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Is a Large Complex Impact Crater Hiding in Plain Sight in Central North Carolina?

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Abstract

A tantalizing series of clues suggests the existence of a regional-scale complex meteorite impact crater in central North Carolina near Raleigh. Although not definitive of an impact origin, the following observations merit further study. The first piece of evidence is a striking semicircular feature visible on the statewide LiDAR imagery. Much of the semicircle is defined by the western edge of the Triassic Durham sub-basin. The semicircle extends beyond the northern termination of the basin and then follows the Tar River ESE for 26 km. The proposed crater is roughly centered within the ca. 300-Ma Rolesville granitic batholith. A combination of LiDAR patterns, regional magnetic and gravity data, and existing geologic mapping supports the recognition that this may constitute a complex crater having a diameter of at least 200 km and including a central uplift and peak ring. Stream drainage patterns and detailed LiDAR lineaments suggest the presence of multiple concentric fault rings within the inferred structure. Under the microscope, grains of quartz and feldspar in rocks from the proposed central uplift area locally display features tentatively interpreted, but so far unconfirmed, to be planar fractures (PFs), isotropic twin lamellae in plagioclase, and possible diaplectic glass. The latter is especially evident in quartz breccia dikes within an area inferred to represent part of the eroded crater floor. A late Permian age date of 255 ± 2 Ma has been obtained for brittle-ductile deformation within an area of the Jonesboro fault zone containing one such dike **(Hames *et al.*, 2001)**. A limited search for shatter cones was conducted in three quarries within the proposed central uplift of the proposed crater structure. No shatter cones were observed, although curved, striated surfaces as well as large conical structures were observed in one of the quarries near Cary, NC. Evidence of hydrothermal activity, common in complex craters, is found within the proposed central uplift and peak ring areas. However, these areas could be related to preexisting alteration systems. Gold recovered from a prospect within the Rolesville batholith in the proposed central uplift contains up to 1.2 % palladium. Previous studies **(Gaughan and Stoddard, 2003; Carpenter and Reid, 2015)** have argued that areas near the center of the proposed impact structure have been uplifted 10-15 km, consistent with the possibility of an impact-induced central uplift **(e.g., Wieland *et al.*, 2005)**. Preservation of unannealed high strain features in the quartz breccia dikes suggests the timing of the proposed impact would post-date the late Permian metamorphism in the area, ca. 260 Ma **(Hatcher, 2008)**. Furthermore, Carnian-stage and younger Triassic sedimentary rocks fill a portion of the proposed central crater. Therefore, the proposed Raleigh impact likely occurred between the late Permian and the middle to late Triassic. Could it be linked to a major extinction event and perhaps even the breakup of Pangea?

Introduction

If at first the idea is not absurd, then there is no hope for it.
Albert Einstein

A plot of public domain state-wide legacy Light Detecting and Ranging (LiDAR) digital elevation data in North Carolina reveals a striking circular feature centered on the Raleigh, NC area. The partial near-perfect circular feature has a diameter of 92 kilometers **(Figure 1)**. It resembles many of the eroded hypervelocity impact craters formed on earth by large cosmic projectiles. Many such circular features on earth are not impact craters. Could this be one that is an impact crater?

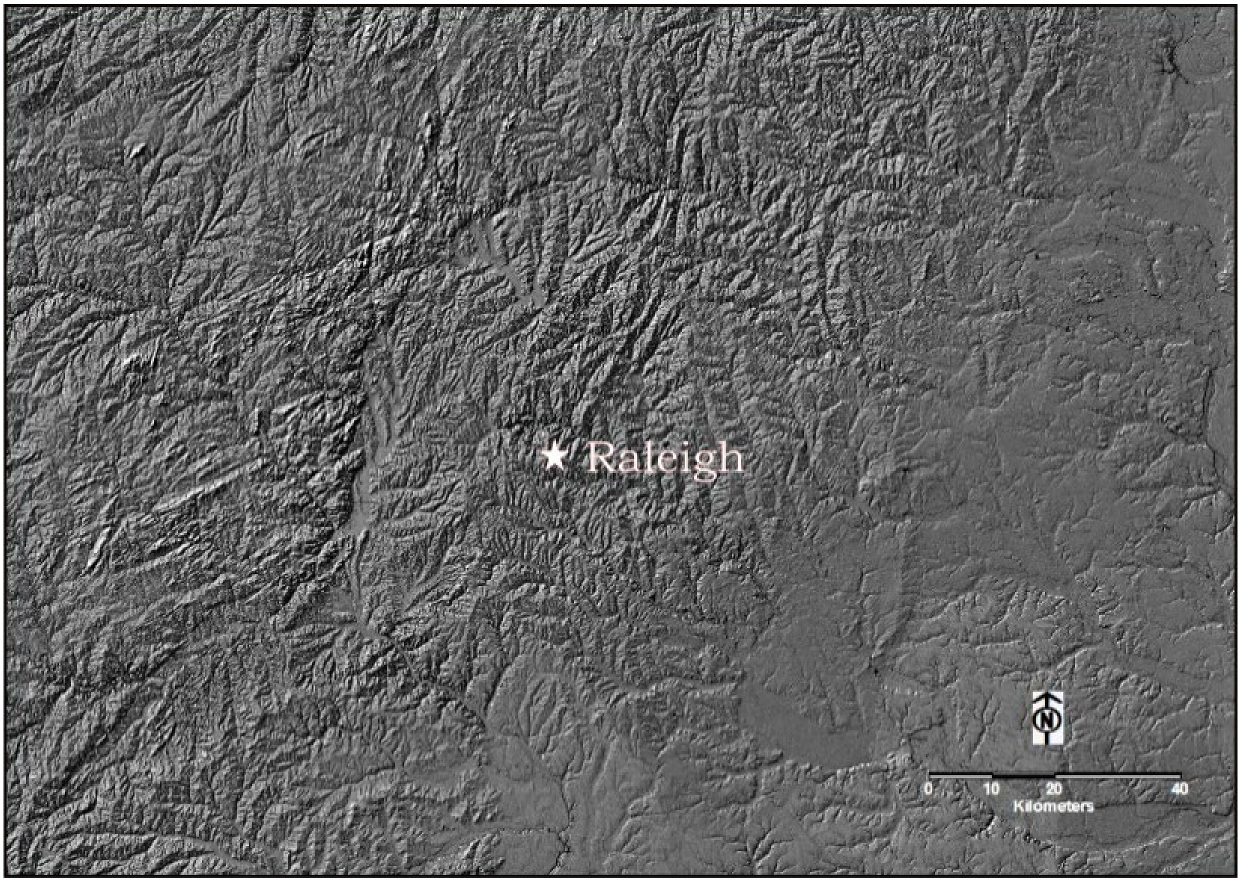


Figure 1: Legacy Light Detecting and Ranging (LiDAR) Hillshade image for central North Carolina. Circular feature is near center of image above. (North Carolina legacy LiDAR is available at: https://sdd.nc.gov/)

Large projectiles in the range of 50 meters or more in diameter and with velocities >11 km/sec strike the earth with little velocity decrease after passing through the atmosphere. They form hypervelocity impact craters upon impact. Their undiminished energy is released at the point of contact with the earth, producing shock waves that radiate outward from that point.

Pressures generated in the target rocks far exceed pressures generated by any other geological processes. These pressures diminish rather quickly with depth but not before forming either simple or complex impact craters. This process only takes a matter of a few minutes at most. On earth, craters over four kilometers in diameter are referred to as complex craters. These are characterized by a central uplift area at the center of the crater and can have a topographically uplifted annular ring surrounding the central uplift. This structure is referred to as the peak ring. Annular faults surround the peak ring and represent material collapsing inward to form the final crater structure **(French, 1998; French and Koeberl, 2010).**

Many known hypervelocity impact craters have attracted initial attention due to the presence of a circular feature such as the one detected in the LiDAR data for the Raleigh area. Suspect circular features may be the result of topographic or physiographic features or of geologic features such as exposed bedrock with intense localized deformation. Some impact craters have been brought to researchers' attention by regional circular anomalies on geophysical or remote sensing maps.

The only generally accepted proofs of an impact structure **(French, 1998; French and Koeberl, 2010)** are the presence of :

- Shatter cones
- Unique shock metamorphic effects detected at the individual mineral grain level by petrographic methods
- Geochemical signatures of an impactor in the rocks of the structure.

Evaluation of the Proposed Raleigh Impact Crater

Shatter Cones

The presence of shatter cones is the only accepted impact indicator observable in the field. They are very distinctive cone-like structures with fractures that radiate downward from the apex of the cone. Commonly these fractures resemble a horse tail in appearance. They vary in size from a few centimeters to as much as 30 meters or more in length **(Baratoux and Reimold, 2016)**.

Three quarries have been visited in the central uplift of the proposed Raleigh impact structure in a search for shatter cones. No definitive shatter cones were observed in these quarries, although curved, striated surfaces **(Figure 2)** as well as large conical structures **(Figure 2)** were observed in the Triangle quarry near Cary, NC. The search continues.

Figure 2: Large conical structures and some striated surfaces are present in the Wake Stone Corporation's Triangle quarry near Cary, NC but these are not convincing shatter cones.

Unique Shock Metamorphic Effects

Shock metamorphic effects include planar microstructures in quartz and feldspar. The planar features include both planar fractures (**PFs**) and planar deformation features (**PDFs**). Planar fractures are closely spaced parallel open fractures. Although common in the rocks of hypervelocity impact areas they are not necessarily diagnostic of an impact as they can be formed in other ways. Fortunately, planar fractures often occur with more diagnostic shock metamorphic effects such as **PDFs**. **PDFs** are closely spaced sets of parallel planes which often form in multiple sets along specific crystallographic planes within mineral grains. Rather than open fractures, the planes are zones that have been transformed into an amorphous phase by hypervelocity shock. The presence of **PDFs** within mineral grains of hypervelocity impacted rocks is accepted as proof of an impact. Usually, they are more readily identified in quartz than feldspar due to the simpler crystal structure and lack of cleavage in quartz. Shock metamorphic effects can cause conversion of both quartz and feldspar to glass without melting, while still retaining the original crystal outline. This is called diaplectic glass. Total melting without retaining the original mineral outline occurs at higher temperatures and pressures **(French, 1998; French and Koeberl, 2010)**.

Thin sections of rock from the central area of the proposed impact crater have been examined using a petrographic microscope in search for shock metamorphic effects within individual mineral crystals. Most of these thin sections were from the collections of the North Carolina Geological Survey. Of the 1382 thin sections examined, 90 (6.5%) contained unconfirmed but possible shock metamorphic features**.**

One of the primary proofs of an impact, PDFs in quartz, was not identified in any of these thin sections. Many roughly-parallel planar sets of features are present in the slides but none have been found that meet the strict criteria of thickness, continuity and perfectly parallel alignment required for PDFs in quartz.

Most of the potential shock metamorphic features were found in feldspars. Alternating isotropic twin planes in feldspars that remain isotropic upon full rotation of the microscope stage are common. Thin deformation planes that cross twin planes and alternate from isotropic to non-isotropic as they cross adjacent twin planes (inclined deformation lamellae) are common as well **(Figure3)**. These also remain isotropic with full rotation of the microscope stage. The isotropic portions of these feldspar crystals stand out in higher relief than the non-isotropic portions when viewed in plane-polarized light. **Pickersgill (2014) and (2019) and Pickersgill *et al.* (2015)** studied shock metamorphic effects on feldspar at the Mistastin impact structure in Canada. They found that shock metamorphic effects on feldspar including alternating twin deformation lamellae, inclined deformation lamellae and partial to complete transformation of feldspar to glass was restricted to environments of hypervelocity shock by a bolide impact. **French and Koeberl (2010)** recommend the following criteria for diaplectic feldspar confirmation: 1) identification of grains as isotropic and pseudomorphs of plagioclase, 2) composition that matches monomineralic plagioclase feldspar as seen by EPMA (Electron Probe Microanalyzer) and 3) an amorphous state as confirmed by µXRD (Micro X-Ray Diffraction). Advanced analytical methods such as these should be used to confirm or deny the many potential shock metamorphic features noted in feldspars of the potential Raleigh impact structure.

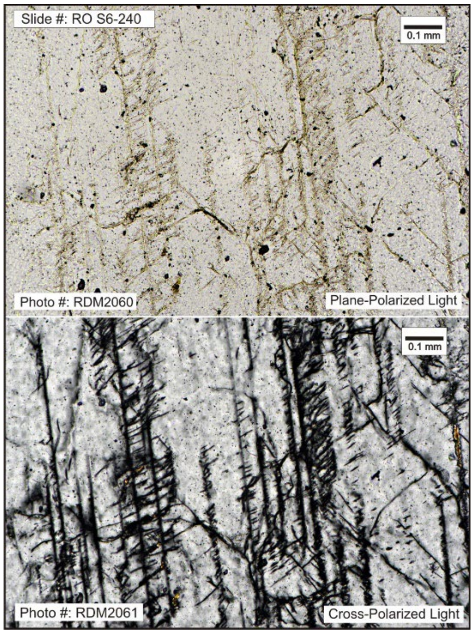


Figure 3: Plagioclase feldspar in granite: Plane-polarized light- Plagioclase with twin plane lamellae. Cross-polarized light- Alternating isotropic twin planes with cross-cutting inclined alternating isotropic deformation lamellae remain isotropic with full stage rotation. (Rolesville 7.5' quadrangle)

The most interesting shock metamorphic features were observed in 15 thin sections from three different locations within the proposed crater area **(Figure 4)**. The rock in each case is a quartz breccia with rock fragments that are both rounded and angular. Some fragments come from wall rock adjacent to the quartz breccia while other fragments are lithologies with no apparent local source. The fragments are embedded in a cryptocrystalline matrix with a fluidal flow texture. Rotation of some fragments can be seen within the matrix. Secondary quartz crystal growth is present and surrounds some fragments **(Figures 5 and 6)**. **Figure 7** contains a photograph of a sawed sample of the Louisburg breccia dike. These occurrences are likely breccia dikes formed below the crater floor within fractures and faults. They appear to contain both diaplectic as well as total melt glass **(Figure 8 and 9)**. Dark-colored areas of some thin sections contain abundant, apparently glassy fragments and could be small pseudotachylite veinlets **(Figure 10)**. The polarizing-light microscopic analyses need to be confirmed using alternative methods as recommended by **French and Koeberl (2010)**.

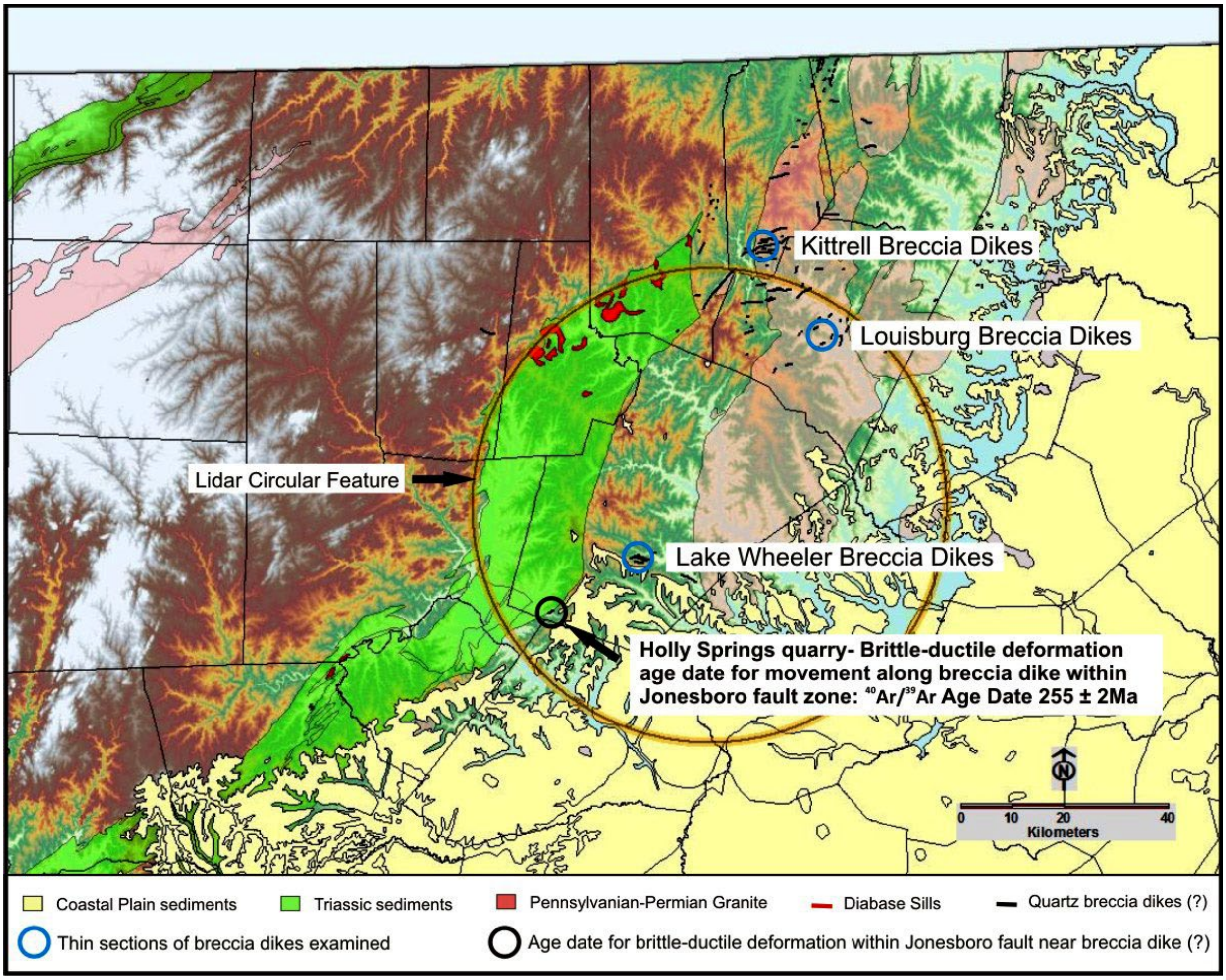


Figure 4: Raleigh area quartz breccia dikes(?) on regional simplified geology and color legacy LiDAR elevation base. Breccia dikes(?) are from the USGS-North Carolina Geological Survey cooperative 7.5' geologic mapping program. Individual maps are listed in the References section at the end of this paper.

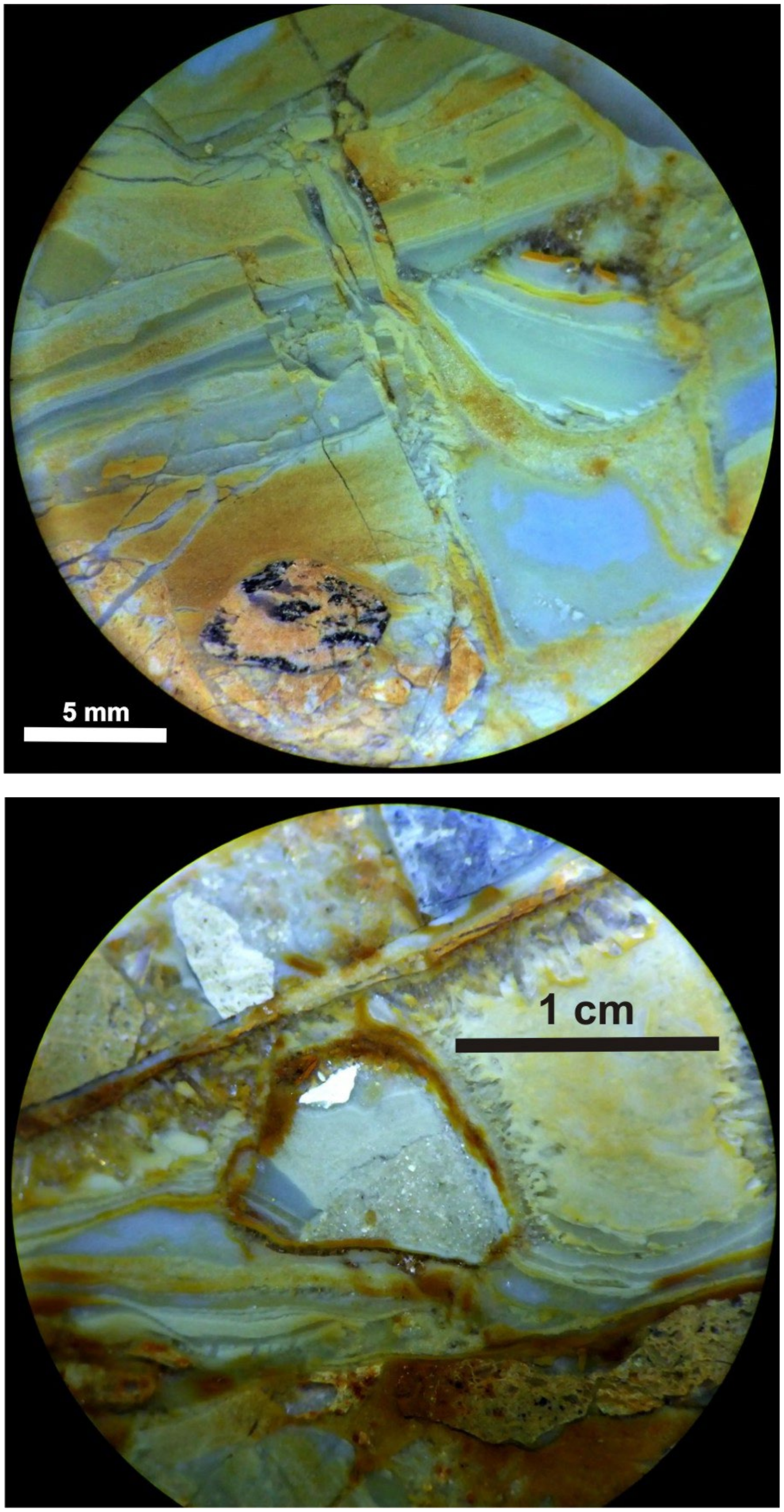


Figure 5: Louisburg breccia dike samples displaying fragments with multiple rock types (both samples from LB-1). Fragments vary from rounded to angular. Brittle fractures are common. Dike is located within Rolesville batholith.

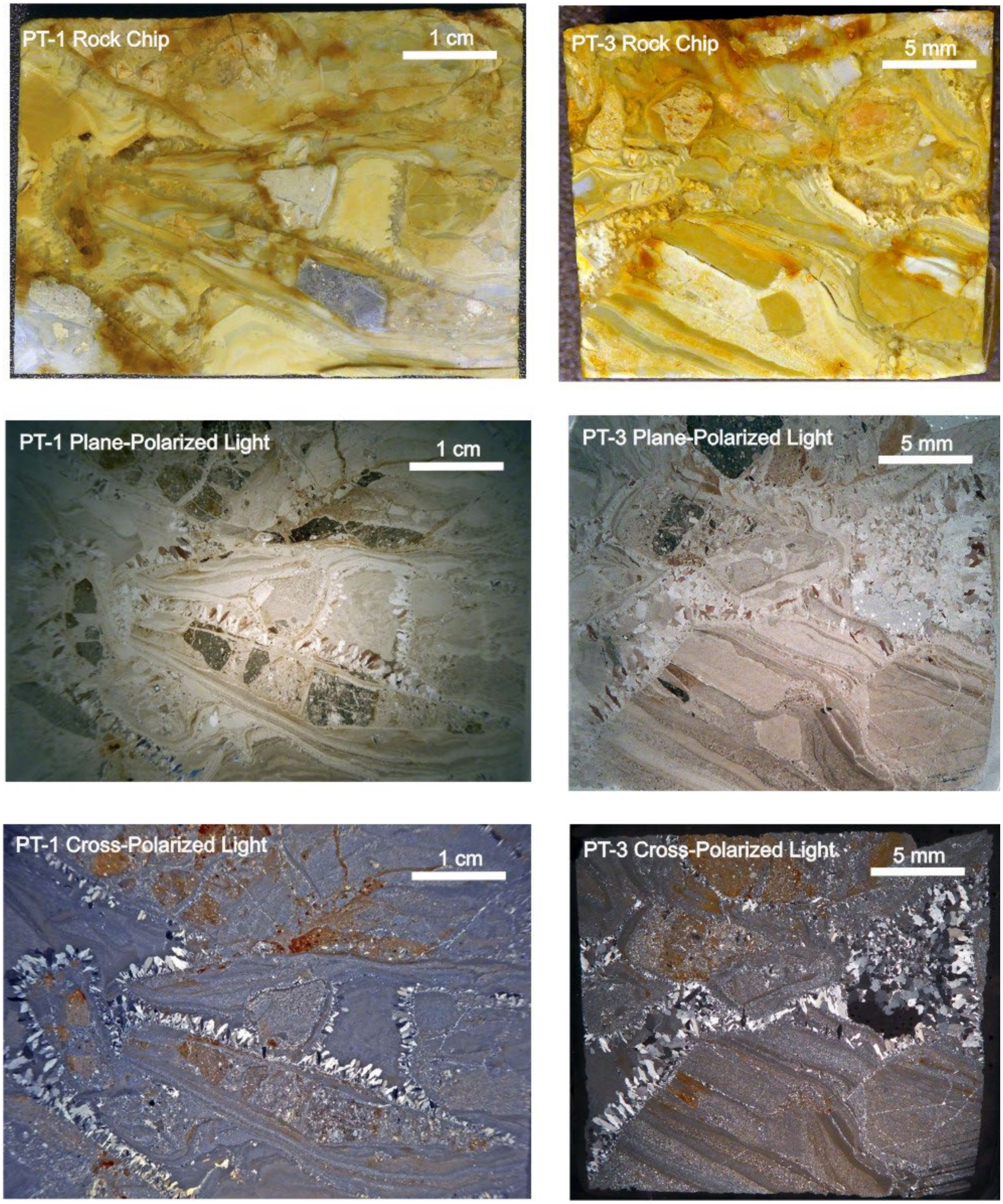


Figure 6: Thin sections PT-1 and PT-3 and rock chips from which thin the sections were made. Both sections are from Louisburg breccia dike (LB-1). Macro views of rock chips, plane-polarized views and cross-polarized views of thin sections are included. Sample shows brittle fracturing, fluidal flow and rotated fragments. Some fragments include fragments of fragments while others are varied rock types.

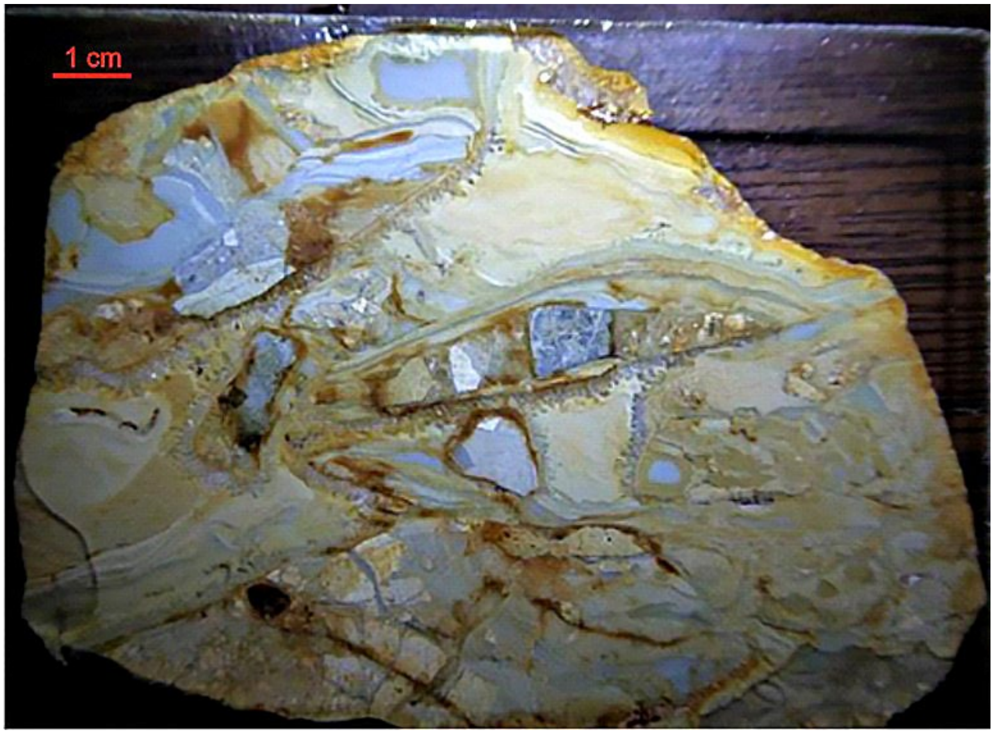


Figure 7: Sawed sample (LB-1) of breccia dike(?) from south of Louisburg, NC. Sample shows angular to rounded fragments in a cherty cryptocrystalline matrix. All three quartz breccia dikes are similar in composition and texture.

Lambert (1981) describes breccia dikes from other impact craters crater and proposes a multi-phase process of dike formation all taking place within a matter of minutes. First, on compression, a breccia dike is formed consisting of fine-grained, monomineralic, well-sorted rounded fragments embedded within a cryptocrystalline matrix that often exhibits fluidal texture (Type A breccia). Upon decompression and rebound angular to subrounded fragments of rock, minerals and glass are drawn from all stratigraphic levels of the target into the fractures, including even the uppermost levels (Type B breccia). Type B breccias can contain both monomict and polymict breccias and most are characterized by clastic texture. Polymict breccias tend to have sharp contacts with country rocks while monomict breccias show a progression of fracturing into the surrounding country rocks. Fragments of Type A breccias have been reported within Type B breccias at several crater locations. Breccia dikes have only been studied within the floors of deeply eroded craters such as Vredefort, Sudbury and Manicouagan where the upper melt sheet has been removed **(Dressler and Reimold, 2004)**. Drilling of a few buried craters, like Chicxulub, has revealed breccia dikes in the crater floor of those structures **(Wittmann *et al.*, 2004)**.

The three dikes we have examined (from the Louisburg, Lake Wheeler and Kittrell areas) are thought to be Type B breccia dikes in the system of identification defined by **Lambert (1981)**. Fragments of Type A breccias are common within these Type B breccias. **Figure 7** is a photo of a hand sample of the Louisburg breccia dike showing a variety of different fragment types within a cryptocrystalline to clastic matrix. Brittle-ductile deformation within the Jonesboro fault zone on the east side of the Triassic Durham sub-basin in the Holly Springs quarry has been dated using laser ^{40}Ar/^{39}Ar techniques. This yielded an age of 255 ± 2 Ma **(Hames *et al.*, 2001)**. One of these quartz breccia dikes occurs within the same zone that produced this late Permian age date **(Figure 4)**. The sample site is about 20 km SW of the Lake Wheeler breccia dikes and lies within the central uplift of the proposed crater.

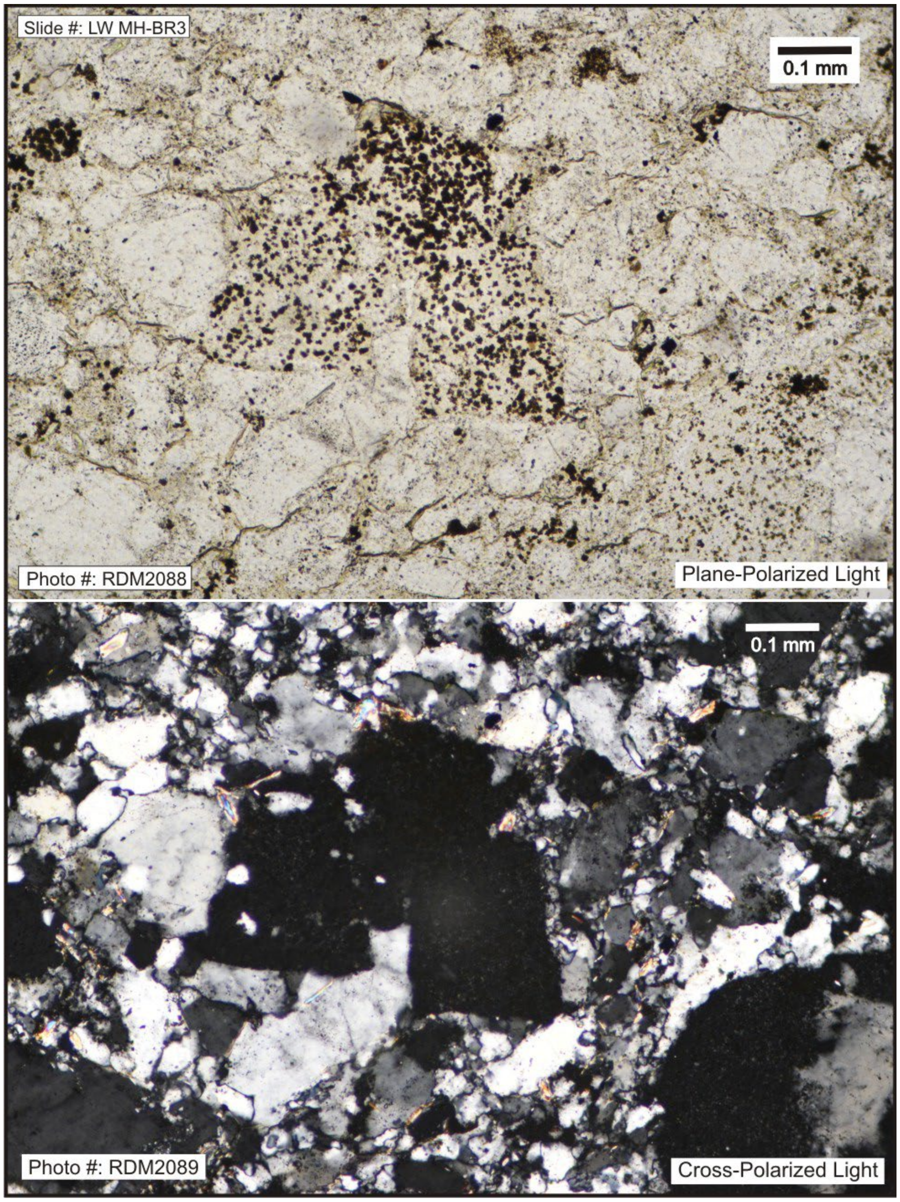


Figure 8: Thin section of breccia dike (?) from Lake Wheeler area (Heller, 1996). Plane-polarized light- Diaplectic feldspar (with black mottles). Cross-polarized light- Isotropic crystals in center of slide retain crystal shape (diaplectic glass?). Possible partial diaplectic glass in lower right corner of photomicrograph. (Lake Wheeler 7.5' quadrangle)

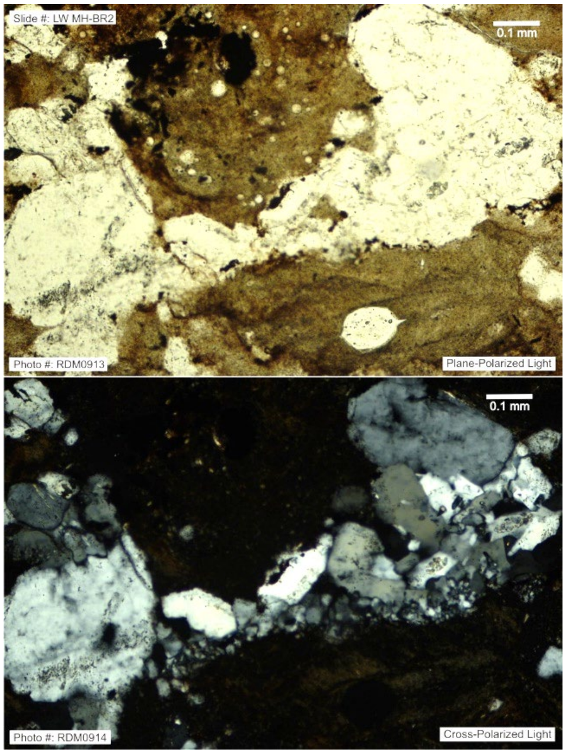


Figure 9: . Thin section of breccia dike from near Louisburg, NC. Plane-polarized light- contains possible dark brown glassy melt and glass beads. Cross-polarized light- Brown glassy-looking areas are isotropic. (Lake Wheeler 7.5’ quadrangle)

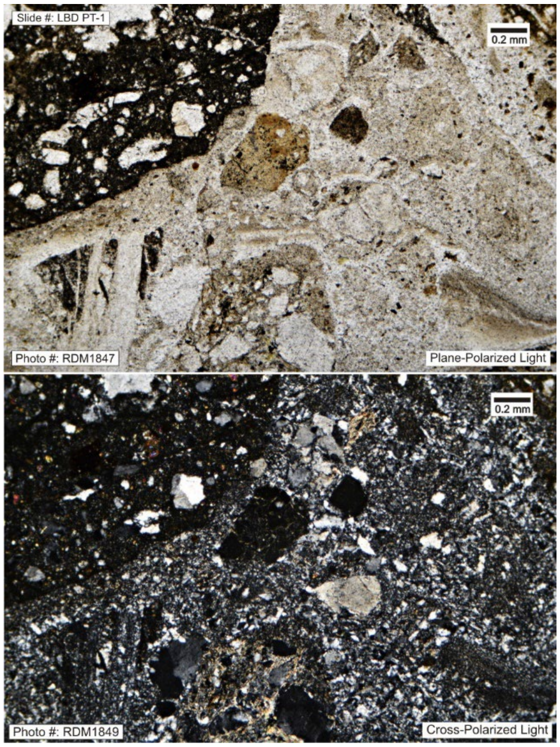


Figure 10: Thin section of breccia dike from near Louisburg, NC. Plane-polarized light- Possible pseudotachylite, upper left of slide. Cross-polarized light- Dark grains such as those just above the center of slide are nearly all isotropic (glass?). (Louisburg 7.5’ quadrangle)

Shock metamorphic effects are most commonly found in fragments within crater-fill breccias and impact melts. Some may be present within the crater floor or within breccia dikes which fill fractures in the crater floor. They are rare even within well preserved craters and may be absent in highly eroded craters.

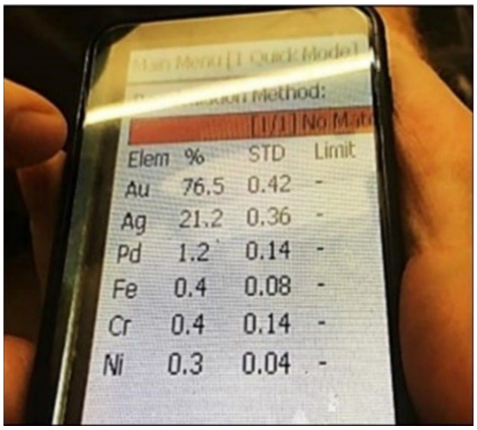
The various types of shock metamorphic effects are dependent on the temperature and pressure of the impacted rocks **(French, 1998; Stöffler, 1971; Grieve, 1990; Grieve and Pesonen, 1992).**

Geochemical signatures of an impactor in the rocks of the structure

Analysis of breccias or melt rocks within the impact structure may give clues left by the impactor in the form of excess iridium or other platinum group elements. Unusually high amounts of these elements may be proof of an impact, especially when combined with any of the shock metamorphic effects described above **(French, 1998; French and Koeberl, 2010)**.

No geochemical analyses of breccias or melt rocks from the proposed crater area are available as these have not yet been identified. These rocks within a crater can have unusually high amounts of iridium or other platinum group elements associated with them. Their presence in such elevated amounts is generally considered proof of an impact, especially when combined with presence of shock metamorphic features.

Mineral exploration of an area within the proposed central uplift has identified the presence of a very unusual gold occurrence near Louisburg within saccharoidal quartz veins(?) in the central portion of the Rolesville batholith. The gold prospect is near some of the quartz breccia dikes described above. Analysis of gold recovered from the prospect yielded up to 1.2% palladium as shown in **Figure 11**. Analysis of the gold was performed by desktop X-Ray Fluorescence by the refinery when some of the gold was sold to them **(personal communication, Cascade Refining, Charlotte, NC)**. Silver, iron, chromium and nickel were also present in the gold in significant amounts. Gold mineralization within saccharoidal quartz veins(?) has been found at the Portis mine in northeast Franklin County and the Argo mine in Nash County, both about 30 km N-NE of Louisburg. Neither of these prospects are within granite, although two sills of diorite or granodiorite have been reported at the Portis mine **(Carpenter, 1976)**.



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Elem  %     STD   Limit
Au    76.5  0.42  -
Ag    21.2  0.36  -
Pd    1.2   0.14  -
Fe    0.4   0.08  -
Cr    0.4   0.14  -
Ni    0.3   0.04  -
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Figure 11: Analysis of gold from prospect within proposed central uplift area of proposed crater.

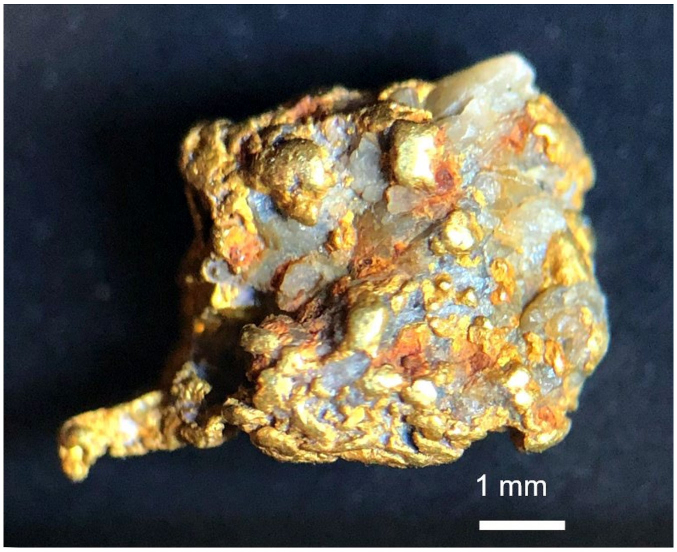

Figure 12: Gold in quartz from palladium-bearing gold prospect. Sample recovered from a depth of 100 feet within rotary drill hole. Gold stands out in relief as rounded nuggets within saccharoidal quartz.

Regional Geology Review of Proposed Crater Area

The location of the circular LiDAR feature is shown as an orange circle on the LiDAR base maps **(Figures 4 and 13)**. The Durham Triassic sub-basin and Rolesville batholith (Pennsylvanian-Permian granite) are shown for geological perspective.

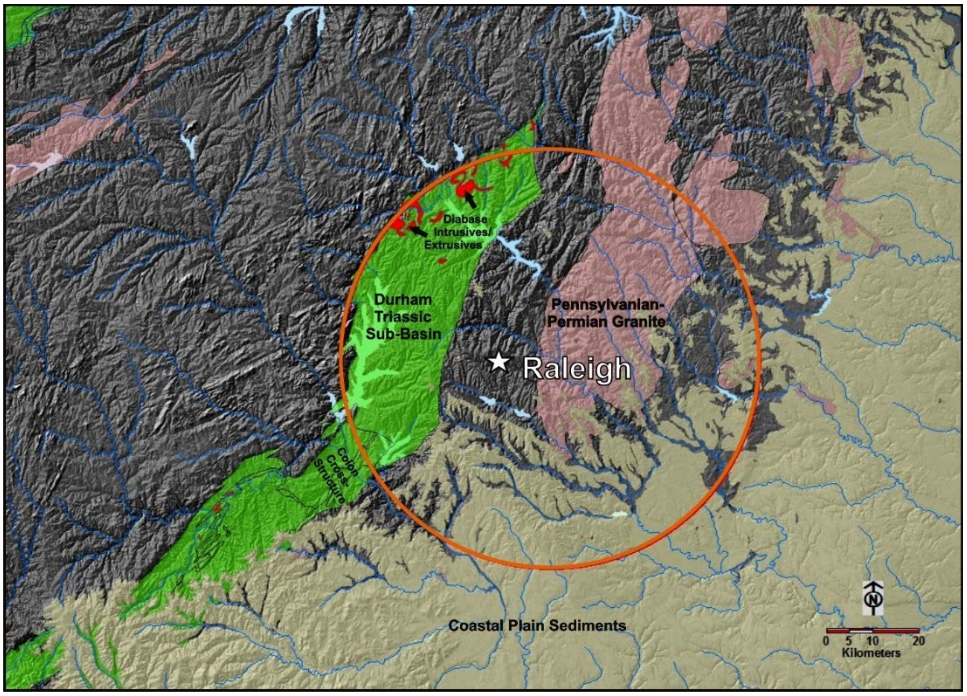

Figure 13: Location of the circular LiDAR feature (orange circle) relative to the Durham Triassic sub-basin and Pennsylvanian-Permian Rolesville batholith. LiDAR hillshade base.

The geology of the area within and surrounding the circular LiDAR feature is complex. It includes Neoproterozoic to Paleozoic gneisses and schists of middle to upper amphibolite metamorphic facies, metamorphosed ultramafic rocks, greenschist facies Neoproterozoic to Paleozoic volcanic and sedimentary rocks, both metamorphosed and un-metamorphosed granitoid intrusive rocks of various ages, and unmetamorphosed younger sediments of the Triassic basins and Atlantic Coastal Plain. The N-NE trending Nutbush Creek strike-slip fault zone crosscuts the circular feature, as does the Jonesboro normal fault, which constitutes the eastern border fault of the Triassic Durham sub-basin.

The circular LiDAR feature corresponds closely to the western contact of the Durham Triassic basin. The basin is a half graben that steps downward toward the east via a series of half grabens, eventually attaining a depth of around 2000 meters. The curvature of the basin's western margin conforms to the circular LiDAR feature. This suggests that the basin sediments may fill a pre-existing circular depression.

A series of Jurassic diabase sills and some possible flows are found along the northwestern basin margin **(Figures 4 and 13)**. Geophysical studies have shown that a semi-continuous basaltic intrusive body greater than 250 m thick has ascended along a major fissure or fissures into the basin along a path corresponding to the basin's NW border. The basaltic intrusive thins to about 100 m toward the middle of the basin **(Bolich *et al.*, 1985).** Large complex impact craters typically have deep-seated fractures and deformation along the central uplift-peak ring interface **(Morgan *et al.*, 2000)**. Fractures within the interface might have served as conduits for the mafic intrusion. Several diabase dikes located along the western margin and within the basin conform to the curve of the circular LiDAR feature **(Figure 14)**. The circular LiDAR feature may represent such an interface supporting the presence of both a central uplift and a peak ring structure as seen in **Figure 15**.

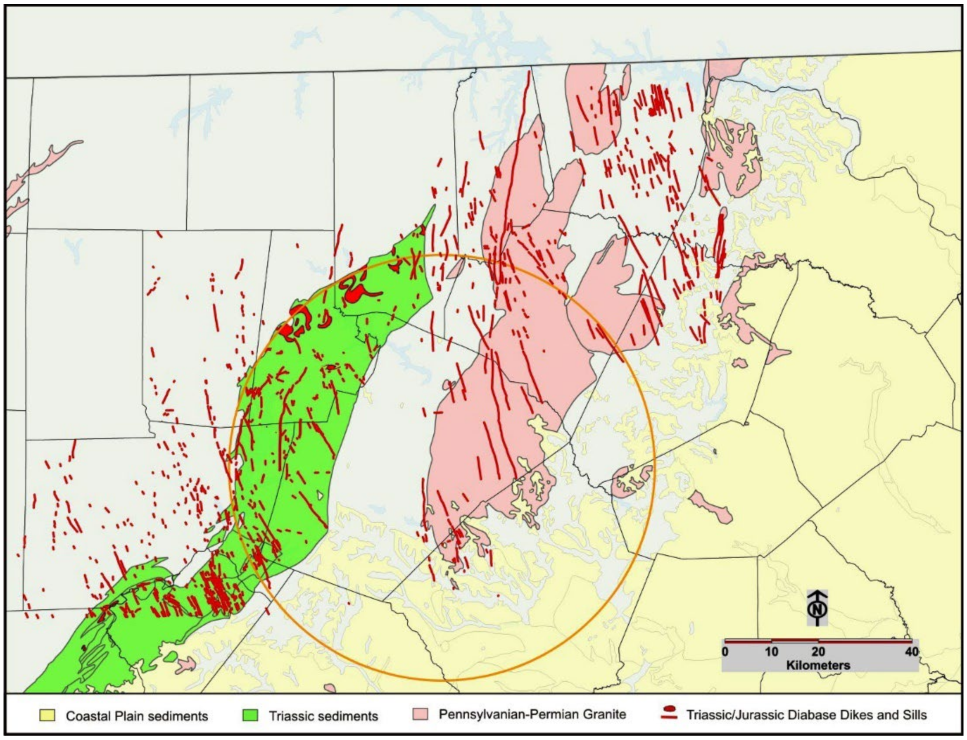

Figure 14: Diabase dikes and sills from maps of the USGS-NCGS 7.5' cooperative geologic mapping program. See References for individual quadrangle maps used.

Following the circle clockwise, we see that it extends beyond the northern termination of the Triassic basin and proceeds to follow the Tar River closely for 26 km. It cuts across the Carolina terrane and thin slices of the Crabtree and Raleigh terranes before crossing the Pennsylvanian-Permian Rolesville batholith and Castalia granite. At this point, the circle emerges in the Spring Hope terrane where the metasedimentary and metavolcanic rocks are folded into regional overturned folds whose axes parallel the circular LiDAR feature. Sediments of the Atlantic Coastal Plain obscure much of this area on the southeastern portion of the circle and outcrops of bedrock are poor, if present at all. The circular feature emerges from the Coastal Plain near the town of Lillington where it passes along the Cape Fear River at the high cliffs overlooking the river at Raven Rock State Park. It then crosses the Crabtree and Carolina terranes before cutting across the Durham Triassic basin and emerging on the west side. Here it rejoins the western contact of the basin near New Hope Overlook State Recreation Area.

The portion of the circle that crosses the SW Durham Triassic basin corresponds to the northern limit of the Colon cross-structure which separates the Durham sub-basin from the Sanford sub-basin **(Randazzo and Copeland, 1976)**. The cross-structure is a significant rise in the basement below the Triassic basins where they meet. It may represent a topographic expression of the peak ring of the potential impact crater **(Figure 15)**, downfaulted by the Triassic Jonesboro fault. Deep drilling for oil near the Colon cross-structure encountered 87 meters of gypsum-rich shale, sandstone, and conglomerate of Triassic age lying unconformably on the greenschist-grade Carolina terrane. This was different from anything seen at the surface of the basin and was thought to possibly be an early rift or pre-rift sequence not preserved outside the floor of the basin **(Olsen *et al.*, 1991).** Gypsum-bearing sediments or alteration products are found on the crater floors of several impact craters such as the Haughton and St. Martin impact craters in Canada **(Osinski *et al.*, 2005) (Leybourne *et al.*, 2007)**. Gypsum within these craters may be due to impact related alteration or evaporite deposits within a restricted basin.

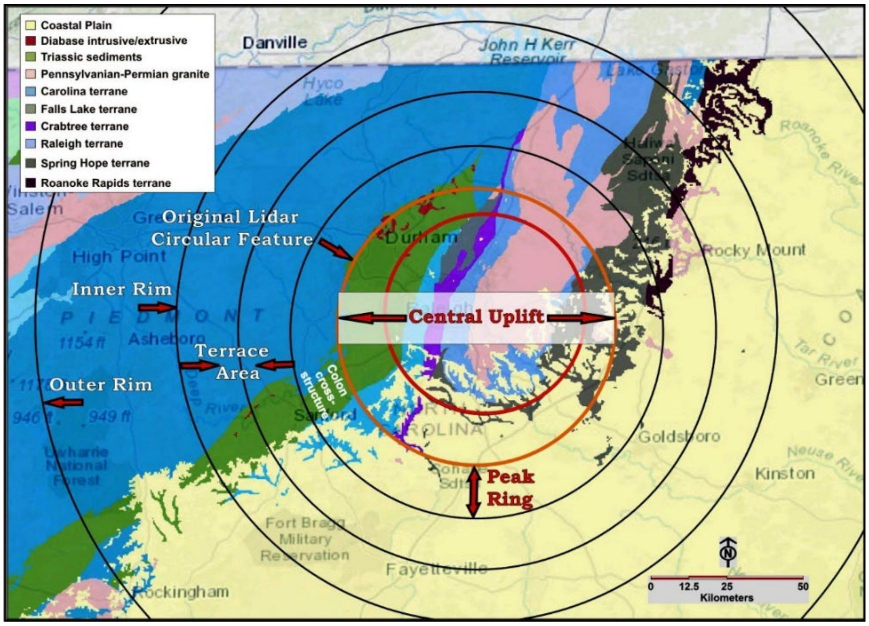

Figure 15: Possible peak ring and central uplift on regional geologic map. Off-center circular feature within original circular LiDAR feature is from total magnetic field map. Proposed outer and inner rims, terrace area, peak ring and central uplift have been added. Base map is North Carolina terrane map at the link below:
https://ncdenr.maps.arcgis.com/apps/MapSeries/index.html?appid=0a7ccd9394734ff6aa2434d2528ddf12

Studies within the area labeled central uplift **(Figure 15)** suggest that the area has experienced uplift of the Rolesville batholith and the area immediately west by as much as 10-15 km since the Permian **(Gaughan and Stoddard, 2003; Carpenter and Reid, 2014)**. Some of this uplift could be related to an impact and subsequent formation of a central uplift at the center of the proposed Raleigh impact structure **(Melosh, 1989)**. Depths of emplacement for other Pennsylvanian-Permian plutons range from 8 to 19 km, based on contact metamorphic assemblages **(McSween et al., 1991)** so at least some of the uplift is due to Alleghanian tectonic events.

The hillshade LiDAR map and the **North Carolina Geologic Map (1985)** were used to identify hypothetical annular faults west of the peak ring. The circles on the maps in **Figure 16** are purely conjectural approximations of these likely annular faults based on "best fit" using these maps. In reality, the trace of such annular faults would be much less perfect than this depiction considering the complexity of impact dynamics. The Haughton impact structure in Canada is a good example to demonstrate this reality **(Osinski *et al.*, 2005)**. Like many craters on Earth, it is a jumble of radial and concentric fault-bounded blocks arranged in a roughly concentric pattern. Confidence in these circular features becomes lower with increasing distance from the center of the proposed Raleigh impact structure.

The North Carolina legacy LiDAR data were used to identify local changes in the strike of LiDAR lineaments, especially those that parallel annular circles that are concentric to the original circular LiDAR feature **(Figure 16)**. We speculate that during the collapse of outward-ejected material back toward the center to form the final crater, silicified rock associated with large alteration zones or felsic volcanic centers may serve as ramps on which less cohesive materials slide toward the center of the crater. This may occur as acoustic fluidization wanes with decreasing energy. Preservation of such hypothetical ramps may aid in identification of annular faults. Resistant bedrock outcrops appear as topographic highs and also include crystalline resistant outcrops far out into the Coastal Plain, as noted on the map in **Figure 16**.

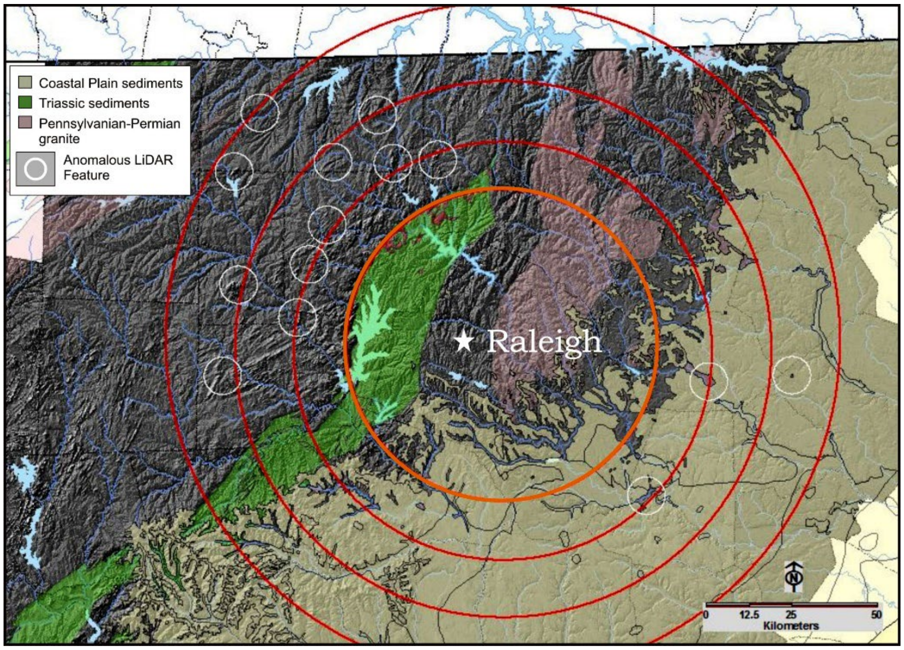

Figure 16: Legacy LiDAR map of some possible resistant rock ramps consistent with annular fault components of the terrace area of the proposed Raleigh crater. Geologic units from North Carolina Geologic Map. (North Carolina Geological Survey, 1985)

Figure 17 is a portion of the Geologic Map of North Carolina **(North Carolina Geological Survey, 1985)** representing the same area as the LiDAR map in **Figure 16**. It also shows the proposed annular faults from **Figure 16**. As previously mentioned, the western border of the Triassic Durham sub-basin is a near perfect fit for a significant portion of the proposed central uplift-peak ring interface. The outer fault circle on the map closely follows a major break in regional strike of lithologic units in eastern Randolph and western Chatham counties. The outer peak ring circle has two outcrops far out in the Coastal Plain sediments, one is granite and the other is metavolcanic rocks. We speculate that this may hint at the possibility of a less eroded peak ring with preserved topographic expression, mostly covered by the Coastal Plain. The entire potential Raleigh impact structure may be less eroded beneath the Coastal Plain sediments.

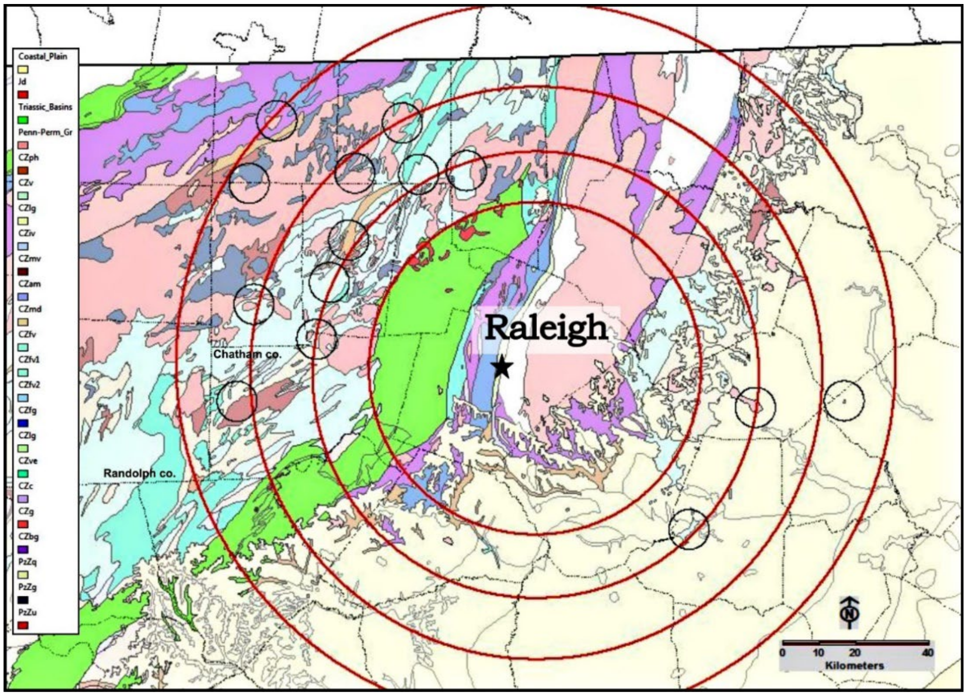

Figure 17: Portion of Geologic Map of North Carolina for the same area as the LiDAR map in Figure 14. For lithologic descriptions see the link below for the North Carolina Geologic Map: https://ncdenr.maps.arcgis.com/apps/MapSeries/index.html?appid=a8281cbd24b84239b29cd2ca798d4a10 (North Carolina Geological Survey, 1985)

Regional Magnetic Map

A regional total field magnetic anomaly map of central North Carolina including the area of the original circular LiDAR feature (orange circle) is presented in **Figure 18**. The white circular features on the map are annular faults based on LiDAR and geology. The two red circles represent regional magnetic map circular features.

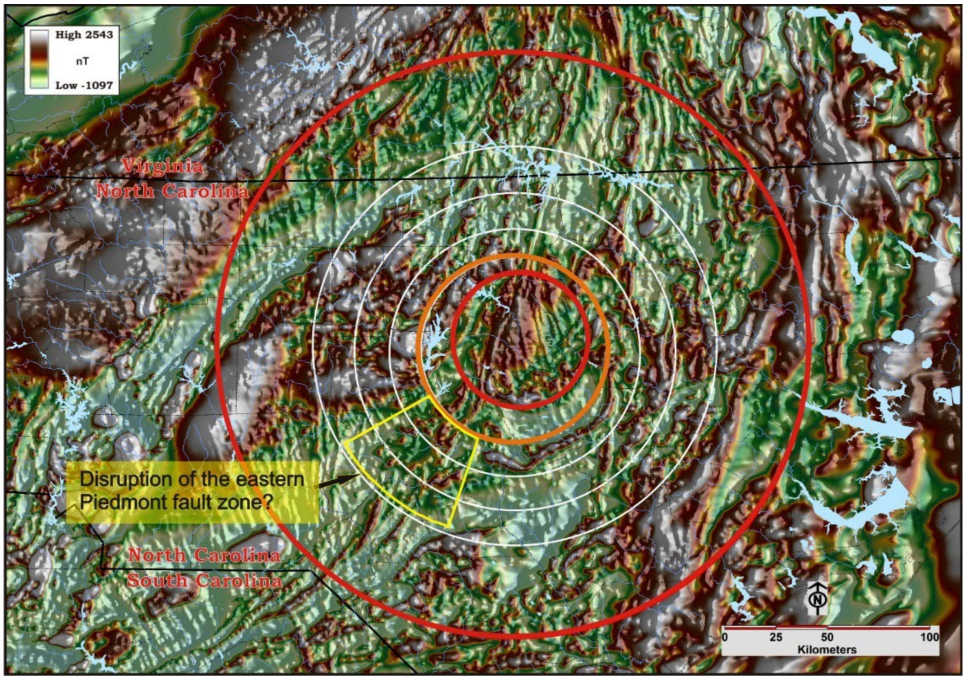

Figure 18: Regional total magnetic field anomaly map of central North Carolina with circular features. Orange circle is original LiDAR circular feature. White circular features are annular faults based on LiDAR and geology. Red circles represent regional magnetic circular features. (Jorgensen, 2001); [Magnetic anomaly maps and data for North America (usgs.gov)])

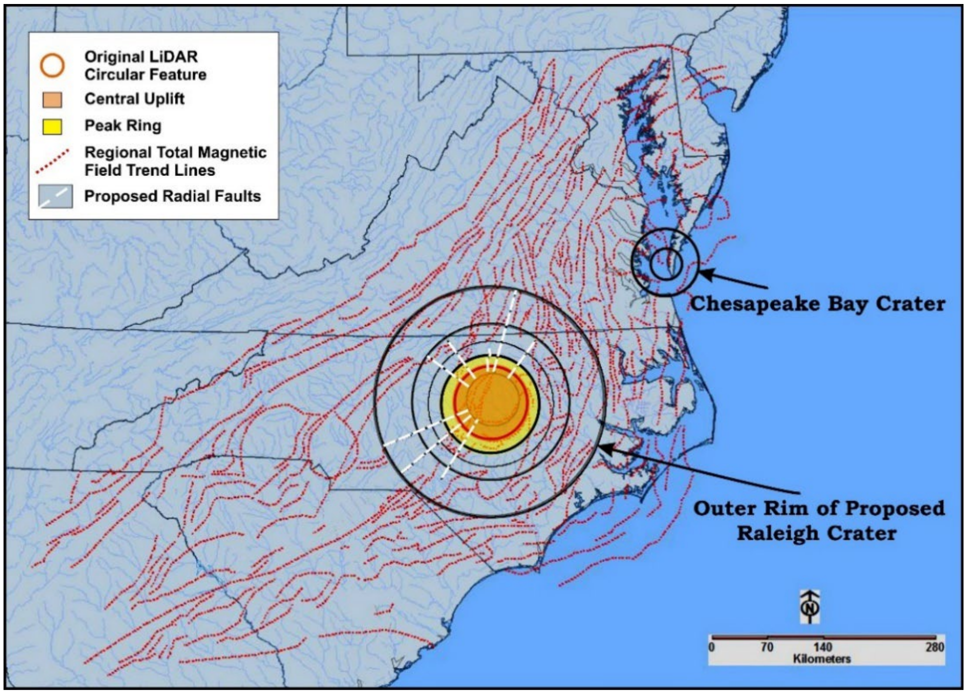

Figure 19: Regional total magnetic field trend lines traced from the total magnetic field anomaly map for the Southeastern U.S. (excluding diabase dikes). Includes location of the ca. 35-Ma Chesapeake Bay Impact Crater (Horton and Izett, 2005).

Regional total magnetic field trend lines were traced from the total magnetic field anomaly map for the Southeastern U.S. (excluding diabase dikes) and are shown in **Figure 19**. This map suggests a "wrap-around" of trend features surrounding the proposed Raleigh impact crater. The nearby ca. 35 Ma Chesapeake Bay impact crater is also shown on the map. Several potential radial faults are proposed based on geology, geophysics and topography and appear on the map as dashed white lines.

The area labeled "central uplift" in **Figure 15** is dominated by a magnetic high. This magnetic high is likely produced by gneisses and schists of middle to upper amphibolite metamorphic facies located along the west side of the Rolesville batholith. The magnetically high area along the NW quadrant of the circular LiDAR feature in **Figure 18** is likely produced by the basaltic intrusive and extrusive rocks in this area along the northwest border of the Durham Triassic sub-basin as previously discussed. Metasedimentary and metavolcanic rocks of the Spring Hope terrane are represented by broad lows and thin highs in the southeastern quarter of the circle. These rocks form regional overturned folds with axes that conform to the curvature of the original circular LiDAR feature. Another circular feature can be seen within the original circular LiDAR feature. It is off-centered toward the N-NE with respect to the original circular feature. This has been drawn in **Figure 15**. The inner circle's relationship to the regional geologic map is given in **Figures 15** and **20**.

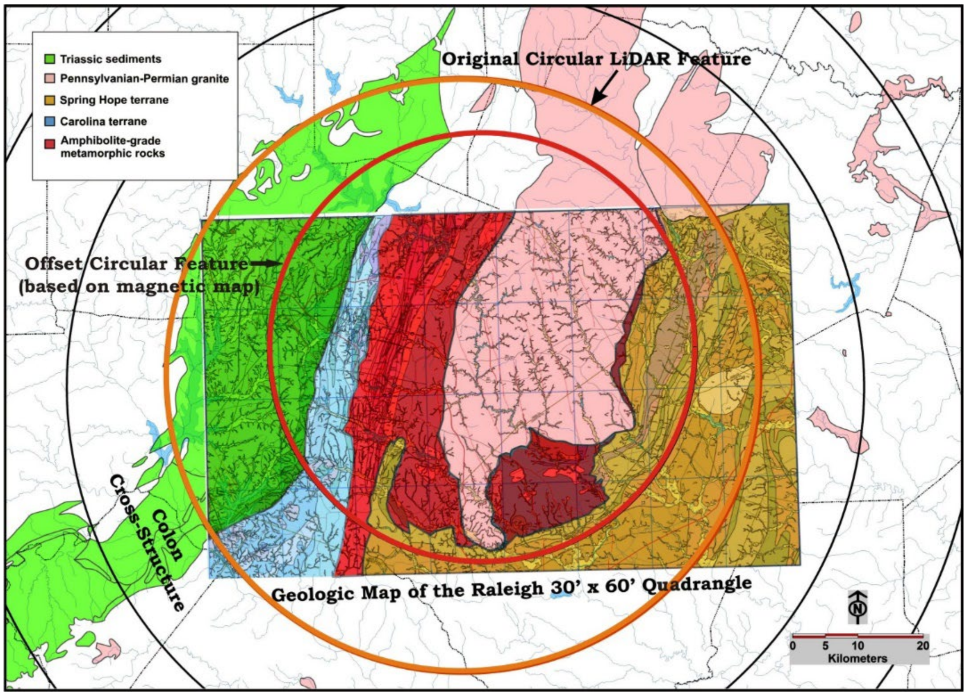

Figure 20: Inner offset circular feature on simplified Raleigh 30x60 minute quadrangle geologic map. (Clark *et al.*, 2004)

The inner "nested" offset circular magnetic feature passes through two major strike changes in the Jonesboro fault, the eastern border fault of the Triassic Durham sub-basin.

Where the Jonesboro fault crosses the SW quadrant of the inner “nested” circle the fault strike changes abruptly from NE to N-NE. The eastern border of the Durham Triassic sub-basin crosses the circle again in its northwest quadrant and the basin contact once more turns sharply, from NE to N-NW. At this point the Jonesboro fault continues NE but it no longer is in contact with Triassic sediments. The NE end of the Durham Triassic sub-basin is terminated along the N-NW trending Fishing Creek Fault **(Robitaille, 2004)**. Much of the southern half of the inner circle follows closely the transition between the greenschist-facies Spring Hope terrane and the amphibolite-facies terranes to the north **(Figure 20)**. The circle also corresponds to major strike changes in the contacts of the Rolesville batholith. The overall view of the total magnetic field map within the circular LiDAR feature is one of distinctive circular patterns despite a geologically complex area.

Applying techniques developed by **Ormo et al., 2013** in studies of craters on Earth and Mars as well as in experiments, and simulations we suspect that the Raleigh crater impactor may have arrived from the N-NE at a low angle. As noted in **Figure 18**, the narrow linear *en echelon* magnetic highs of the Eastern Piedmont Fault System **(Hatcher et al., 1977)** extending from central Georgia to Virginia appear to become disrupted between the inner rim and central uplift of the SW portion of the proposed Raleigh impact structure. This also may support an impactor arriving from the N-NE at a low angle.

Magnetic maps of impact craters are highly dependent upon the nature of the target rocks in terms of whether the crater area contains magnetic highs or lows. The most distinctive characteristic of magnetic maps within the core of craters is the roughly circular presentation pattern of the highs and lows.

Regional Gravity Map

The complete Bouguer gravity map of central North Carolina features broad NE-SW trending areas of high and low gravity that follow regional geologic trends **(Figure 21)**. A large circular low area overlaps the inner circle and closely corresponds to the Rolesville batholith. The broad area of high gravity values in the western half of the map corresponds to the Carolina terrane which is believed to have evolved over mafic oceanic crust **(Sampson *et al.*, 1995)**. The circular and arcuate areas of low gravity to the east of the Carolina terrane are mostly related to granitic intrusive rocks. The complexity of the geology of the central North Carolina area makes interpretation of the gravity map difficult but in general circular anomalous areas are obvious in the eastern half of the proposed impact structure as can be seen in **Figure 21**. The high gravity values in the western portion of the proposed crater area are potentially a reflection of the mafic basement rocks of the Carolina terrane which could potentially mask any reduction in gravity values produced by lowered density owing to fracturing.

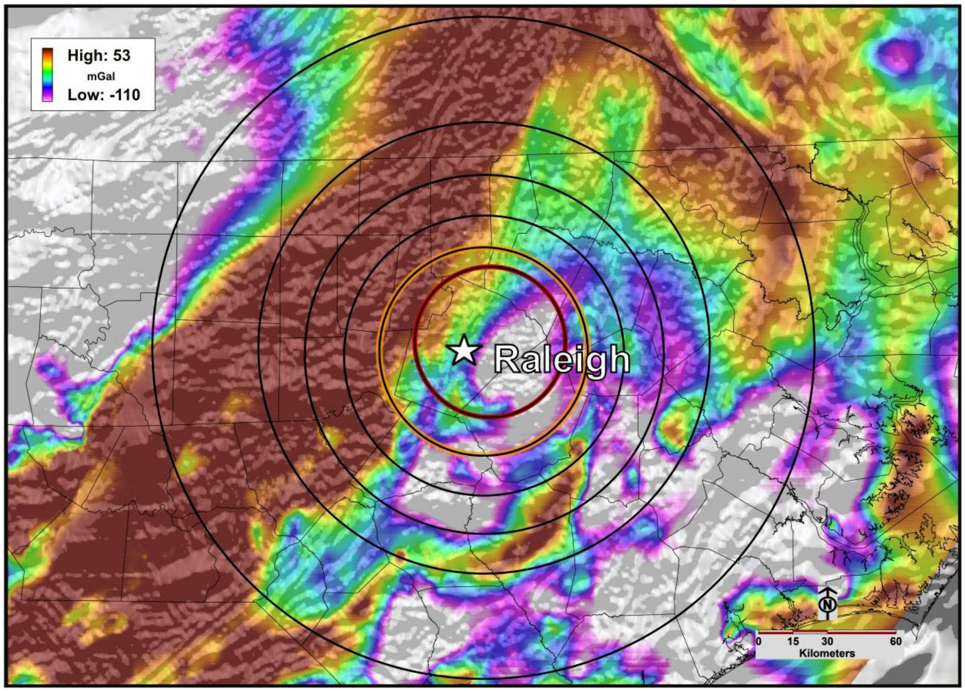

Figure 21: Colored complete Bouguer gravity map over black and white hillshade regional total field magnetic map. (Jorgensen, 2001); [Gravity Data | NCEI (noaa.gov)

Geochemistry of Stream Sediments from NURE Data

Below are plots of selected stream sediment analyses from the National Uranium Resource Evaluation Program (NURE) **(Figure 22)**. They show enrichment of uranium, thorium and rare earth elements within the proposed crater area in addition to other more common elements like barium and potassium. Coastal Plain sediments S-SW (potentially down range from the central area of the proposed Raleigh crater) are enriched in uranium, thorium and rare earth elements as well. Local sources of stream sediments can be inferred from regional geologic maps and may or may not have any relation to the proposed Raleigh crater. These heavy-mineral-sourced elements could be the result of reworking of the down-range debris field from the proposed Raleigh crater.

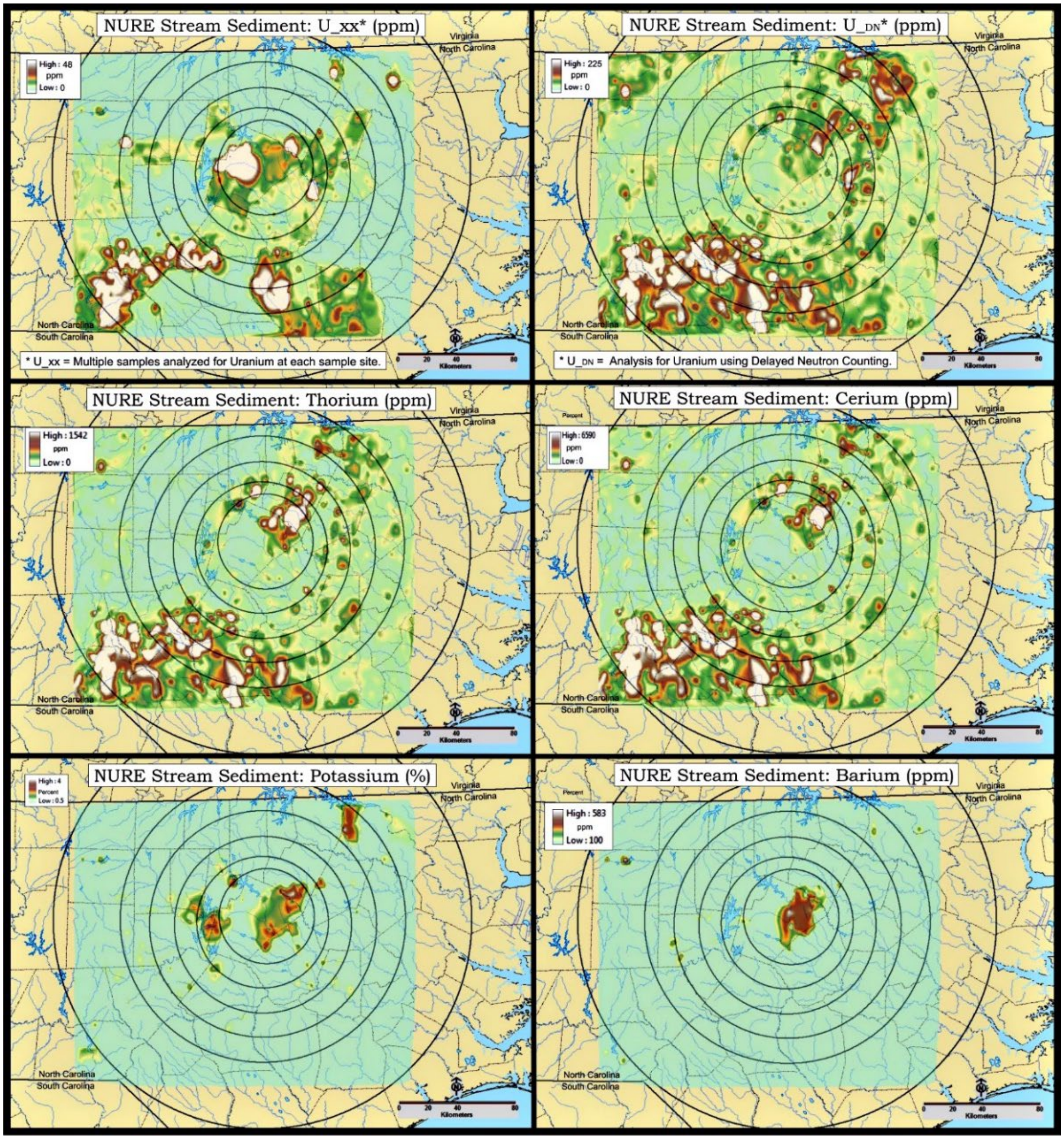

Figure 22: Selected stream sediment analyses from the National Uranium Resource Evaluation Program (NURE).

Coincident anomalous potassium and barium are present within the central uplift of the proposed crater. These anomalous elements are likely present in feldspar within the Rolesville batholith as they are found within the boundaries of this body. The barium anomaly appears to be confined to only the central uplift portion of the batholith.

Lineaments, Joints, and Fractures within the Proposed Crater Area

Lineaments were traced from the NC Legacy LiDAR data set for central North Carolina to make the detailed lineament map in **Figure 23**.

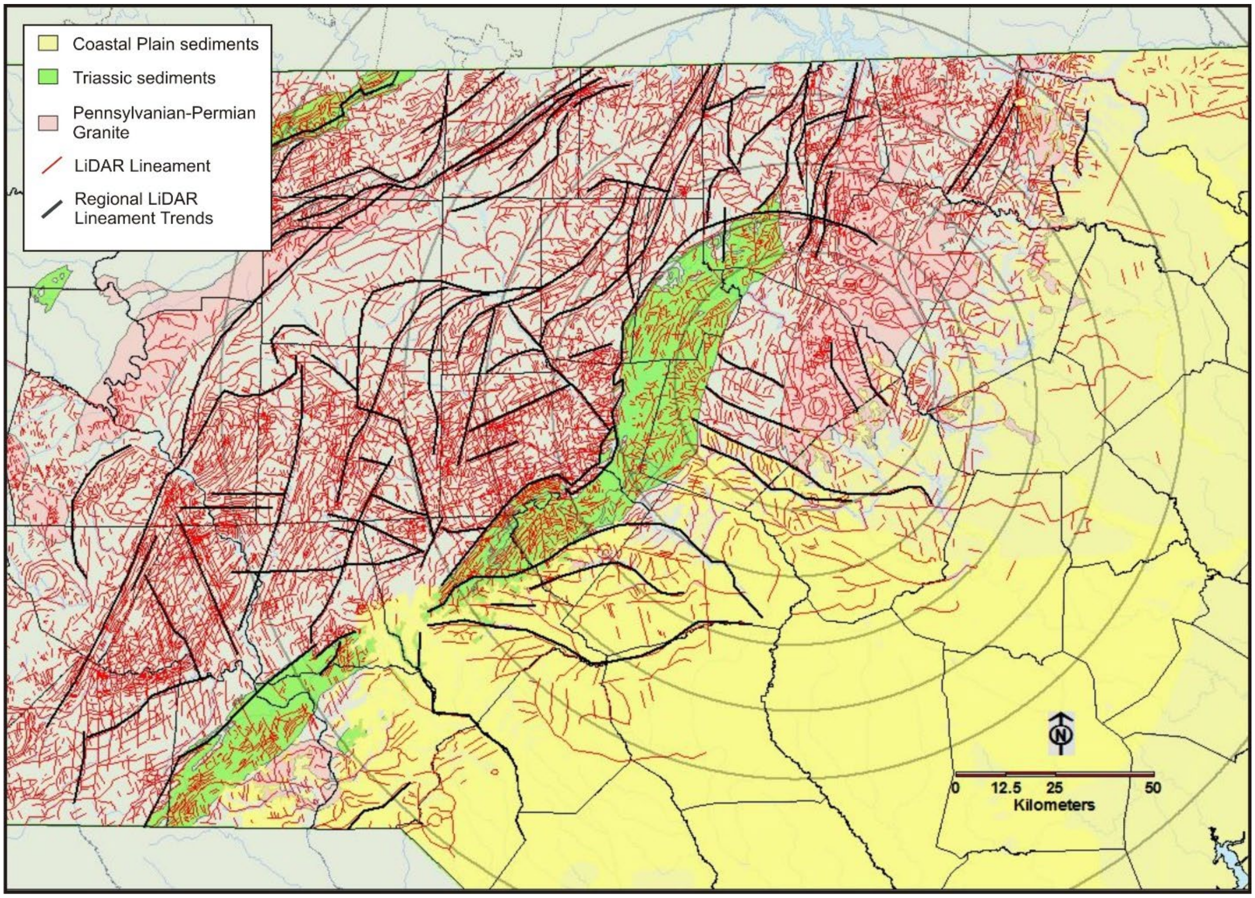

Figure 23: Detailed LiDAR lineaments traced from legacy North Carolina hillshade LiDAR map. Bold black lines highlight regional trends.

Most of the lineaments in **Figure 23** are related to geologic features shown on regional geologic maps. Within the Carolina terrane, some domains of similar structural trends are likely separated by faults. A splay of radiating lineaments emanating from the Virginia state line broadens out to the southwest along and to the west of the proposed peak ring.

Prominent parallel W-NW lineaments within the proposed peak ring have been mapped as brittle normal faults by **Heller (1996) and Heller *et al.*(1998)**. One of these faults is present at Lake Wheeler where it is intersected at a high angle by the strike-slip Nutbush Creek fault zone. In their paper on structural indicators for oblique impact trajectories, **Kenkman et al. (2012)** describe the presence of such a fault environment within the central uplift areas of craters with low impact trajectories. Normal faults are formed on the downrange side of the central uplift perpendicular to the impact trajectory. Strike slip faults form parallel to the trajectory of the impactor, with the largest movement downrange along the trajectory axis with decrease in movement outwards in the cross-range areas of the central uplift. Quartz breccias are present within both N-NE and W-NW faults at Lake Wheeler. Thin sections from these quartz breccias contained the most candidates for possible remnants of shock metamorphic features of the three quartz breccia sites where thin sections were reviewed. Candidates for possible remnants of glassy melt, diaplectic quartz and feldspar, partial diaplectic quartz were all detected within these likely injected quartz dikes in the proposed crater floor.

The presence of H-type orthogonal fractures has been noted within the proposed Raleigh crater at all scales from macro to micro. The fractures (joints) are characterized by short fracture segments connecting longer perpendicular fractures. Structural data have been reported for each 7.5’ geologic map completed in the last few years by the North Carolina Geological Survey. **Figure 24** shows rose diagrams of joints from those completed quadrangle maps. The predominant joint directions strongly follow circular features of the proposed crater as has been noted in fracture systems within terrestrial impact craters such as the much smaller Barringer Crater **(Kumar and Kring, 2008)**.

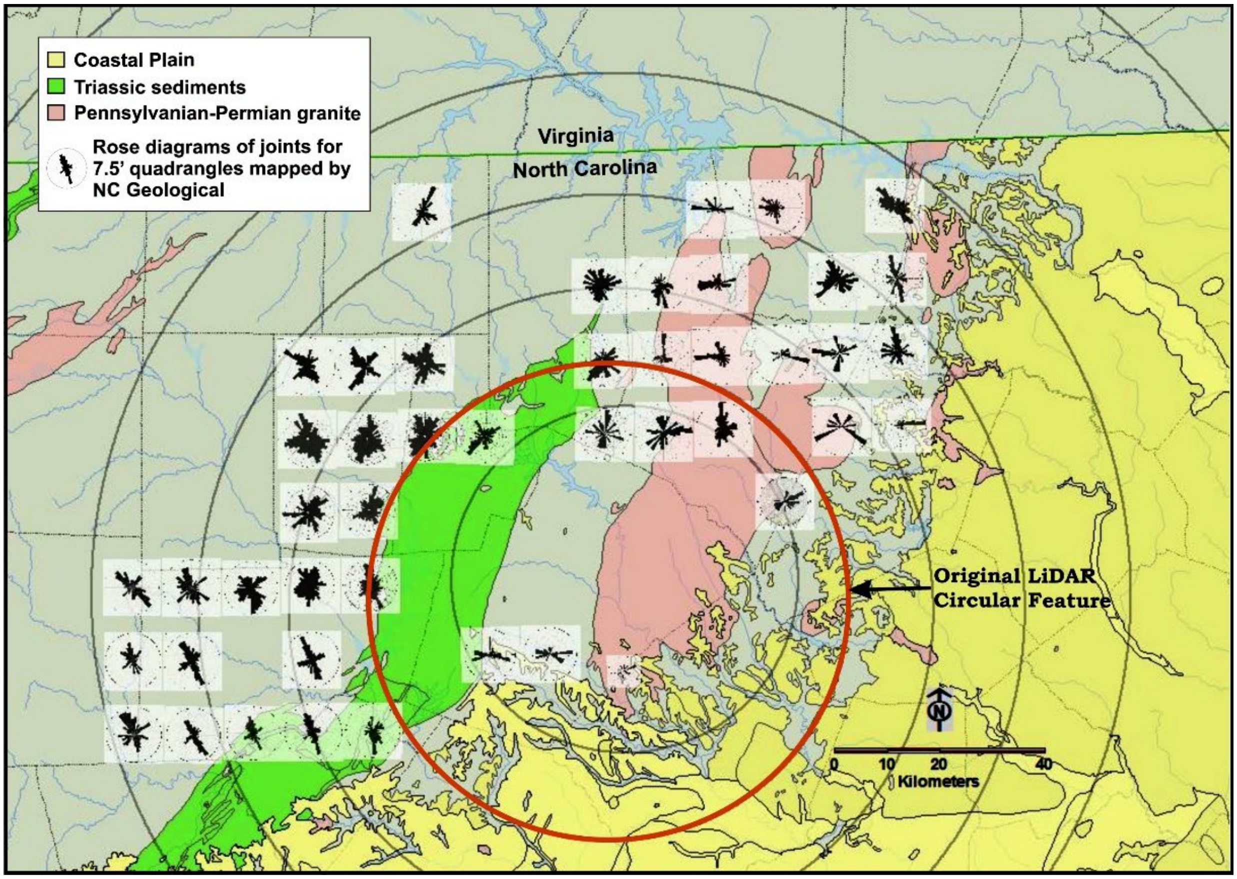

Figure 24: Rose diagrams of joints from NCGS 7.5’ geologic quadrangle maps. See References for individual quadrangle maps used.

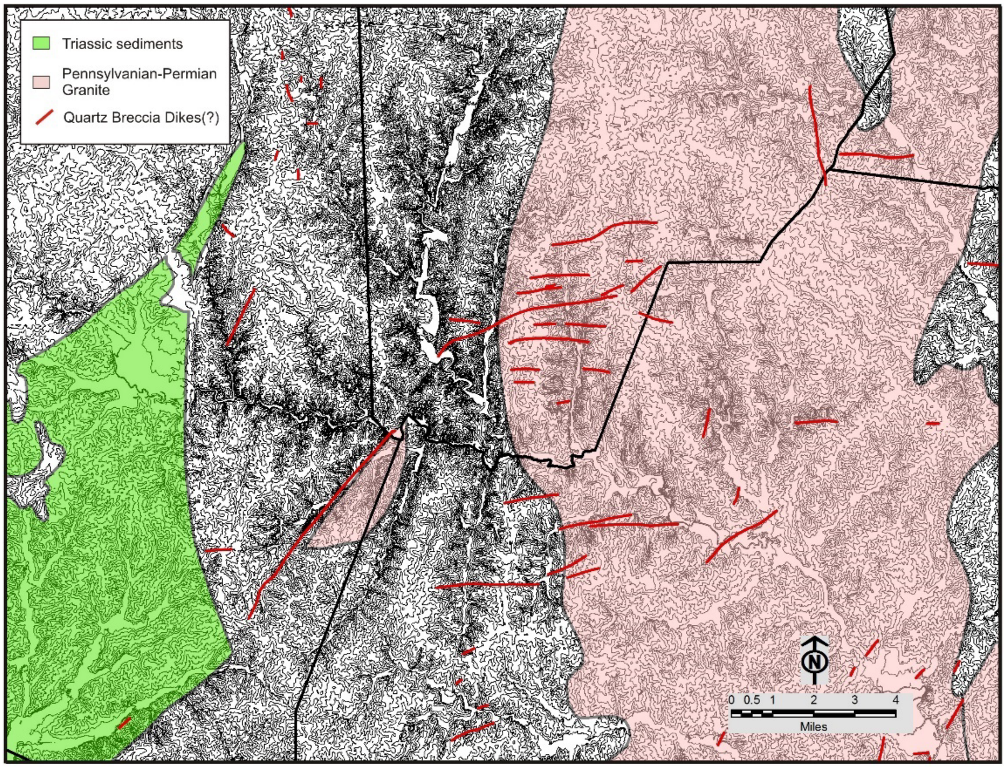

Figure 25: Macro scale H-type orthogonal fractures expressed by topographic relief near stream systems in the Kittrell, NC area. Red lines are quartz breccia dikes which seem to favor these fractures, especially the E-W direction in this case. (Grimes, 2000; Robitaille, 2004).

Stream Patterns within Proposed Raleigh Impact Crater Area

The circular shapes of impact structures are often reflected in the stream drainage patterns. The central uplift, annular trough, peak ring, as well as the concentric normal faults and outer rim all may influence stream patterns. At the same time, there is the competing influence of the preexisting local geology which may result in masking the craters presence. With time, erosion may entirely erase the evidence of the impact crater as it is gradually stripped, exposing its deeper less prominent layers.

Figure 26 shows stream patterns of major streams within the proposed Raleigh crater area. This regional view shows a broadly circular wrap-around of major streams as the outer areas of the proposed structure are approached from the proposed crater's central area. This is compatible with regional stream patterns seen in very large craters such as Vredefort in South Africa **(Mihalyi and Szabo, 2008)**.

A closer view of detailed streams within the proposed crater's central area in **Figure 26** shows more patterns noted in major crater impacts worldwide. One of the largest rivers in the central area, the Neuse (**No. 1** on **Figure 26**), has cut through the central uplift and peak ring, bisecting the central core of the structure by headward erosion. Similar headward-eroding centrally-located major streams are noted within the Manicouagan, Ries, Popigai and Siljan craters **(Mihalyi *et al.*, 2008)**.

The offset portion of the central uplift of the potential Raleigh structure remains elevated resulting in a radial stream drainage pattern along most of the outer rim of the central uplift **(No. 2** on **Figure 26)**. Some streams follow the central uplift-peak ring boundary closely, resulting in arcuate stream segments **(No. 3** on **Figures 26)**. Similar arcuate stream segments are found along the offset inner central uplift boundary as well. Many impact craters display these arcuate stream segments. The Manicouagan impact crater in Canada is a good example where an annular trough is still well defined and is filled by a lake **(Mihalyi and Szabo, 2008)**.

Some streams cut through the rim of the crater by headward erosion and capture other streams **(No. 4** on **Figure 26)**. In such cases, a sharp bend may occur in the river's course. Good examples of this are seen in Ries, Charlevoix, Popigai and Siljan craters **(Mihalyi *et al.*, 2008)**.

Even though the geology of the proposed Raleigh crater area is complex, stream patterns hinting at the potential presence of a major impact can clearly be seen, especially when viewed in the context of other supporting data.

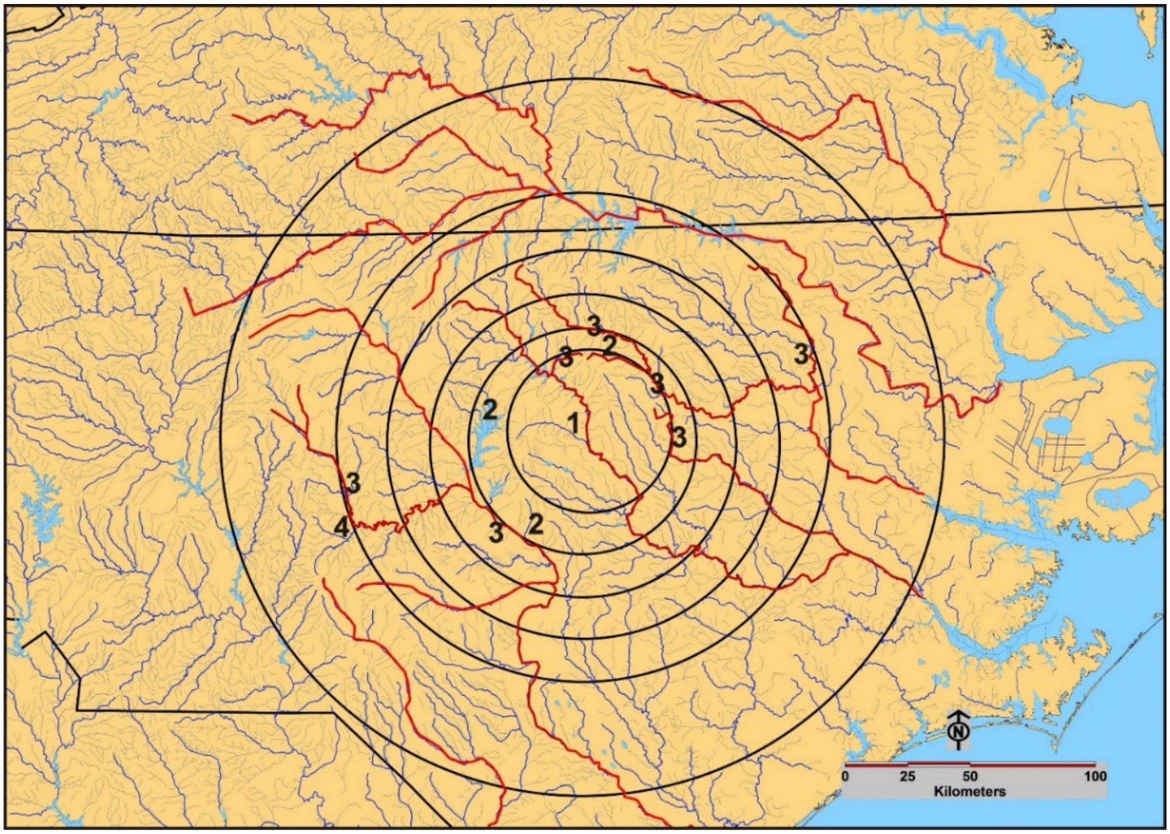

Figure 26: Major stream drainage map of the proposed Raleigh Impact Crater. Numbers refer to drainage features found in hypervelocity impact craters discussed in text.

Hydrothermal Activity within the Proposed Raleigh Impact Crater

Hydrothermal alteration has been recognized within numerous complex impact craters on earth. With an abundance of water on earth and plenty of heat supplied by the meteorite impact, hydrothermal activity with sufficient longevity to alter existing minerals and produce new ones is generated. Hydrothermal cells set up within conduits that allow water to enter and become heated by the thick impact melt breccia above the crater floor. This can happen along faults or within the highly fractured central uplift of the structure near its outer edges. If the structure is large enough to have a peak ring it can also be the focus of hydrothermal cells. Initially, water is driven from the system by the massive heat and energy of the impact, resulting in an early period of vapor-dominated alteration and mineral growth. This early alteration is dominated by quartz and pyrite precipitation. Water reenters the system rather quickly and minerals including calcite and selenite may be precipitated from solution. Iron minerals may be precipitated in the later stages of mineralization. **(Osinski *et al.*, 2005)**

Historic mines and prospects believed to have been formed by hydrothermal activity are plotted in **Figure 27**. These are mostly from the US Geological Survey's Mineral Resource Data System (MRDS). Sericitic alteration can be produced by hydrothermal alteration within impact systems and has been added to the map. **(North Carolina Geologic Map, 1985)**

At this stage of study, no attempt has been made to identify the cause of the alteration present within the proposed Raleigh crater area. It is interesting to note that five iron prospects occur in the favorable zone around the outer proposed central uplift and peak ring areas.

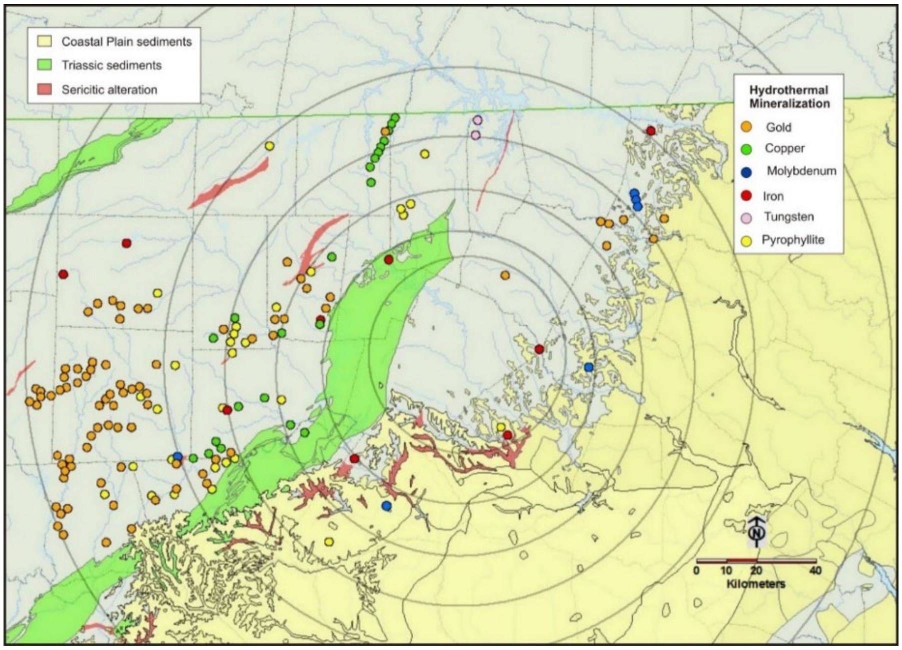

Figure 27: Hydrothermal mineral deposits plotted from the Mineral Resources Data System (MRDS) of the US Geological Survey. Areas of sericite alteration from regional geologic mapping of the NC Geological Survey. (North Carolina Geological Survey, 1985)

Conclusions

The presence of a near-perfect circular feature on LiDAR maps of central North Carolina has led to an investigation of whether this feature could be part of a hypervelocity impact structure. A review of regional geologic, magnetic, gravity and LiDAR mapping of the central North Carolina area reveals support for the possible presence of an impact crater. The circular LiDAR feature corresponds to the western boundary of the Triassic Durham sub-basin. The Triassic basin appears to fill a circular bowl-like depression. Axes of overturned arcuate folds in the Spring Hope volcanic and sedimentary terrane on the east and south sides of the circular feature parallel its trace as well. Where the circular feature crosses the SW end of the Durham sub-basin, it marks the northern edge of the Colon cross-structure, a sharp rise in the basement between the Triassic Sanford and Durham sub-basins. Arcuate stream segments follow portions of the feature. We hypothesize that the Colon cross-structure is possibly the downfaulted expression of a proposed peak ring structure.

The legacy LiDAR data have been evaluated for changes in lineament patterns which may reveal the location of potential annular faults and ramps formed during the potential excavation and modification phases of crater formation. Based on these data in combination with other geologic and geophysical data annular faults are proposed. These proposed faults are supported by stream drainage patterns within the central North Carolina area.

Magnetic and gravity data indicate the presence of a roughly circular central area of a proposed crater centered on the ca. 300-Ma Rolesville granitic batholith in the Raleigh area. It is likely that the circular feature first noted on the LiDAR represents the central uplift-peak ring interface. Magnetic data gives credence to the presence of an offset inner circle within the central uplift. This scenario is supported by topographic data as the inner circular area is elevated above its surroundings and stream maps show radial drainage outward. The inner off-set circle parallels the contact between greenschist-facies rocks of the Spring Hope terrane and amphibolite-facies gneisses and schists of the Raleigh belt slightly to the north. Regional gravity data are consistent with a proposed impact structure, especially in the eastern half of the structure. Basement rocks of the Carolina terrane, thought to be mafic, are problematic for interpretation of the gravity data for the western half of the structure. The diameter of the proposed crater is speculated to be on the order of 200 km. Several studies have concluded that portions of the Rolesville batholith and surrounding rocks have been uplifted 10-15 km, consistent with the possibility of an impact-induced central uplift. The gravity data appears to support this idea.

Thin sections of rock from the proposed central crater area have been examined by polarized light microscopic methods for evidence of hypervelocity shock features in quartz and feldspar. Of 1382 thin sections examined, initially suspected but unconfirmed shock metamorphic features were preliminarily identified in 90 of these. Notably, no PDFs in quartz were identified. The most common features were alternating isotropic twins in feldspar. Inclined deformation lamellae in feldspar were also common. Initially suspected PFs in quartz and feldspar were also noted. A small group of thin sections of quartz breccia rocks contained initially suspected candidates for diaplectic glass, partial diaplectic glass or glassy melt. The best samples are from the Lake Wheeler dikes. These suspected shock features identified by optical methods need to be verified or refuted by non-optical methods such as EPMA and µXRD.

The quartz breccia rocks are here inferred to be dikes in the crater floor. We hypothesize that glass and rock fragments from upper levels of the fault/fracture were violently injected into the zone of weakness during the compression phase of bolide impact and then rock/glassy breccia was drawn into the faults/fractures from all levels during the release phase. These dikes commonly occupy H-type orthogonal faults/fractures. Movement along one such breccia dike from the Jonesboro fault in the Holly Springs quarry has been dated using laser ^{40}Ar/^{39}Ar techniques. This yielded an age of 255 ± 2 Ma **(Hames *et al.*, 2001)**. The sample site is about 20 km SW of the Lake Wheeler breccia dikes and lies within the central uplift of the proposed crater.

Visits to three active quarries in search of shatter cones revealed cone shaped features, curved fractures, faults, and slickensides but did not yet reveal cone-shaped features with the characteristic striations of probable shatter cones.

Stream sediment geochemistry for the central North Carolina area has been plotted to see if there are any elemental correlations with the potential crater system. Uranium, thorium, potassium, cerium and lanthanum all seem to have an affinity for the central uplift of the proposed crater structure. Gold from a prospect within the proposed peak ring has unusually high palladium values (up to 1.2 %). The prospect is within saccharoidal quartz veins(?) and a small placer deposit within the Rolesville granite and is not associated with any known mafic or ultramafic source.

Hydrothermal mineral prospects in the vicinity of the peak ring and outer portions of the central uplift were reviewed in the Mineral Resource Data System of the USGS. Iron, gold and copper prospects are within these favored zones permissible for crater-related hydrothermal alteration. Significant sericitic alteration is found in these areas also, especially around the proposed inner peak ring on the east, south and western sides within the Spring Hope and Carolina terranes. It is not known whether the hydrothermal systems that produced the alteration occurred prior to the proposed impact or coincident with the impact. Some of the prominent topographically-expressed quartz-breccia dikes may represent local hydrothermal systems with sufficient longevity to silicify remnant fragments.

Limited geologic reconnaissance in the central area of the crater has been conducted. We hypothesize that the western border of the Triassic Durham sub-basin is the most likely place to find remnants of possible suevite breccias and the impact melt sheet if they have survived erosion prior to Triassic sedimentation, assuming the impact was pre-Triassic.

Preservation of unannealed high-strain features in the quartz breccia dikes suggests that timing of the proposed impact would post-date the late Permian metamorphism in the area. Carnian-stage and younger Triassic sedimentary rocks appear to fill a portion of the central crater. Therefore, the proposed Raleigh impact crater likely occurred between the late Permian and the end of the Triassic. Could this impact be linked to a major mass extinction and could it have contributed to the breakup of Pangea?

Much work remains to be done before these questions can be answered. However, the idea of a Raleigh impact crater has enough evidence to justify the application of the best available scientific methods in pursuit of the answers.

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