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Wind & Wave, or Cosmic Impact Detritus?

Imaging 50,000 oriented ovoid depressions using LiDAR elevation data elucidates the enigmatic character of the Carolina bays

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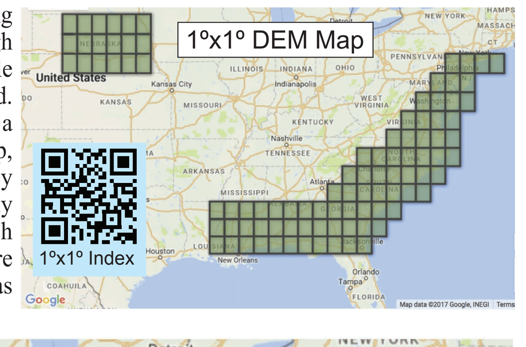
Abstract

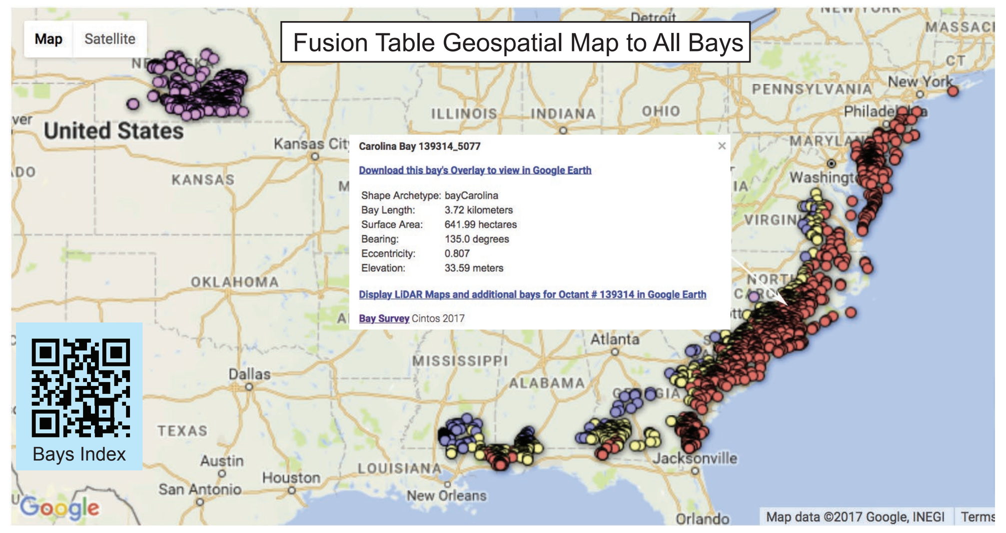
80 years after aerial photography revealed thousands of aligned oval depressions on the USA's Atlantic Coastal Plain, the geomorphology of the "Carolina bays" remains enigmatic. Geologists and astronomers alike hold that invoking a cosmic impact for their genesis is indefensible. Rather, the bays are commonly attributed to gradualistic fluvial, marine and/or aeolian processes operating during the Pleistocene era. The major axis orientations of Carolina bays are noted for varying statistically by latitude, suggesting that, should there be any merit to a cosmic hypothesis, a highly accurate triangulation network and suborbital analysis would yield a locus and allow for identification of a putative impact site. Digital elevation maps using LiDAR technology offer the precision necessary to measure their exquisitely-carved circumferential rims and orientations reliably. To support a comprehensive geospatial survey of Carolina bay landforms (Survey) we generated about a million km² of false-color hsv-shaded bare-earth topographic maps as KML-JPEG tile sets for visualization on virtual globes. Considering the evidence contained in the Survey, we maintain that interdisciplinary research into a possible cosmic origin should be encouraged. Consensus opinion does hold a cosmic impact accountable for an enigmatic Pleistocene event - the Australasian tektite strewn field - despite the failure of a 60-year search to locate the causal astrobleme. Ironically, a cosmic link to the Carolina bays is considered soundly falsified by the identical lack of a causal impact structure. Our conjecture suggests both these events are coeval with a cosmic impact into the Great Lakes area during the Mid-Pleistocene Transition, at 786 ka ± 5 k. All Survey data and imagery produced for the Survey are available on the Internet to support independent research. A table of metrics for 50,000 bays examined for the Survey is available from an on-line Google Fusion Table: `https://goo.gl/XTHKC4` . Each bay is also geospatially referenceable through a map containing clickable placemarks that provide information windows displaying that bay's measurements as well as further links which allows visualization of the associated LiDAR imagery and the bay's planform measurement overlay within the Google Earth virtual globe: `https://goo.gl/EHR4Lf` .

Carolina bay Survey

A detailed Carolina bay survey (Survey) has been underway since 2010 [1]. Our motivation is to socialize the bays - for the pressing ecological reasons, but also to encourage scientists to consider research into how they were created. All our Survey work product is provided freely on the web.

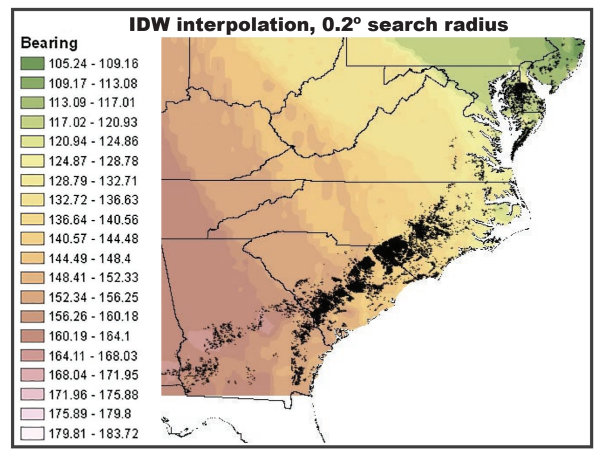
Quadrants of 1° x 1° are the upper gridding elements, and are geospatially accessible through the Google Fusion map shown here, and loadable into a browser using the QR code supplied. Clicking on a tile will yield a link to a low-resolution DEM for the Google Earth app, where a placemark popup will yield all survey information for that quad. To deliver reasonably sized LiDAR DEMs, we have subdivided each quadrant into 16 sub-grids. Imagery layers are supplied interactively from our cloud service as required by the user's field of view.

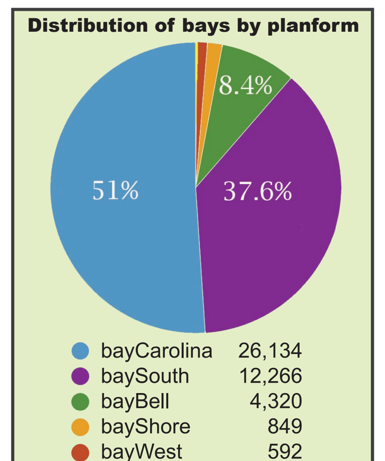




A live geospatially hyperlinked map, generated by the Google Fusion table facility (above), can be opened in a browser window to locate and inspect all 51,000 + bays surveyed. Clicking on a placemark raises a popup with a links to KMZ files for visualization on the Google Earth virtual globe. The interface sub-sets the displayed placemarks to a maximum of 500; zooming in will re-populate. The icons are currently color-coded to indicate the elevation of that bay's "floor".

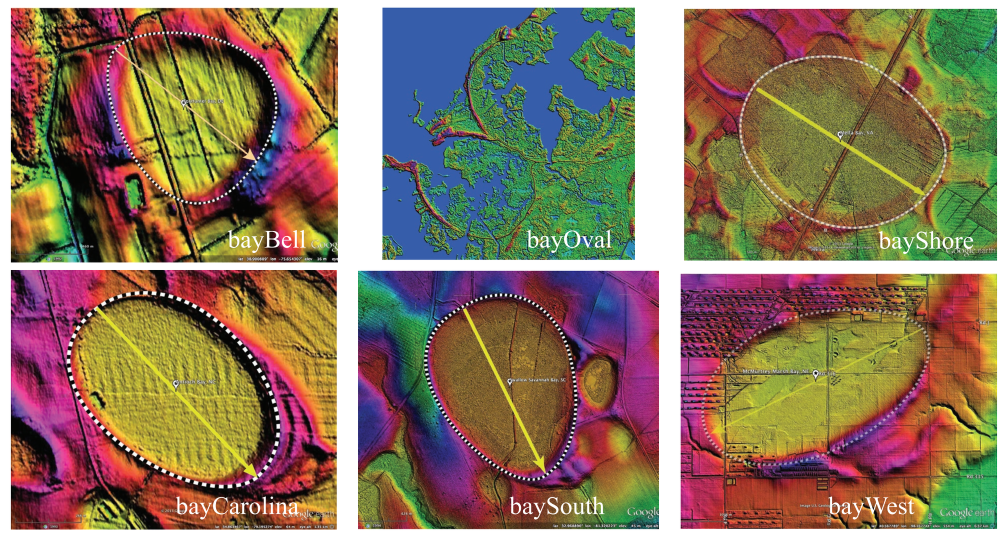
As an example of the statistical studies that can be made from the Survey data, an inverse distance weighted (IDW) interpolation of bay orientations on the East Coast is shown below. The false-color map demonstrates the clockwise rotation of major axis when traveled north to south. When geophysical mass flows are modeled to consider ballistic trajectories over a rotating globe, our analysis suggests the orientations can be triangulated to the Michigan LP [2].

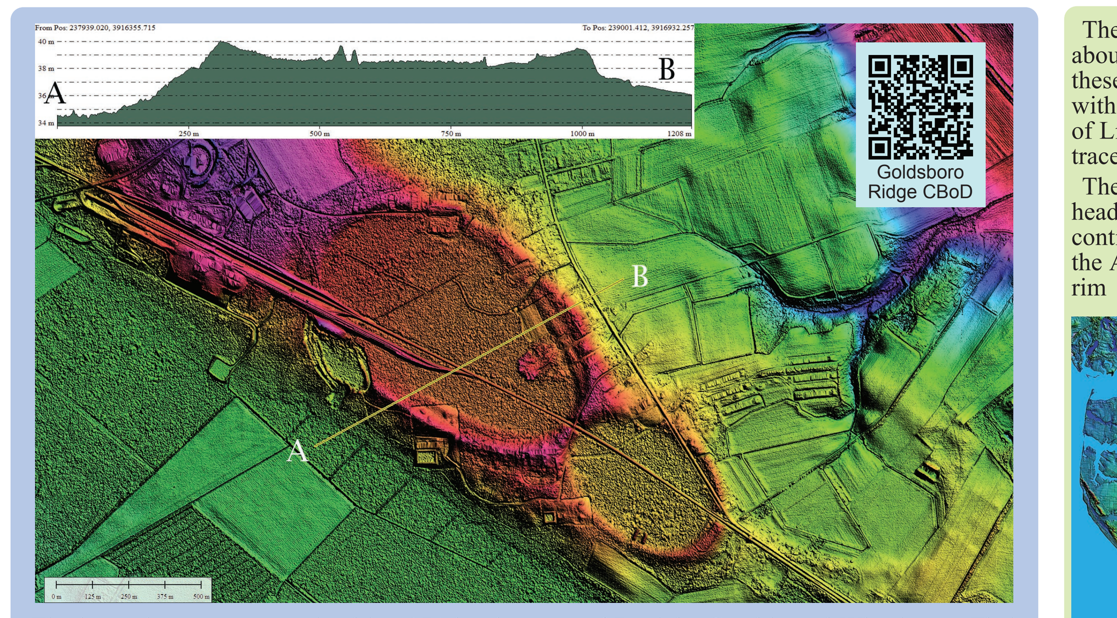




Carolina bay Planforms

The Survey employs six archetypical planform overlays to facilitate measurement of the bays [3]. Each is created as a PNG file and rendered in Google Earth as an image overlay, which is manually placed over a given bay's imagery (satellite or DEM) and adjusted for major & minor axis and orientation. When it is deemed a good match to the 2D planform, the overlay's KML text is processed to yield (with a bit of trig) the subject bay's metrics, and the on-line Fusion database is updated. The overlay KML is also saved as a discrete file on our servers, so that it can be easily recovered onto the Google Earth virtual globe and checked for accuracy. The archetypes are shown in situ below, in order of appearance along the proposed MPT Impact ejecta annulus from New York to Nebraska, demonstrating the statistical variation seen in their orientations. The graph above shows bay distribution by type. The example archetype LiDAR images are hyperlinked (ePoster) for access to all our Google + "Carolina bay of the Day" (CBoD) posts surveyed with the respective archetype shape. The base CBoD blog URL is https://goo.gl/VSwD11





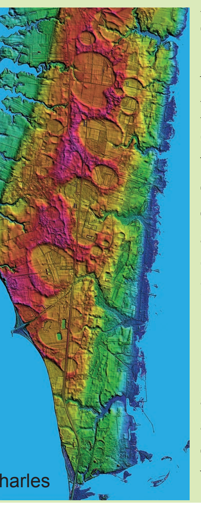
The bays above were examined in 1971 by the team of Daniels, Gamble and Wheeler [4]. Their resulting paper was the inspiration for our cosmic impact-driven geophysical mass flow theory:

...the Carolina Bays do not disturb the underlying Sunderland materials.... The sand in the bay rim is not different from the Goldsboro sand. Therefore, these Carolina Bays are merely surface features associated with the formation of the ridge.

Located near Goldsboro, NC, these bays demonstrate the robust nature of bay rim structure seen in the Survey LiDAR, as they maintain their planform and resist erosional activity around them.

The entire spine of Virginia's Eastern Shore peninsula is laced with about 700 well-expressed Carolina bays. We have documented these as a unique planform, *bayShore*, which is primarily oval, but with a slight flattening of the south-east end. Prior to the availability of LiDAR, less than 100 bays had been resolved along the 100 km trace from Maryland down to Cape Charles.

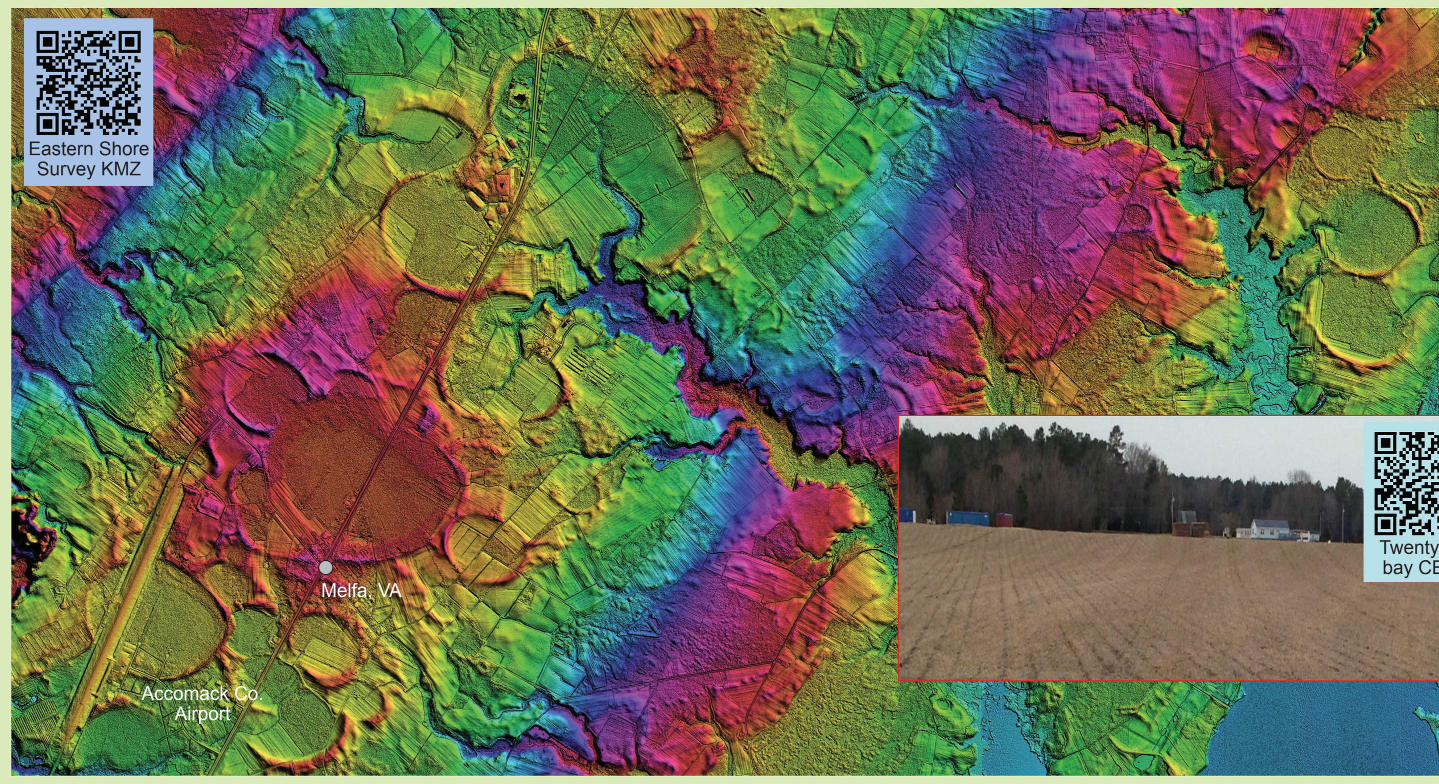
These bays show their resistance to erosion. In some cases, headward migration of streams penetrate the bay, yet the bay continues to announce its presence in the LiDAR. In the lower left, the Accomack Airport has a runway traversing a bay, yet the bay rim remains distinct. Along the lowlands, bays are revealed in LiDAR as being virtually inundated by Chesapeake Bay, yet they persist.

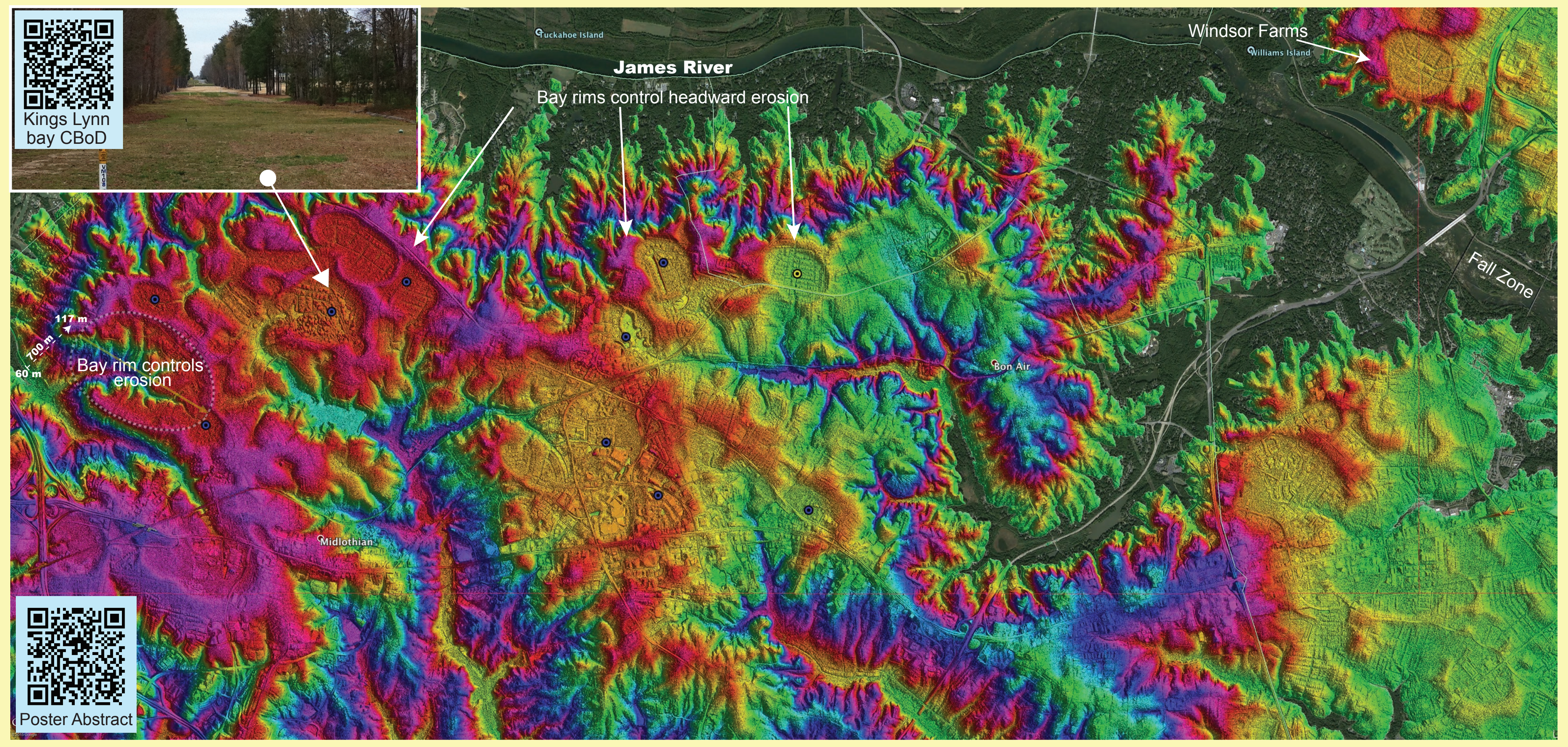


At the southern end of the peninsula, bays have been truncated by Chesapeake Bay's eastward erosion at Butler's Bluff (image on right). The Carolina bay's temporal aspects would be better constrained by dating exercises to determine how long it took to erode away the great expanses of upland (~10m amsl) that these bays were formed on.

QR for LiDAR DEM imagery and Survey data across the Eastern Shore.

In the photo inset on far right, a field's aligned stalks highlight the gentle rise of a bay's western rim, as viewed from the center of the bay, along US Rt 13, which was our CBoD for 1/1/2013.



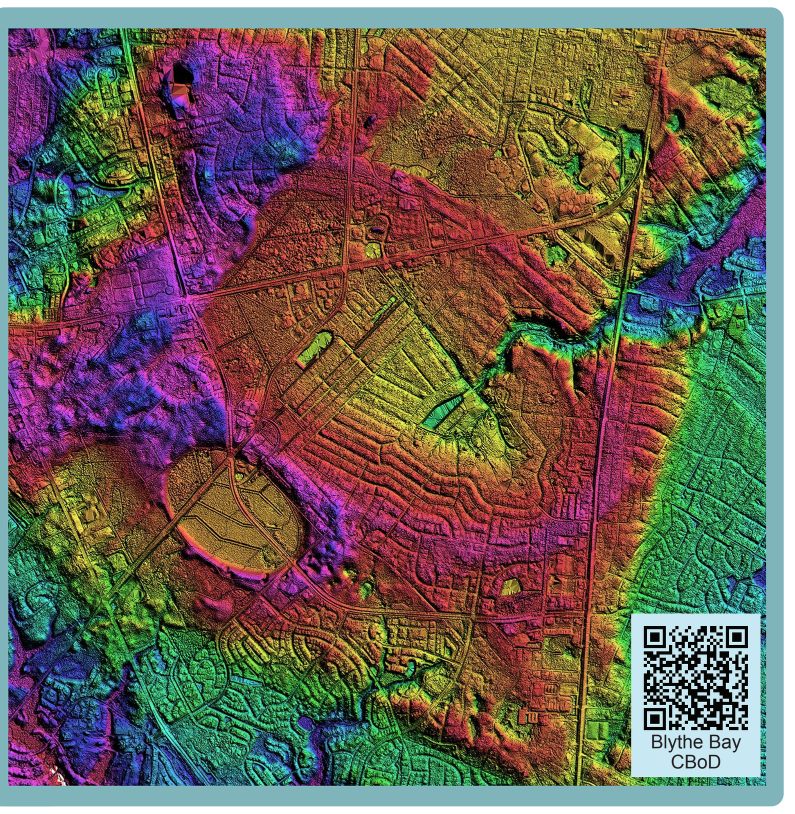


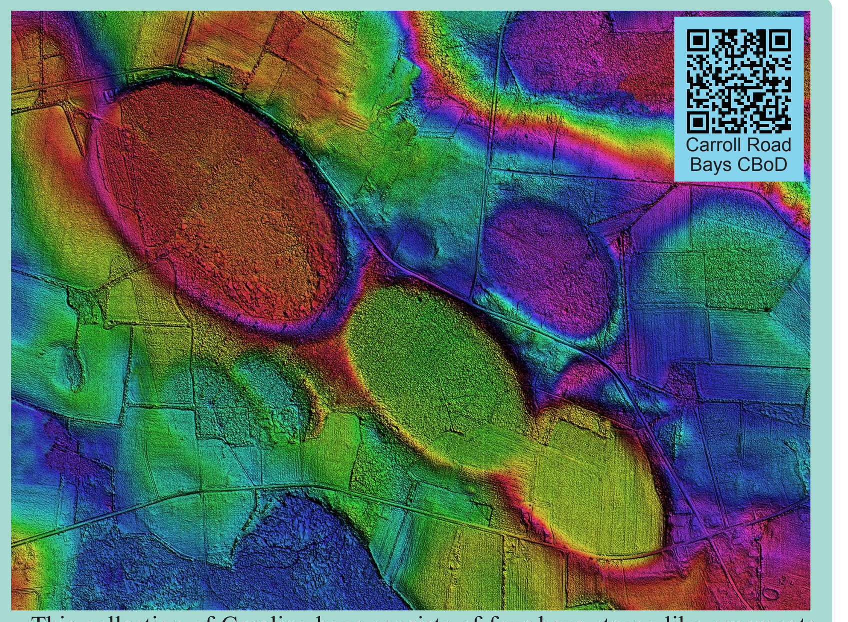
The bays on the left lie within the upper sandy loam member of the Upland Gravels, which in turn rests on solid bedrock, both above and below the fall line, southwest of Richmond, VA [5]. A 20 m geocore was taken in 2016 from a rim near the center of the image, and we hope to perform ^{26}Al-^{10}Be isotopic burial dating [6] to reveal the temporal aspects of their creation. Note the rims along the James River (across top) are controlling southward erosion into the terrace. On the western side of the terrace a large bay has been fully eviscerated by erosion, yet continues to present its planform. The inset photo shows a view from a bay's floor, looking out along an old rail line to the rim 1 km away. A paved road in the distance is apparent as it crosses the rim, and dips into the bay.

Blythe bay, Wilmington, NC (right) has a 3 km major axis, and maintains a powerful presence in LiDAR, despite having been fully transformed into an urban landscape. Sand dunes penetrate from the Cape Fear River flood-plain on the northwest; a stream cuts in from the Atlantic. In the 1940's it was investigated by B.W. Wells. As told by Savage:

His work would later become part of one of the most intriguing research studies in Carolina bay literature. He told the society that in Blythe Bay the interior of which is about thirty-five feet above mean sea level, he had found five or six feet of typical bay peat lying beneath seven feet of plastic clay and fine sedimentation which could only have been deposited there through an invasion by the sea during a temporary re-elevation of the ocean that had occurred long after the bay had come into existence. A delta-like structure within a gap in the bay's rim reinforced Wells' conclusion. [7]

The 1 km bay to its south has been heavily drained, leveled and commercialized since the LiDAR was captured. Note how the southern rim is standing high and defiant over the lowlands running down to the Atlantic Ocean. The QR links to a CBoD post discussing the bay.





This collection of Carolina bays consists of four bays strung like ornaments along Carroll Road, south of Dillon, SC. Bright in LiDAR hsv colors, they each rest at a different elevation upon the same ridge line. The orientations are within 1% of each other. Planform is bayCarolina. QR code for CBoD post.

The southern rim of three of the bays seem to defy gravity and erosional activity, standing high and proud, while the north side of those bays are snuggled into higher elevations of the ridge. One bay is sunk into the ridge.

The most common bay planform is the *bayCarolina* type, seen on the right in vast quantities across North Carolina.

The imagery can be visualized on Google Earth using a kmz at `http://cintos.org/ge/Heart_DEM.kmz`, and referenced in the QR.

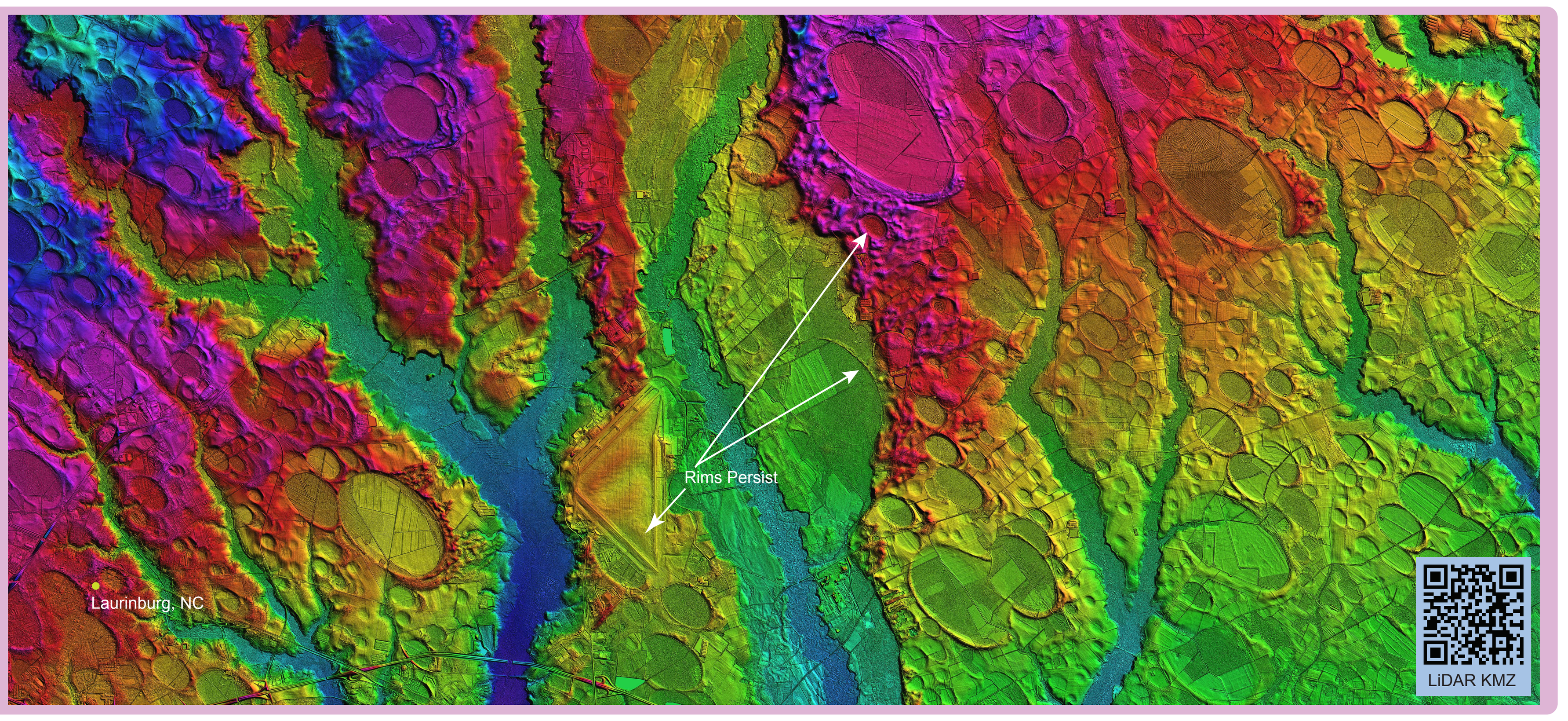
Field of view is ~27 km E-W and ~12 km N-S, encompassing ~330 square km; North at top. Elevations from ~55 masl in lower right to ~85 masl in upper left; a total relief of only 30 m over 30 km.

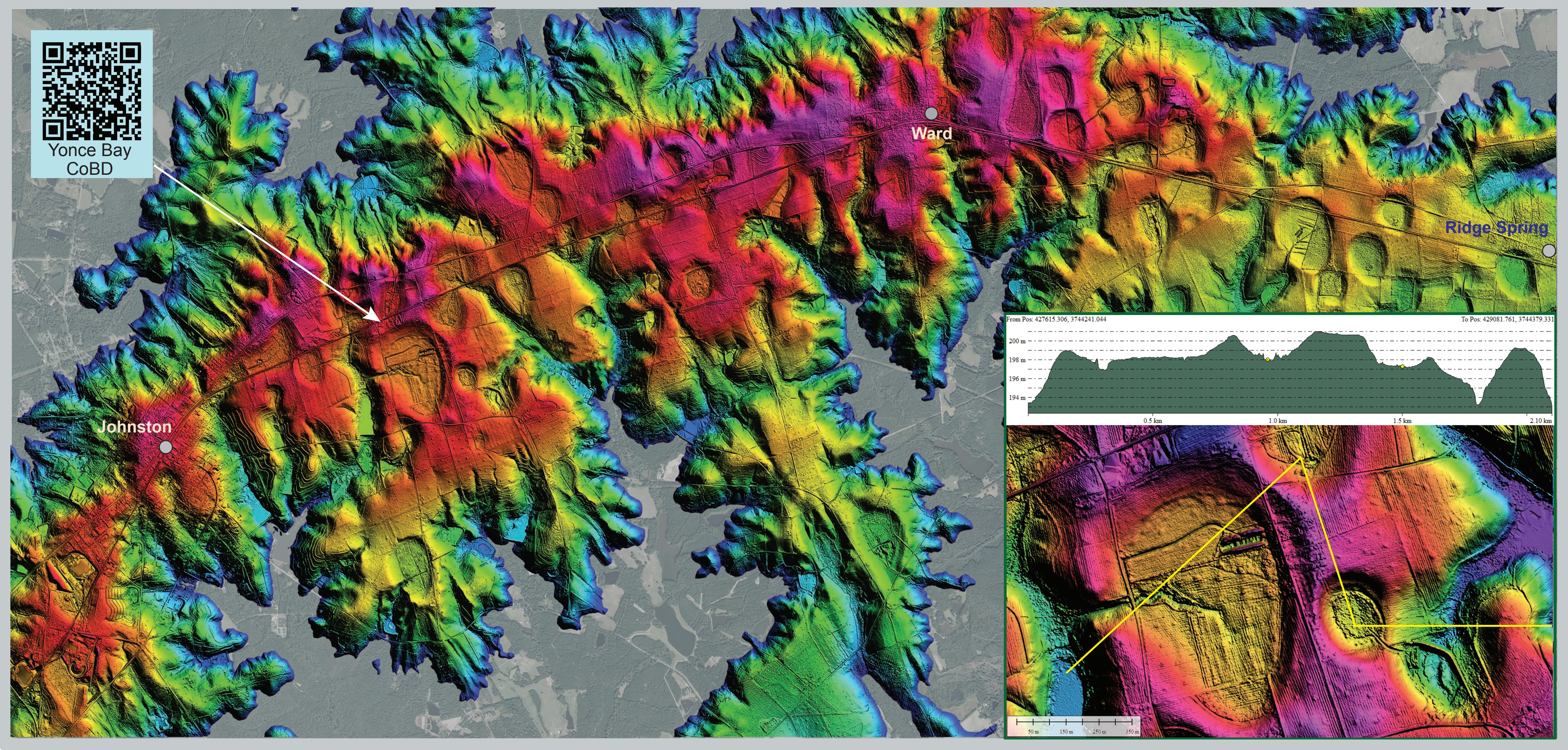
Downtown Laurinburg, NC, on lower left, has many large bays demanding their presence be known. Construction of an airport runway across a bay has failed to obliterate a bay, as the full rim extent is traceable. Similarly, repeated inundation of bays on the flood plain of the adjacent river have failed to erase evidence of their presence. Even when engulfed in vast sheets of dunes, the bays typically remain robustly presented in the archetype planform and parallel orientations maintained. When infiltrated by headward erosion, numerous large bays in this image demonstrate that their rims control the erosion.

Such common attributes demonstrate that these enigmatic landforms are robust and resilient against human modification and natural erosion.

Most of these bays have been ditched, drained, and used for agriculture or to build a city and an airport.

The heart shaped bay's unique shape, upper center, is speculated by us to result from overlapping bays.



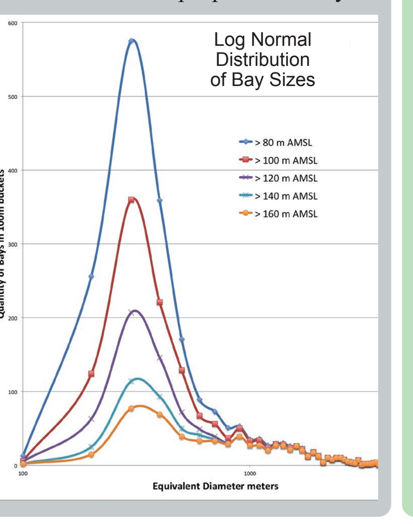


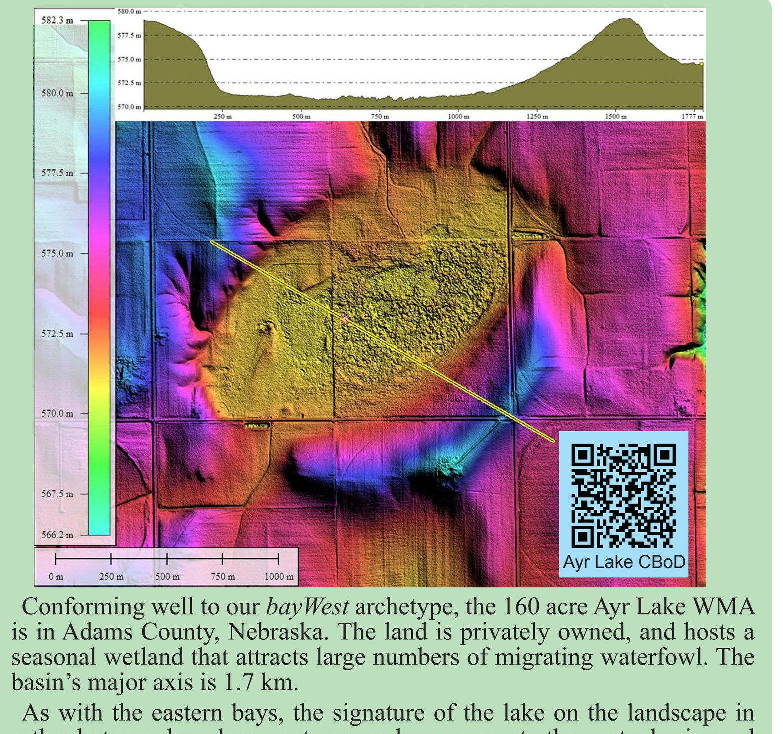
A narrow, sinuous terrace, known locally as *The Ridge*, is a drainage divide arcing ~100 km from Augusta, GA, to Columbia, SC. Its surface is paved with Carolina bays. LiDAR offers a crisp view of its surficial features [8]. The terrace represents a surviving island of Cretaceous terrace that is being encroached upon by headward erosion. Edisto River basin headwaters are eroding the south flank, while on the north flank, tributaries of the Upper Santee and Savannah Rivers are working to dissect the divide.

These bays maintain robust conformance to the archetype baySouth despite the ongoing erosional activities. As shown in the inset elevation map profile, Yonce bay and its neighbors show the progression from hydraulically closed to "Valley Head Basin"[9] as the Ridge eroded over the proposed 800 ky of bay occupation.

Note these are basins set into the terrain, with no "prominent raised rim" on the SE side. We propose that the occasional dune growth seen on bay rims are simply gradualistic surficial activity unrelated to bay creation.

Of 19,000 baySouth basins in the Survey, only 170 lie above 185 m. The Ridge is home to 160 of those. The graph on right charts the log-normal distribution of bay sizes, as seen across the Survey data. In this graphic, we compare the size distribution curve across five elevation ranges above 80 m, suggesting altitude has no control on bay size distribution.





Conforming well to our *bayWest* archetype, the 160 acre Ayr Lake WMA is in Adams County, Nebraska. The land is privately owned, and hosts a seasonal wetland that attracts large numbers of migrating waterfowl. The basin's major axis is 1.7 km.

As with the eastern bays, the signature of the lake on the landscape in orthophotography does not properly represent the actual rimmed depression's shape. Here, the LiDAR once again does the trick in teasing out the true shape of this Nebraska "Rainwater Basin".

The Mid Pleistocene Transition

Our working hypothesis holds that the bays were created as voids in sheets of comminuted terrestrial strata spread as a fluidized geophysical mass flow from a well provenanced cosmic impact at 785 ka ±5 k. This was during the Mid Pleistocene Transition (MPT), so named because a significant number of enigmatic events occurred in that era, such as the M-B geomagnetic reversal, and the transition into 100 ky glacial cycles [10] [11]. Evidence is mounting that there was an anomalous "regolith injection" across the continent at ~800 ka, as seen in glacial tills [12] and karst system deposits [13]. If there is any merit to our hypothesis, more 800 ka dates will appear.

Our proposed MPT date has elicited suggestions that Carolina bays do not exhibit a "great age", as they are "too perfect" in planform. Research into their geomorphology has historically been directed at easily recognized, hydraulically closed examples, but a holistic assessment of the LiDAR shows that erosional and accretionary processes are working to remove the bays [14].

Thom considered that Carolina bays were formed during the mid to late Pleistocene [15]. Recent discussions that the bays are associated with the proposed Younger Dryas Boundary (YDB) impact are easily falsified by extensive temporal data - they are far, far older.

In 1943, B. W Wells reported on Blythe Bay in Wilmington, NC [7]. As reported by Savage:

Wells was quite emphatic that he read a catastrophic genesis for the bays. The referenced paper discusses at length how he felt the majority of bays never hosted bodies of water, but simply grew peat deposits many feet in depth on their moist bottoms. Note that peat bogs do not form in open water. His interpretation of the bay lakes which are in existence today is because that, for a very few, they lie low between major rivers and are controlled by water table levels, while many of the bays with water exist because peat within bays had been burned out in the dry periods of the middle Holocene, based on significant findings of charcoal. [16]

Pollen studies [17] record multiple glacial cycles, and 14C dating had long ago evaluated the age of organic deposits in cored Carolina bay basins to be older than 50 ka. The age of bays based on their existence on Cape Fear River terraces sets a minimum date for bay formation at prior to the Illinoian glaciation [18]. Ivester has found bays older than 100 ka using OSL [19].

The Survey's LiDAR digital elevation maps elucidate bays succumbing to erosion during the dissection of coastal terraces of Cenozoic and Mesozoic age, yet leaving intriguing imprints in Cretaceous terrace remnants at elevations over 200 masl [8]. Carolina bays in lowlands may have been inundated by fluvial and estuarine deposits, only to delicately project their competent rims to the surface when they are unroofed by erosion, or when buried organics in their basins compact and dissolve away. Sheets of dune sands and aeolian loess have overridden and blanketed clusters of bays, yet they continue to offer evidence of their presence. Such findings suggest that once created, a Carolina bay's ovoid shape and orientation is deeply imprinted into the landscape, revealing its presence despite the reworking of surficial deposits, likely due to the differential robustness of the high-energy emplacement of the rim constituents. Exploring the various temporal aspects of such alterations may provide constraints on the timing of bay creation.

Any attempt at dating the age of the bays to the MPT will require performing an extensive suite of cosmic isotopic dating technologies to the bay deposits and underlying strata to elucidate the arrival time of the formative rim. When attempting to date bay creation episodes, workers must discriminate between foundational rim deposits and those of subsequent gradualistic processes.

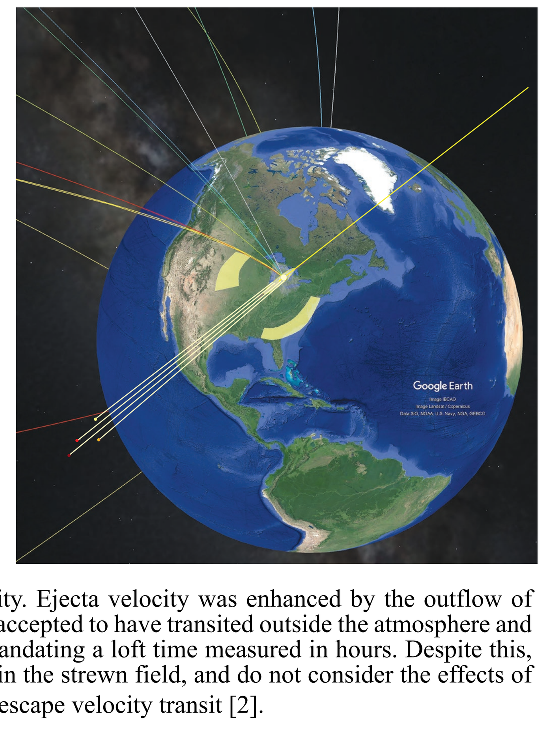
MPT Impact

Hundreds of cosmic impacts have been identified in the Earth's geological record, yet only four are known to have an accessible tektite strewn field. The Australasian strewn field is the largest of those in aerial distribution (China to Madagascar to Antarctica) [20] and estimated tektite mass (~60 billion tons). Although only 800 ky old, it is the only one not paired with an astrobleme.

The Australasian tektites are composed of non-marine sedimentary strata lofted by the MPT Impact, suggesting the missing impact structure must be located on a continental surface [21]. Perhaps these unique impact constraints demand that a truly rare cosmic impact event is at play, one that does not fit the impact model developed over the past 50 years. Urey observed that:

The residual crater may be very difficult to identify; but it might well be looked for while keeping some flexible ideas as to what its properties may be. [22]

The absence of an astrobleme has led to speculation that a "near miss" generated tektites by radiant melting, but that has been falsified [23]. We propose there is a continuum between a fly-by and a classic impact event; there is a statistical probability that a massive cosmic object could intersect the Earth's limb, such that its momentum is not significantly interrupted and most of the impactor's mass continues a heliocentric trajectory. Rather than a high pressure compressive event, the impact was grazing, with shear as the primary excavation agent. Shock metamorphic features would still be produced, but in far less quantities than expected for such a large impact event.



In our proposed scenario, the ground flow is driven laterally away from the trench in a butterfly pattern, creating the Carolina bays along an annulus with an 800-1200 km radius. Tektite precursor sediments near the surface were heated to a molten state by direct contact with the impactor, and expelled vertically out at near escape velocity. Ejecta velocity was enhanced by the outflow of vaporized ice sheet. Australasian tektites are accepted to have transited outside the atmosphere and re-entered at near Earth's escape velocity, mandating a loft time measured in hours. Despite this, most workers are invoking astroblemes within the strewn field, and do not consider the effects of the Earth's rotation during an extended near-escape velocity transit [2].

About the LiDAR

Key to our interpretation of Carolina bay morphology is the visualization of their true planforms, as seen in high resolution DEMs. Bare-earth elevation data has been extracted from LiDAR point-cloud data provided by government agencies through public access data sites. The Global Mapper commercial GIS platform has been used to process all LiDAR data and generate the intriguing landscape shown here. False color shader is HSV, with elevations exaggerated by 20x to punch up the relief. Global Mapper's ability to generate tiled image sets with KML linkages has been leveraged to integrate the imagery into the Google Earth virtual globe environment. When loaded by a user, the seed KML file is only ~1kb. These seeds are interrogated by Google Earth, and based on the user's field-of-view, the Google Earth application contacts our server and downloads images with the appropriate resolution from the tile set. This is the identical process used by Google Earth to load increasingly-higher resolution maps as a user zooms into the globe, keeping the system responsive and reducing load times and bandwidth needs for the image data.

Summary

The Carolina Bay Survey has revealed shallow ovoid basins arrayed along an annulus around the Great Lakes, USA, with their major axis documenting a radial distribution from that area. Bay landforms are unlikely to be primary or secondary impact craters because of their shallow depth. We propose they were formed as voids in an ejecta blanket during a mass geophysical flow of pulverized sedimentary strata, where their primary axis documents the ejecta's arrival vectors. Rather than being "wispy ephemeral" landforms, bay survival in hostile conditions supports a finding that they are very robust landforms, perhaps as a result of their high-energy emplacement. Our working hypothesis holds that a cosmic impact event occurred at the MPT. In the depths of MIS-20, the target in Michigan was encased in a ~2 km-thick Laurentian glacial ice sheet, providing a low-impedance shield [24] over the target sediments. Ironically, the "Australasian tektites" are considered by scientists to be ejecta from a cosmic impact, despite the failure to locate the impact site. We suggest the two events are the result of a single cosmic impact at 785 ka ±5 k.

Future research goals include application of ^{26}Al-^{10}Be isotopic burial dating techniques to the surfaces beneath these landforms [6]. Samples of sandstones and shales from the Lower Michigan Peninsula have been collected for chemical and isotopic analysis, and will be compared with results of similar analysis on Carolina bay rim deposits and Australasian tektites.

References

ePoster Note: references, QR codes and planform examples are hyperlinked for web access.

[1] Davias, M.E. & Gilbride, J.L. (2011) AGU FM EP52C-08; [2] Davias M.E. & Harris T.H.S. (2015) GSA N-C Section AwP Vol. 47, No. 5, p.4; [3] Davias, M.E. (2013) GSA AwP Vol. 45, No. 7, p.722; [4] Daniels, Gamble & Wheeler (1971) Southeastern Geology, Vol 12, #3; [5] Davias, M.E. (2015) GSA AwP Vol. 47, No. 7, p.550; [6] Balco, G.A. & Rovey II, C.W. (2008) AJS Online, Vol. 308 no. 10; [7] Wells, B. W., and Boyce, S. G. (1953) Jour. Mitchell Society, Vol. 69; [8] Davias, M.E. (2017) GSA AwP Vol. 49, No. 3; [9] Farrell, K. (2015) GSA SE - Paper No. 13-3; [10] Frank Schmeder, et al. (2000) Earth and Planetary Science Letters 179; [11] Head, M.J., et al. (2008) Episodes, Vol. 31, no. 2; [12] Balco, G.A. et al. (2007) Fate of the preglacial regolith beneath the Laurentide Ice Sheet, unpublished manuscript; [13] Anthony, D.M. & Granger, D.E. (2006) GSA Spec. Paper 404; [14] Davias, M.E. (2015) GSA Annual Meeting AwP Vol. 47, No. 7; [15] Thom, B.G. (1970) GSA Bulletin 81:783-814; [16] Savage, H., Jr. (1982) The Mysterious Carolina Bays, U of SC Press; [17] Frey, D.G. (1955) Ecology, Vol. 36, No. 4; [18] Soller, D.R. (1988) U.S.G.S Prof. Paper 1466-A; [19] Brooks, M., et al (2001) Southeastern Archeology, Vol. 40, No. 4; [20] Folco, L. et al. (2009) Geochimica et Cosmochimica Acta, 73; [21] Blum, J.D., et al. (1992) Geochimica et Cosmochimica Acta, Vol. 56; [22] Urey, H.C. (1957) Origin Of Tektites, Nature Vol. 179; [23] Goderis, S. et al. (2017) Geochimica et Cosmochimica Acta, Vol. 217; [24] Stickle, A.M. & Schultz, P. H. (2012) Journal of Geophysical Research, Vol. 117, E07006