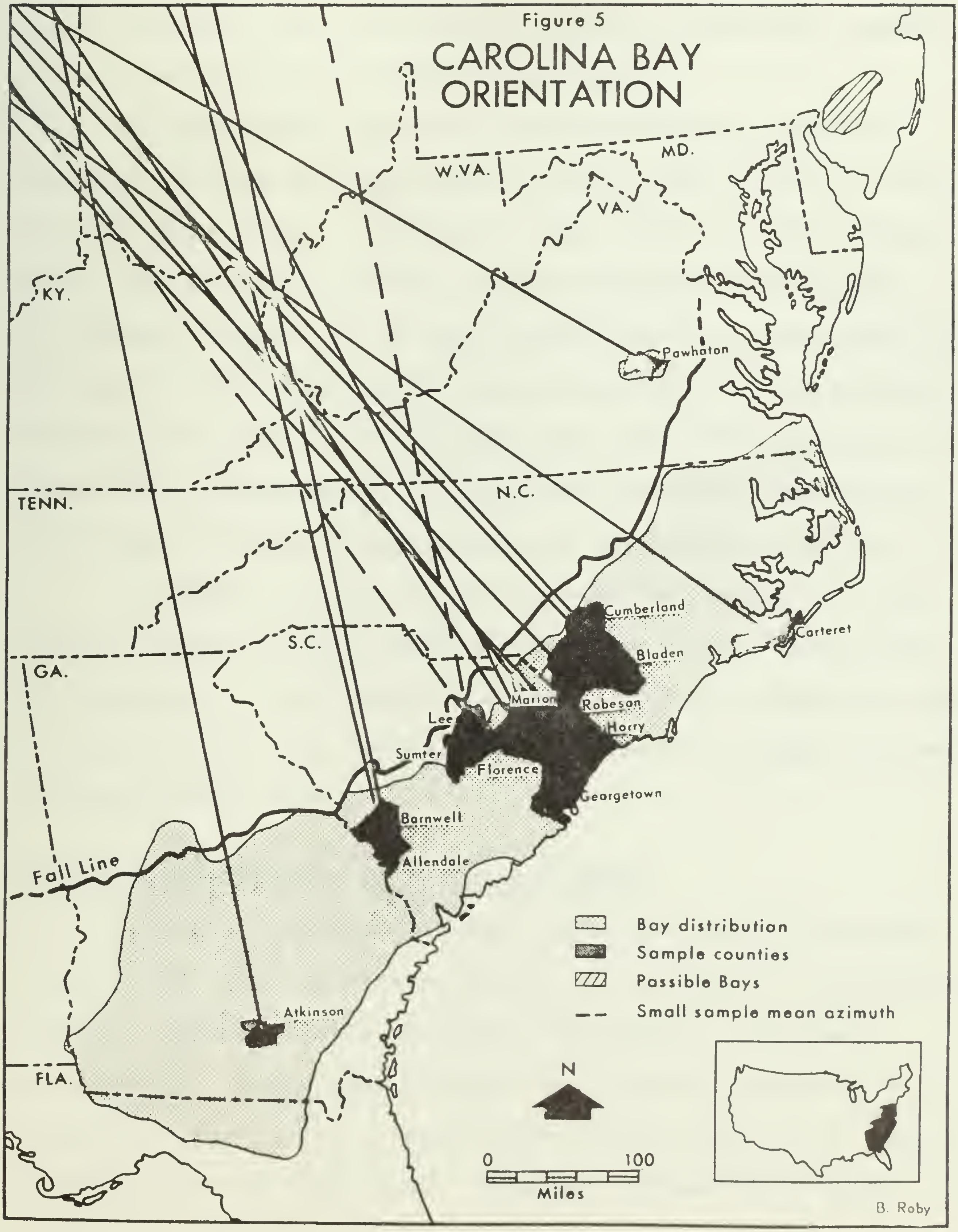
*Sample size too small

The mean azimuths for the fourteen sample counties are plotted on Figure 5. They display radial alignment, but more significantly, they have an apparent focus in either southern Ohio or Indiana which indicates the possibility of a point source. Other than measurement errors, variations in mean orientation per county may indicate localized effects or not quite simultaneous explosions and the resulting shock waves. The azimuths tend to support the possibility of a cometary bay forming mechanism.

In addition to the radial orientation, Table 6 also indicates that certain counties, notably those furthest south and north, have much larger standard deviations than the counties in southern North Carolina and northern South Carolina. Some of this variation represents county sample sizes, because the counties with the smallest standard deviations are also the counties with the largest number of samples. Certainly, some portion of the markedly increased variation actually represents an increasingly divergent localized bay alignment.

If a comet nucleus on a low angle northwest trajectory was either fragmented or continuously fragmented as it approached the Earth, some fragments would be deflected further from the actual incoming trajectory. Continued ablation and further fragmentation of each segment of the nucleus, plus the effects of not quite simultaneous air blasts may account for the divergent azimuths in the sampled counties. Thus, bays furthest from the

Figure 5


CAROLINA BAY ORIENTATION
MD.
W.VA.
VA.
KY.
Pawhaton
TENN.
N.C.
Cumberland
S.C.
Carteret
GA.
Bladen
Marion
Robeson
Lee
Horry
Sumter
Florence
Georgetown
Barnwell
Allendale
Fall Line
Bay distribution
Sample counties
Passible Bays
Small sample mean azimuth
Atkinson
FLA.
N
0
100
Miles
B. Roby

main trajectory could be expected to have much larger azimuthal standard deviations. Following the same logic, Bladen County, North Carolina, with the smallest standard deviation appears to be directly on the collision trajectory.

The increased variation away from the main trajectory may also account for the manner in which bays overlap. Bays in Cumberland County, adjacent to the inferred impact trajectory, tend to overlap either lengthwise along major axes or in complex clusters of as many as fourteen bays superposed in one area. Since Cumberland County is so near to the proposed collision trajectory, the complex bays and chains of bays may represent a rapid series of explosions and shock waves generated from further fragmentation of the remaining nucleus.

Lengthwise overlap along the main trajectory is to be expected because of the smaller variation in the dispersion of fragments. Where fragment dispersion is the greatest, less overlap should occur and bays should either be single or overlap along minor axes.

Research Implications of a Cometary Model

We have eliminated all but one of the extraterrestrial Carolina Bay forming possibilities on the basis of availability, orbital characteristics, physical attributes, and impact morphometry. We further refined the remaining possibility by suggesting that a bay forming comet did not need to be large to form half a million bays. However, it must have been

volatile; it must have followed a flat northwest trajectory because rims are better developed in the southeast quadrant, and it must have been fragmented somewhere to the northwest and eventually explode near the surface but in the atmosphere. The physics of such a series of catastrophic atmospheric explosions added to impact velocities at possibly greater than 51 km/sec are very complex. To the best of our knowledge no one has speculated about the nature of, or the bay forming energies available with, such shock waves. Nor since 1936 (MacCarthy) has anyone speculated about the relationship between shock waves and Carolina Bay morphology. These two avenues of research are needed before a cometary bay forming mechanism could be widely accepted.

As happened when aerial photographs of Carolina Bays were first seen (Melton and Schriever, 1933), we were immediately struck by the too remarkable regularity and uniformity with which bay morphology repeated itself. As physical geographers we doubted that either simple or complex sets of terrestrial mechanisms could conspire to create exceedingly regular forms on one portion of the Atlantic Coastal Plain without forming similar and equally widespread features elsewhere in similar coastal environments. It seemed to us that either the area is unique or the causal mechanism is not terrestrial. Furthermore, if the cause is not terrestrial, it almost certainly was a comet. Neither the impact of a large

asteroid nor the splash effects of a meteoretic shower could form Carolina Bays. This section, then, represents pure speculation about some of the terrestrial constraints concerned with such a unique event and suggests possible directions whereby this model can be tested.

If Carolina Bays represent residual scars of a truly singular extraterrestrial event, the bays must be young -- an attribute accepted by many terrestrial theorists as well. For example, Price (1968) indicated one or more periods of late Pleistocene bay development, whereas Thom (1970) indicated either a Farmdalian (28,000 - 22,000 B.P.) or a Woodfordian (22,000 - 12,500 B.P.) age. Age is a more critical factor when an extraterrestrial mechanism is invoked. Bays formed virtually instantaneously by explosions of cometary fragments are residual features. Subsequent modifications of such scars by normal terrestrial processes would rapidly obliterate all traces in unconsolidated sediments such as the Coastal Plain. Study of bays in Figure 2 suggests that bays remain quite distinct, essentially unaltered except for infilling; thus, the bays must be quite young -- either late Wisconsinan or early Holocene.

Very few samples of buried peat in the bays have been dated. Thom (1970) had a 6600 B.P. radiocarbon date from the basal peat in one South Carolina bay although he cited a greater than 38,000 B.P. date from the basal peat in a North Carolina bay. It is difficult to equate the two results. The bays may

be Wisconsinan in age. On the other hand, anomalous dates do occur, so little reliance can be placed on the few dates which have been acquired. Sequential samples along a vertical profile in several bays need to be dated and at least one date from the basal organic fill in a large sample of bays should be taken. Such a dating program will permit the Carolina Bays to be more precisely defined in time, and, more particularly, may indicate the possibility of simultaneous origin.

As was indicated earlier in the description of the Tunguska site, the vegetation in the area at the time the Carolina Bays formed may have been severely stressed by the shock waves from exploding cometary fragments. The larger vegetation would have been destroyed over sizable areas such as Bladen County, North Carolina, where well over half of the entire area is covered by bays. If such a shock occurred, perhaps a record of the event might be preserved by the pollen rain into the newly formed depressions. Assuming a rapid sequence of successional plants until equilibrium was restored, the basal organic fill in the bays might be one avenue by which a cometary origin could be tested.

When the shallow Campo del Cielo craters were examined (Cassidy and other, 1965), the authors found a modern soil developed in crater ejecta with a pre-impact soil buried beneath the debris. Search for such a compound soil profile beneath bay rims is an additional research possibility which might

support an extraterrestrial model. The problem is compounded because certain soils in the area have thick, residual, light-colored, silica sand concentrations in their A_2 horizons (Johnson, personal communication). Such a sand is an almost sterile end product of weathering. It would not weather significantly more, even if it were to be displaced up to the surface. This may be one reason why rim sands stand out so distinctly on aerial photographs even though the form is low and relatively indistinct on the ground.

Other than the physics of an unconfined near surface air blast, the single most critical problem for the extraterrestrial model suggested in this paper concerns the apparent selectivity of bay locations. Known extraterrestrial impact craters are randomly distributed with respect to geology. Known Carolina Bays are not. Until recently, when Goodwin and Johnson (1970) described bays in fluvial sands and gravels on the Piedmont in Virginia, all bays were believed to be confined to the Coastal Plain and better developed in sandy environments than in clay-rich ones (Whitehead and Tan, 1969; Thom, 1970). Some of the sandy areas where bays occur are Pleistocene river terraces, others are in dune complexes, still others are associated with marine terraces of different ages. If cometary fragments exploded, the displacement depth would depend in part on the cohesiveness of the unconsolidated surficial sediments. Although the analogy from a bomb crater to a bay is not direct,

Baldwin (1963, p. 183) said that a sandy loam texture yielded larger bomb craters than a clay-rich texture for an equal expenditure of energy. Depressions created in clay-rich soils would be smaller, more shallow, and far less easy to recognize on aerial photographs. Assuming Piedmont bays exist, current methods in remote sensing may detect bays which cannot be recognized on conventional black and white photographs.

Many excellent descriptions of bay morphology exist although explanations of the attributes differ. Therefore, throughout this section we have concentrated on non-traditional approaches to Carolina Bays and the possible relationships between the diverse approaches and an extraterrestrial causal mechanism. Bay morphology is also important. Various morphologic characteristics have been used in both supporting and refuting earlier extraterrestrial models. We can add little that is new in this regard except to note that cometary explosions in the atmosphere would not distort the underlying strata in the process of creating shallow depressions, nor would shock waves leave residual traces which could be identified in the mineralogy of the bays.

CONCLUSION

The proposed model with shock waves from cometary fragments exploding above the surface creating a series of similar landforms is conceptually very simple, and is far less complex

than most of the terrestrial models postulated recently. For geometrically regular forms such as Carolina Bays we prefer a simple causal mechanism if it is feasible.

Examination of impact mechanics and Carolina Bay morphometry eliminates traditional impact phenomena resulting from meteoroid swarms or asteroids. However, the unique orbital and physical characteristics of a comet favor a model in which a high velocity retrograde comet or a low velocity prograde comet collided with the Earth. The incoming nucleus approached from the northwest and fragmented. The fragments, diverging from the main trajectory, volatized and subsequently exploded in the atmosphere near the surface. The resultant shock waves created shallow elliptical depressions which are best displayed in the sandy sediments of the Coastal Plain.

This model is not fully substantiated. But, given the terrestrial and extraterrestrial constraints used in this paper, a comet remains a viable alternative worthy of further consideration. We hope that the physics of such an event can be explored, and that these results support our contention. We believe that a multidirected research effort will eventually result in a concensus about a truly enigmatic set of landforms.

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```
$JØB
      DIMENSIØN TA(20),AV(13),BV(13),CM(13),CKM(13),CPM(13),DIAM(13)
      DIMENSIØN DIAME(13),TCM(13),ADIAM(13),ADIAME(13),TCME(13)
      READ(5,11) NC,NR
   11 FØRMAT(9X,I1,9X,I1)
      DØ 500 JJ=1,NR
      READ(5,19)(TA(J),J=1,20)
   19 FØRMAT(20A4)
      READ(5,21) CD,NDU,RC,DM,CS,EW
   21 FØRMAT(F10.2,4X,I1,4X,F10.0,F6.2,2F5.2)
      DØ 500 KK=1,NC
      IF(NDU.EQ.2) CD=CD*3.2808
      DØ 30 J=1,13
      AV(J)=J+6
      IF(AV(J).GT.10.) AV(J)=AV(J)+(AV(J)-10.)*4.
      IF(AV(J).GT.50.) AV(J)=51.
   30 CØNTINUE
      DØ 40 J=1,13
   40 BV(J)=AV(J)*1.6093
      PK=300./((4.992*10.**19)**(1./CS))
      E=((CD/PK)**CS)*1./EW
      DØ 46 J=1,13
      CM(J)=E/(.5*(BV(J)*10.**5)**2)
      CKM(J)=CM(J)/1000.
      CPM(J)=CKM(J)/454.
      DIAM(J)=(2.*(((.75*CM(J))/(DM*(22./7.)))**(1./3.)))/100.
   46 DIAME(J)=DIAM(J)*3.2808
      WRITE(6,41) (TA(J),J=1,20)
   41 FØRMAT('1',20A4,////)
      WRITE(6,42) CD,RC,DM,CS,EW
   42 FØRMAT(1X,'CRATER DIAMETER= ',F11.2,3X,'FEET',/1X,'NUMBER ØF CRATE
     *RS= ',F10.0,/1X,'DENSITY ØF IMPACTING MATERIAL= ',F7.2,3X,'GM/CC',
     */1X,'CUBE SCALING USED= ',F6.2,/1X,'ENERGY AVAILABLE FØR IMPACT= '
     *,F6.2,///)
      WRITE(6,43) E
   43 FØRMAT(1X,'SINGLE CRATER PARAMETERS',//1X,'(ENERGY NEEDED= ',E13.7
     *,'  ERGS',///9X,'VELØCITY(KM/SEC)   DIAMETER(M)   MASS(KGM)   *
     * VELØCITY(MILES/SEC)   DIAMETER(FT)   MASS(LBS)',/)
      DØ 50 J=1,13
      WRITE(6,44) BV(J),DIAM(J),CKM(J),AV(J),DIAME(J),CPM(J)
   44 FØRMAT(13X,F6.2,11X,F6.2,5X,E10.3,3X,'*',8X,F6.2,14X,F6.2,6X,E10.3
     *)
   50 CØNTINUE
      DØ 60 J=1,13
      TCM(J)=CM(J)*RC
      ADIAM(J)=(2.*(((.75*TCM(J))/(DM*(22./7.)))**(1./3.)))/(10.**5)
      ADIAME(J)=ADIAM(J)*.6214
      TCM(J)=TCM(J)/(10.**6)
   60 TCME(J)=TCM(J)/4.4092
      EE=E*RC
      WRITE(6,61) RC,EE
   61 FØRMAT(1X,///////1X,'ALL CRATER PARAMETERS',//1X,'NUMBER ØF CRATER
     *S= ',F10.0,/1X,'TØTAL ENERGY NEEDED= ',E13.7,'  ERGS',//9X,'VELØCI
     *TY(KM/SEC)   DIAMETER(KM)   MASS(MT)   *   VELØCITY(MILES/SEC)
     *DIAMETER(MILES)   MASS(SHT TØN)',/)
      DØ 70 J=1,13
   70 WRITE(6,71) BV(J),ADIAM(J),TCM(J),AV(J),ADIAME(J),TCME(J)
   71 FØRMAT(13X,F6.2,12X,F6.2,5X,E10.3,2X,'*',11X,F6.2,13X,F6.2,10X,E10
     *.3)
  500 CØNTINUE
      STOP
      END
```

DEPARTMENT OF GEOGRAPHY

UNIVERSITY OF ILLINOIS at Urbana-Champaign

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