Early modification stage dynamics of shallow crater-filling units, Wetumpka impact structure, Alabama

by

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Abstract

Wetumpka, Alabama, USA is the site of a Late Cretaceous, marine-target impact crater structure located on the inner Coastal Plain of Alabama. During Late Cretaceous, Wetumpka was located offshore from a barrier-island shoreline, and the impact target area was a shallow continental shelf of the sea that formed the northern reaches of the Gulf of Mexico. The target consisted of Upper Cretaceous sediments that were unconformably overlying Piedmont schists and gneisses.

This thesis focuses on the systematic analysis of shallow crater-filling sediments by conducting field work to produce a geologic cross section through the northwestern interior of the 5-km diameter Wetumpka impact structure. Thus, the timing of impact-related events and mega- and microscopic features are related in order to understand the dynamics of the syn- and post-impact modification events.

From northwest to southeast, the transect encountered deformed crystalline rim terrain, a zone of crystalline blocks, sedimentary target megablocks, a folded and faulted overturned rim flap sequence (i.e., a trans-crater slide), resurge chalk deposits, and interior polymict impact breccia. Core drilling near the transect indicates that sedimentary target megablocks occur below sections of impactite sand, with resurge chalk deposits resting upon these facies in topographically low or down-faulted areas and an interior impact breccia unit lying above other units. The relative timing of the resurge chalk deposits, impactite sand injection dikes, trans-crater slide, and emplacement the interior

impact breccia is determined based on the formative events that generated the units seen in the geological transect. In some respects, the crater-filling sequence at Wetumpka is similar to some other marine impact structures on Earth. All units studied are related to the early modification stage of the Wetumpka impact structure's development and likely represent the last few minutes in Wetumpka's early sequence of events.

Acknowledgments

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INTRODUCTION

The surface of the Earth is roughly 70% water, therefore cosmic impacts on Earth have occurred most often at sea. Current knowledge about impact processes and impact craters is based mainly on dry-target laboratory experiments, computer modeling, extraterrestrial examples, and evidence from terrestrial impacts on land (Ormö and Lindström, 2000). In general, marine impacts are less well-understood than dry, terrestrial targets.

Wetumpka, Alabama, USA is the site of a Late Cretaceous, marine-target impact crater structure located on the inner Coastal Plain of Alabama (Figure 1). During Late Cretaceous, Wetumpka was located offshore from a barrier-island shoreline and the impact target area was a submerged continental shelf of the sea that formed the northern reaches of the Gulf of Mexico.

Craters of at least a few kilometers in diameter that formed in shallow water exhibit many of the morphological features indicative of their size, such as Chesapeake Bay crater (Ormö and Lindström, 2000). Additionally, marine-target impacts will show evidence of powerful hydrodynamic erosional forces owing to the sudden displacement and return of seawater, including hydraulic reworking and deposition of extant and/or impact-generated materials, which is not found in dry-target impact structures (von Dalwigk and Ormö, 2001; Poag et al., 2004). Complex dry-target impact craters are characterized by a central peak, a flat basin floor, and mass-wasting features of significant size within the structure (Melosh, 1989). Marine-target impact structures deviate from morphologies of dry impacts in a variety of ways. For example, Wetumpka is large enough to be a complex target crater but a well-developed central peak is not evident.

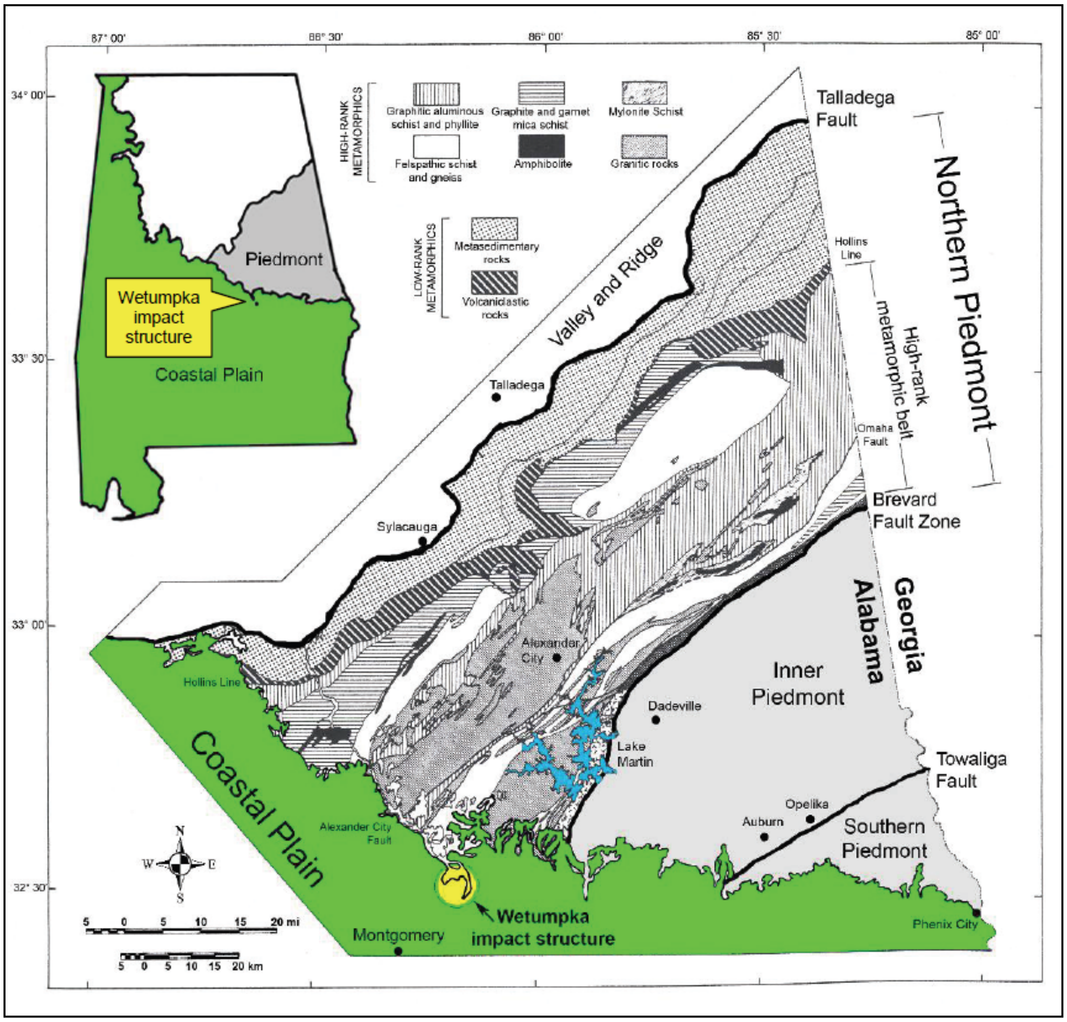

Figure 1: Regional map showing the geologic setting of the Wetumpka impact structure near the southwestern edge of the high-rank metamorphic belt of the northern Piedmont physiographic province. Adapted from Neathery et al. (1976); Taken from Johnson (2007).

Statement of Purpose

The investigation of impact structures is a relatively new field of study, which has expanded rapidly only in the last few decades (Melosh, 1989). Studies of impact craters include analyses of processes and mechanisms of crater formation, modification, and structural development of craters, mineralogical and geochemical studies, and numerical modeling of the physical processes of the crater formation. Sedimentary processes of crater-filling successions have not been widely discussed. Depositional successions within impact craters are associated commonly with violent episodes of sedimentation, providing clues for identification and recognition of impact craters as well as help to develop a better understanding of the impact-cratering process (Azad et al., 2015).

This thesis will focus on the systematic analysis of shallow crater-filling sediments by conducting field work to produce a geologic cross section through the northwestern interior of Wetumpka impact structure. Thus, the timing of impact related events and mega- and microscopic features will be related to understand the dynamics of the syn- and post-impact modification events. In addition, Wetumpka will be compared to other terrestrial impact craters to establish analogous features.

Crater Formation

The cratering process is divided into three stages, each based on the main deformation mechanism: contact and compression, excavation, and modification (French, 1998). The contact and compression stage begins at the instant the leading edge of the projectile makes contact with the ground surface. When the projectile contacts the target material, a shockwave is produced in both the projectile and target. This stage lasts only as long as the time it takes for the wave to travel through the projectile from front to back, then back to front. At this point, the projectile is vaporized. The time required for the shock wave to travel from the projectile/target interface to the rear edge of the projectile is approximately equal to the time it takes the projectile to travel the distance of one diameter at its original velocity. The shock waves transmitted into the target rocks can exceed 10 km/s, but velocity decreases rapidly as they travel away from the impact point (French, 1998). The contact and compression stage generally lasts less than a second for most impacts, after which the projectile plays no further role in crater formation.

During the contact and compression stage, shock waves deform the crystal structures of many minerals, most notably quartz and feldspar. Also, Planar deformation features (PDFs) have been observed also in pyroxene, amphiboles, and several accessory phases (apatite, sillimanite, cordierite, garnet, scapolite, and zircon) (Stoffler, 1972). PDFs are shock produced microstructures that occur as multiple sets of closed, extremely narrow, parallel planar regions that are typically spaced at < 2-3 μm (French, 1998). PDFs in quartz and feldspars and partial melting of feldspars are unique products of meteoritic impacts. Less is known about PDF formation and orientation in other minerals, because these minerals have not been studied in detail. The development of distinctive shock-metamorphic features such as PDFs in zircons and in denser mafic minerals like amphibole, pyroxene, and olivine occurs at higher pressures and over a more limited pressure range than for quartz and feldspar. At pressures <30 GPa, sufficient to form PDFs in both quartz and feldspar, the most common shock effects observed in mafic minerals are planar fractures, mechanical twins, and general comminution (Stoffler, 1972).

In 1998, shocked materials, in particular shocked quartz, was found in Wetumpka's polymict breccia below 300 ft (91 m) in both central wells drilled (King et al., 2002). Later, shocked quartz was found in a central surficial breccia unit within the crater (Morrow and King, 2007).

The excavation stage occurs when the crater is opened and most disintegrated material is either ejected or pushed downward. During this stage, upper target rocks are ejected while deeper target rocks are compressed and driven downward to form a bowl-shaped transient crater. The duration of the excavation stage can range from a few seconds up to a few minutes and ends when the shock and release waves can no longer excavate or displace target rock. The transient crater will reach its maximum size and near-surface rocks are uplifted to form the overturned transient crater rim (French, 1998). The ideal transient crater is a bowl-shaped depression with a structurally uplifted rim. Its maximum depth is approximately one-third its diameter (Maxwell, 1977; Croft, 1985).

The modification stage begins immediately after the excavation stage. At this point in crater formation, the primary driving modification mechanisms are gravity and rock mechanics. Gravity takes over and will cause the collapse of the transient crater walls. This collapse can mix target rocks with fall-back ejecta to form a mixed breccia lens. The modification stage has no clearly marked end, and the modification processes of uplift and collapse merge gradually into the normal processes of geological mass movement, isostatic uplift, erosion, and sedimentation. Early modification is generally viewed as the rapid phase of modification change, and later modification is relatively very gradual. This thesis focuses on the early phase of modification.

Sedimentary Processes in Marine Impact Craters

This thesis will focus on many of the dynamic processes of a marine impact, Wetumpka, by describing and interpreting the physical relationships between shallow rock units that occur in the field and related drill-core holes. Impact structures formed during an impact event experience unusual processes of hydraulic erosion, stratigraphic reworking, and deposition not experienced in dry targets. Figure 2 characterizes the general syn-impact processes of a bolide impact into a shallow marine environment like Wetumpka's, including emplacement of slump-back breccia, debris flow, and trans-crater slide.

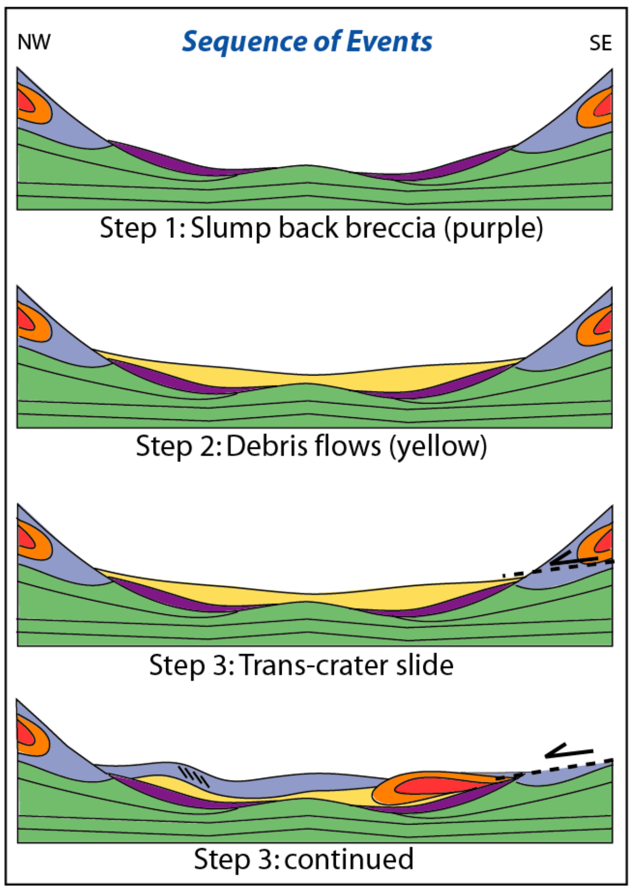

Figure 2: Schematic diagram showing conceptual stages of Wetumpka impact crater formation in a shallow, near shore, marine-target setting.

Wetumpka has some simple crater-type characteristics but is also comparable to a complex crater. Simple, bowl-shaped impact craters in shallow seas are initially formed in much the same way as subaerial craters (Ormö and Lindström, 2000). A well developed, elevated rim wall may form and act as a barrier to instantaneous resurge of water. The simple crater initially behaves more like a subaerial crater and the sedimentary processes in the crater are comparable, in some ways, to subaerial ones (Azad et al., 2012). Sedimentation in such craters starts with the collapse of the transient cavity, immediately followed by avalanches, slides, and earthflows towards the crater center and deposits as breccia lenses, commonly filling almost half of the original crater cavity (French, 1998).

Concentric morphology develops in submarine, complex craters at a target site consisting of thick, low-strength sedimentary rocks. In such craters, central uplift starts to develop before the transient crater has reached its final diameter, resulting in formation of low, weak or unstable rim walls (Ormö and Lindström, 2000). An instantaneous, powerful resurge with centripetal bottom currents erodes the sea floor and may form resurge gullies dissecting the crater rim wall or may completely obliterate the raised crater rim (Dypvik and Jansa, 2003).

The transient cavity is the bowl-shaped depression produced by a symmetric excavation flow from the complex processes that drive the target rock outward from the impact point (French, 1998). The amount of collapse of the transient cavity is largely dependent on the size and composition of the bolide, target composition, and height of the water column (Ormö and Lindström, 2000). Numerical modeling suggests that a large bolide (i.e., where impactor size exceeds the height of sea water column) impacting a target consisting of thick sedimentary successions can cause large-scale collapse of the transient cavity resulting in deposition of thick columns of impact-generated debris by gravity slides, slumps, rock or debris avalanches (Kenkmann et al., 2009). Impact in greater water depths (i.e., where water depth greater than impactor size) with similar target composition may cause much of the upper transient crater development in the water and a relatively small cavity in the sea-floor, resulting in reduced collapse and limited extent of impact-debris generations (Ormö et al. 2002; Shuvalov et al. 2005). The collapse of the water mass and a low rim-wall allow instantaneous, powerful sea-water resurge mixing with impact-generated debris (scouring and entraining from target and ejecta materials both from outside and inside of the crater), large earthquakes, mega-tsunamis, and strong wave currents formed during bolide impact would cause slope instability within the crater and result in the generation of large-scale, clast-rich mass-movements within the crater (Azad et al., 2015).

Mass-movement mechanisms: application for marine impacts

The sedimentary processes at the early modification stage are mostly gravity-dominated, e.g., gravity slides, slumps, rock avalanches or debris avalanches occurring during the initial stages of crater modification. The succeeding early post-impact stage of crater sedimentation is mostly mass-flow (sediment flow) dominated, e.g., debris flows, concentrated density flows that eventually evolve into fluid flows, such as, density and turbidity flows, at later stages of crater modification (Azad et al., 2015). These sedimentary processes are controlled by crater dimensions, rock type and physical properties of the target stratigraphy (subaqueous/shallow marine, deep marine), water depth, bolide size and composition, degree of slope failure and temporary fluidization of sediments during crater modification (Melosh, 1989). The late post-impact crater sedimentation is mostly turbidity flows and related suspension deposition (Azad et al., 2015).

According to the Highland and Bobrowsky (2008), there are four basic landslide types: falls; slides; spreads; and flows. Falls begin with the detachment of soil or rock, or both, from a steep slope along a surface on which little or no shear displacement has occurred. The material subsequently descends mainly by falling, bouncing, or rolling. A slide is a downslope movement of soil or rock mass occurring on surfaces of rupture or on relatively thin zones of intense shear strain. Movement does not initially occur simultaneously over the whole of what eventually becomes the surface of rupture; the volume of displacing material enlarges from an area of local failure. A spread is an extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads may result from liquefaction or flow (and extrusion) of the softer underlying material. Types of spreads include block spreads, liquefaction spreads, and lateral spreads.

Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. In rock spreads, solid ground extends and fractures, pulling away slowly from stable ground and moving over the weaker layer without necessarily forming a recognizable surface of rupture. The softer, weaker unit may, under certain conditions, squeeze upward into fractures that divide the extending layer into blocks. In earth spreads, the upper stable layer extends along a weaker underlying unit that has flowed following liquefaction or plastic deformation. If the weaker unit is relatively thick, the overriding fractured blocks may subside into it, translate, rotate, disintegrate, liquefy, or even flow. Areas affected may start small in size and have a few cracks that may spread quickly, affecting areas of hundreds of meters in width. Travel may be slow to moderate and sometimes rapid after certain triggering mechanisms, such as an earthquake. Ground may then slowly spread over time from a few millimeters per day to tens of square meters per day (Highland and Bobrowsky, 2008).

A flow is a spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved. The component velocities in the displacing mass of a flow resemble those in a viscous liquid. Commonly, there is a gradation of change from slides to flows, depending on water content, mobility, and evolution of the movement. Debris flows are prevalent in steep gullies and canyons. They are a form of rapid mass movement in which loose soil, rock, and in some instances organic matter, combine with water to form a slurry that flows downslope. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow. The velocity of travel can be rapid to extremely rapid (56 km/hr) depending on consistency and slope angle. Debris flows are commonly caused by intense surface-water flow that erodes and mobilizes loose soil or rock on steep slopes. Earthflows occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earthflow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy and flow for several kilometers. Size commonly increases through head scarp retrogression. Slides or lateral spreads may also evolve downslope into earthflows. Earthflows can range from very slow (creep) to rapid. Debris avalanches are a larger type of flow. These are extremely rapid, open-slope flows formed when an unstable slope collapses and the resulting debris is rapidly transported away from the slope. Some large avalanches have been known to transport material blocks as large as 3 kilometers in size, several kilometers from their source (Highland and Bobrowsky, 2008).

The kinematics of flow-like motion varies. During slow, steady motion phases, the deformation may be concentrated on the main shear surface, analogous to a translational slide. During surges, numerous internal shears (imbricate thrusts) develop and combine with distributed internal strains of the plastic mass to generate flow-like morphology (Hungr et al., 2013). Turbidity flows are rapid, downhill, flows of water caused by increased density due to high volumes of sediment.

GEOLOGIC SETTING

Centered at 32°31.2'N, 86°10.4'W, the Wetumpka impact crater resides on the Coastal Plain at the southwestern edge of the high-rank metamorphic belt of the northern Piedmont (see Figure 2).

According to King et al. (2002; 2003), the Wetumpka impact was an early Campanian, catastrophic event resulting from a hyper-velocity, celestial object impacting a shallow carbonate marine shelf. Because the impact occurred in a continental shelf setting and near to the shoreline, paleo-water depths varied significantly and down dip across a distance equal to the Wetumpka rim diameter (or ~ 5 km). In other words, the target area, likely became slightly more shallow and the sediment layers highly thinner toward the north, i.e., in the direction of the coeval shoreline (King et al., 2006). If the paleoslope of the near-shore shelf was like the average slope of a shallow, passive-margin continental shelf today (~2 m/km; Sheppard, 1963), the difference in water depth from the northern rim to the southern rim, across 5 km, would have been ~10 m (King et al., 2006). It seems likely that the slight difference in water depth and sedimentary thickness across the target area is important in the events that transpired during the early modification stage of this impact structure.

Pre-existing paleogeographic studies of the eastern U.S. Gulf Coastal region during Late Cretaceous showed that the Wetumpka impact occurred in shallow marine water (King et al., 2002, 2003); Figure 3). Paleo-water depth is based on ichnosedimentologic evidence (Rindsberg, 1986) and depth-sensitive, eye morphology of constituent ostracodes (Puckett, 1996) in coeval target strata. Although this water layer shallowed to the north, it was deep enough to be considered the uppermost unit of target stratigraphy. This is so because of the effect that surface water has on resultant crater morphologies and subaqueous strata during bolide impacts (Kieffer and Simonds, 1980; Melosh, 1982; Ormö and Lindström, 2000; Dypvik and Jansa, 2003).

Figure 3: A paleogeographic map showing the interpreted setting for the Late Cretaceous Wetumpka impact event. Modified from King et al. (2006). Outset photograph taken from Colorado Plateau Geosystems.

The region's target stratigraphy was rather uncomplicated despite its proximity to the southernmost Appalachian Piedmont terrain. It is currently thought that the paleo-seafloor at the time of impact consisted of unconsolidated, water-saturated, marine sediments overlying older fluvial sediments previously interpreted to have been approximately 120 m thick (King, 1997). In reverse stratigraphic order, the Wetumpka target consisted of 1) less than 100 m of marine water; 2) poorly consolidated sediment (comprising three Upper Cretaceous stratigraphic units – a few meters of chalky ooze, ~ 30 m of paralic marine sand, and ~ 60 m of terrestrial clayey sand and gravels), and, at base; 3) a weathered crystalline basement. The target stratigraphic units, in the order mentioned above are the Mooreville Chalk (resedimented), the Eutaw Formation, and the Tuscaloosa Group (King et al., 2006). At the time of the impact, they were resting unconformably above the regional, meta-sedimentary and meta-igneous, pre-Cretaceous, crystalline basement rock (Neathery et al., 1976). The Mooreville Chalk in and near the crater is a resedimented deposit (King and Ormö, 2011)

The crystalline piedmont basement surface has a modern, southwestward dip of approximately 8.5 m/km (King et al., 2003), and likely was similarly inclined during Late Cretaceous. The nature of the target and the basement surface slope are assumed to have played a significant role in the cratering process at Wetumpka, particularly in the late excavation and early modification stages. The local structural dip likely contributed to a significantly greater component of sedimentary material ultimately residing in the southern part (i.e., the down-dip part) of the structure's rim (King et al., 2004). The rim's lithic heterogeneity caused the southern and southwestern part to be more porous and thus less stable than other parts. For this reason, this part of the rim was especially susceptible to an early collapse (King et al., 2006).

Today, Wetumpka is characterized by a wide, horseshoe-shaped crystalline rim, an interior region of broken and redistributed sedimentary target formations, and an extra-structure terrain on the south-southwestern side, which is composed of structurally disturbed target formations (King et al. 2002, 2003). The latter has been faulted, slumped, and in some instances overturned. The extant crater rim spans ~270 degrees of arc and is open on the south-southwest, the same side as the structurally disturbed terrain just noted. The northwest-southeast diameter of the horseshoe-shaped crystalline rim itself is ~5 km, but impact-related deformation beyond the rim extends the structural diameter to ~7.6 km (Figure 4) (King et al., 2003).

Within the intra-structure terrain, a unit named the surficial polymict impact breccia crops out discontinuously over a small area. This polymict impact breccia unit is one of the youngest, post-impact units in this terrain. It contains a significant number of impact-affected quartz grains (i.e., quartz grains bearing planar microstructures) as reported by Morrow and King (2007). In outcrop, the impact breccia unit is matrix supported, exhibits a very poorly sorted texture, and contains weathered clasts and blocks of metamorphic and sedimentary rock. This proximal ejecta unit is presumed to be derived from the shallow reaches of the crystalline target materials (King et al., in press, 2015).

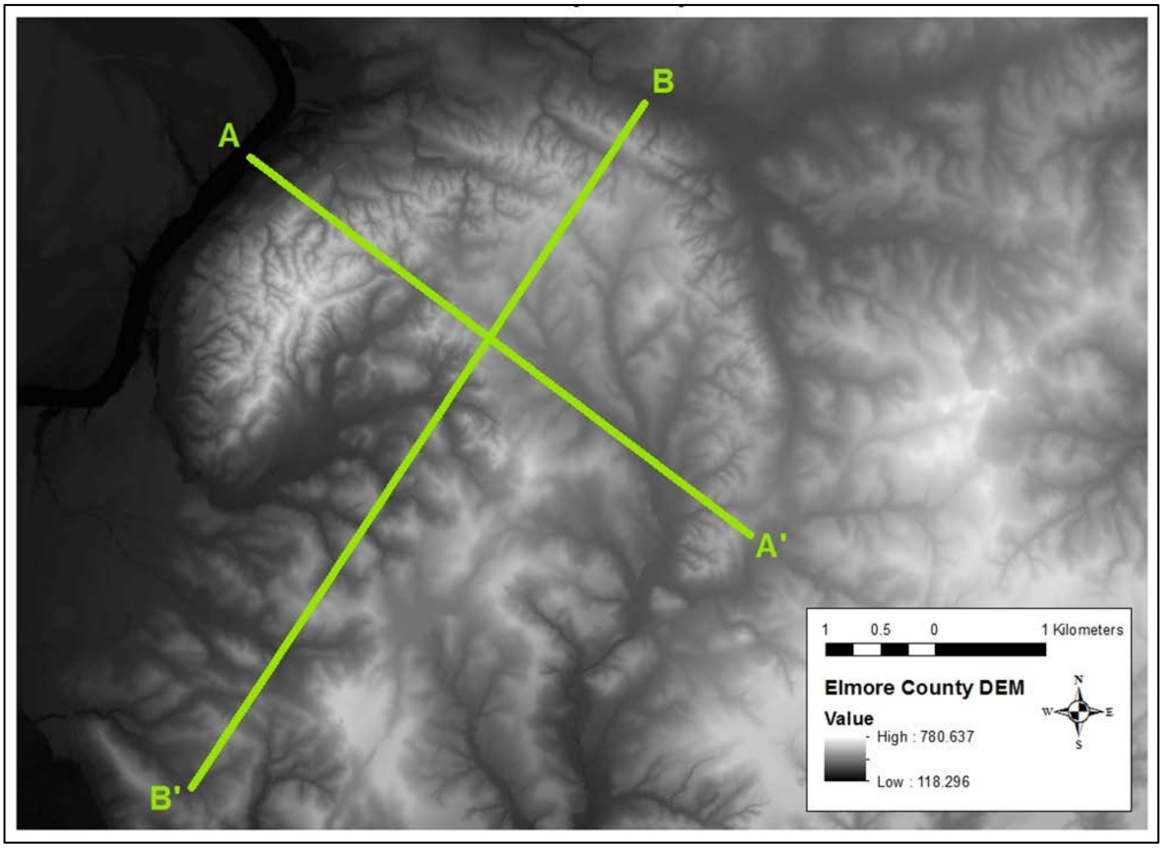

Figure 4: LiDAR-based DEM of Wetumpka impact structure, Alabama showing northwest and southeast diameters of Wetumpka impact structure (i.e., A - A') is 5 km. B – B' is ~ 7.6 km.

Pre-impact Stratigraphy

The meteorite impact affected both the crystalline basement rocks and relatively unconsolidated overlying Upper Cretaceous sediments. The crater rim is composed of Emuckfaw Group lithologies and minor amounts of Kowaliga Gneiss. Sedimentary material of Tuscaloosa Group and Eutaw Formation occupy the interior of the crater, with the exception of a centrally-located, impact-derived unit that has both crystalline and sedimentary components and patches of reworked (tsunami-deposited) Mooreville Chalk.

The following is a description of each lithological unit in ascending order, summarized from Nelson (2000).

Eastern Blue Ridge

Emuckfaw Group. The Emuckfaw Group is structurally complex, having been subjected to several deformation events (Tull, 1975; 1978). Dominant foliation strikes northeast and dips southeast. Lithologies are considerably varied (Neathery, 1975a; Bieler and Deininger, 1987). The basal Josie Leg Member contains abundant garnet that may be up to 1 cm in diameter. Metagreywackes and metapelites of this member are generally medium-grained schists composed of muscovite, biotite, plagioclase, quartz, and garnet. The structurally overlying Timbergut Member is compositionally mature and garnets are rare. In this member, metasediments are biotite-muscovite-quartz schists that locally approach composition of quartzite. Schists may have minor amounts of plagioclase, potassium feldspar, and garnet. The Timbergut Member also has locally thick units of calc-silicate rock. Bentley and Neathery (1970) noted exposures of graphite-bearing schists. Metagraywackes may contain locally abundant secondary quartz veins (Neathery, 1976).

Kowaliga Gneiss. The Kowaliga Gneiss was informally named by Bentley and Neathery (1970) for exposures along Kowaliga Creek, Elmore County, Alabama. Green and Lesher (1987) examined exposures of Kowaliga Gneiss and described strongly foliated and lineated (S-L, foliation fabric) with foliation defined by (1) grain-shaped fabric in feldspar and biotite and (2) separation of ellipsoid-shaped clusters of biotite. Foliation generally dips east to southeast at 20° to 25°, whereas lineation defined by the shape of the biotite clusters and individual biotite grains plunges southward at 5° to 10°.

Bieler and Deininger (1987) listed several features diagnostic for the Kowaliga Gneiss; e.g., plagioclase is the dominant feldspar, and biotite is abundant (muscovite is nearly absent). Also noted was that mineralogic criteria is perhaps more important than textural criteria for distinguishing Kowaliga from other granitoid bodies. Bentley and Neathery (1970) noted that feldspar augen are composed of either orthoclase or plagioclase, that augen may be relatively large (up to 10 cm in diameter) but are generally less than 2 cm in diameter, and that most are idioblastic with less common xenoblastic texture.

Upper Cretaceous Sedimentary Units

In ascending order, Coastal Plain sediments within the study area include the Coker and Gordo Formations of the Tuscaloosa Group, the Eutaw Formation, and the Mooreville Chalk (resedimented). These units have not been significantly compacted or cemented. They are cohesive but friable sediments, which are not considered true rock (King, 1994).

Tuscaloosa Group. In western Alabama, the Tuscaloosa Group is divided into four formations; Cottondale, Eoline, Coker, and Gordo. Near the study area, only Coker and Gordo formations are recognized. In eastern Alabama to western Georgia, Tuscaloosa is undifferentiated and designated an undivided group (Nelson, 2000).

The Tuscaloosa Group unconformably overlies crystalline rock of the Alabama Piedmont eastern Blue Ridge belt. Tuscaloosa sediments are mainly fluvial deposits (Smith and King, 1983). Crystalline-rock topography initially controlled deposition of Tuscaloosa sediments; however, topographic influence progressively diminished as alluvial plains covered basement rock (Smith and King, 1983).

Reinhardt et al. (1986) provide a general description of Tuscaloosa Group sediments cropping out in eastern Alabama. Sediments are deposited in 3-to-6 m fining-upward sequences with a basal sandy conglomerate grading upward into more fine-grained planar and trough cross-stratified arkosic sand. Tops of sequences consist of massive or mottled silty to sandy clay. Locally, deposits of leaves or silicified and lignitized wood, and zones of intensive bioturbation occur in the Tuscaloosa.

Several studies have described the Tuscaloosa Group in and near the study area. Taylor (1973) used several criteria to differentiate between Coker and Gordo Formations. The Coker Formation consists of variegated, massively bedded clays that are locally sandy or bioturbated. Colors of sediments range from dusky red to reddish brown to greenish gray. Gordo Formation has a gravelly base and generally consists of cross-bedded sands and gravels, but locally may have lenticular, laminated to massive clay bodies. Smith and King (1983) differentiated between formations, noting Gordo has large amounts of gravel. Jones (1967) noted that contact between formations can be easily traced using a basal ironstone layer. Clays of the Coker Formation tend to be red-tinted as opposed to clays in the Gordo Formation that are commonly tinted purple. Raymond et al. (1988) describe the Coker Formation as consisting of light colored, fine-to medium-grained, cross-bedded micaceous sands and micaceous clays. Gravel beds are rare and contain quartz and chert pebbles. They describe the Gordo Formation as predominantly cross-bedded sands that locally are gravelly. Clays are in lenticular beds that locally may be carbonaceous. Basal layers of the Gordo are gravel and sand composed of quartz and chert.

Eutaw Formation. The Eutaw Formation disconformably overlies the Tuscaloosa Group throughout its extent (Frazier and Taylor, 1980). The Eutaw Formation varies considerably in lithology from Georgia to Alabama and from up-dip to down-dip occurrences (Frazier and Freeman, 1983). In eastern and central Alabama, the Eutaw Formation is interpreted as a transgressive marine unit (Frazier and Taylor, 1980). Raymond et al. (1988) describe Eutaw sediments as light brown to gray, fine-to medium-grained micaceous, well-sorted, cross-bedded, locally fossiliferous and glauconitic sand. Eutaw may also contain beds of micaceous silty clay, carbonaceous clay, minor plant debris, and lignite fragments and layers. Frazier and Taylor (1980) note that, in eastern Alabama, lithofacies can divided in two units: (1) a lower yellow clay and (2) and upper fossil-rich mud and argillaceous sand. In contrast, central Alabama lithofacies are bioturbated gravelly sands overlain by alternating layers of well-sorted, cross-stratified fine sand and mud. Alternating layers are in turn, overlain by mud deposits containing shell and lignitized wood fragments. *Ophiomorpha* is abundant. Other fossils include *Ostrea cretacea* Morton, *Exogyra* shell fragments, pelecypod molds, and shark and fish teeth (Frazier and Taylor, 1980).

Mooreville Chalk. Target stratigraphy’s uppermost formation is the Mooreville Chalk. The Mooreville Chalk is comprised of an unnamed lower member, which thickens from 79 m in western Alabama to 183 m in Montgomery County of east-central Alabama, and an upper unit consisting of three hard limestone beds and intercalated marls, designated Arcola Limestone Member (Copeland, 1968). The Arcola is not formed in the impact area in Late Cretaceous, thus the impact was pre-Arcola. In western Alabama, the Mooreville Chalk is the lowermost unit within the Selma Group. In eastern

Alabama and western Georgia, the Mooreville Chalk grades into the age-equivalent sandy beds of the Blufftown Formation (King, 1987). King (1987) identified 10 facies within Mooreville Chalk and noted that the unit has varying lithologies ranging from clay and marl to limestone and sandstone. Raymond et al. (1988) describe the Mooreville as consisting of varying hues of gray clay, fossiliferous chalk, and chalky marl. The lower parts of the formation comprise calcareous sand containing phosphatic pellets, phosphatic internal molds, and quartz pellets. Near the Mooreville base, beds may be composed of glauconitic and clayey marl.

The Mooreville Chalk is a distinctive inner Coastal Plain formation that crops out, except for the Wetumpka area, in an east-west outcrop belt across central Alabama. The outcrop belt is present approximately 25 to 30 km south of the Wetumpka impact structure. Therefore, the Mooreville Chalk within the impact structure is an anomalous occurrence that is not part of the outcrop belt (Ormö et al., 2010). The Mooreville Chalk at Wetumpka is confined strictly to irregularly shaped aerial tracts within the structure's interior terrain and elongate-shaped tracts in the southern part of the interior terrain and the whole of the exterior terrain. Both within the interior and the exterior terrains, Mooreville Chalk is in contact with older Upper Cretaceous target units (i.e., the subjacent Eutaw Formation (littoral sands and shales) and the older Tuscaloosa Group (fluvial channel and overbank sequences) (King and Petruny, 2009).

PREVIOUS WORKS

During the late 19th century, Eugene A. Smith, Alabama's second state geologist, described Wetumpka's geology as disturbed, unusual, and peculiar. During the winter field season of 1969-70, Thornton L. Neathery discovered the same unusual and peculiar geology noted by Smith while mapping Elmore County. Neathery et al. (1976) suggested Wetumpka as an "astrobleme." Their paper, however, lacked conclusive proof of impact origin. In particular, they did not find shocked quartz grains or other shocked minerals.

Wolf et al. (1997) conducted a gravity survey that bisected the entire crater from west to east (Figure 5). The resulting data showed a total gravity anomaly of approximately 10mGal, which is consistent in appearance and magnitude with gravity anomalies associated with meteorite impact craters. The negative gravity anomaly with a central "bump" associated with the structure's interior correlates with brecciated rocks of the central area, which may be underlain by a deeper brecciated zone of basement rocks (Wolf et al., 1997).

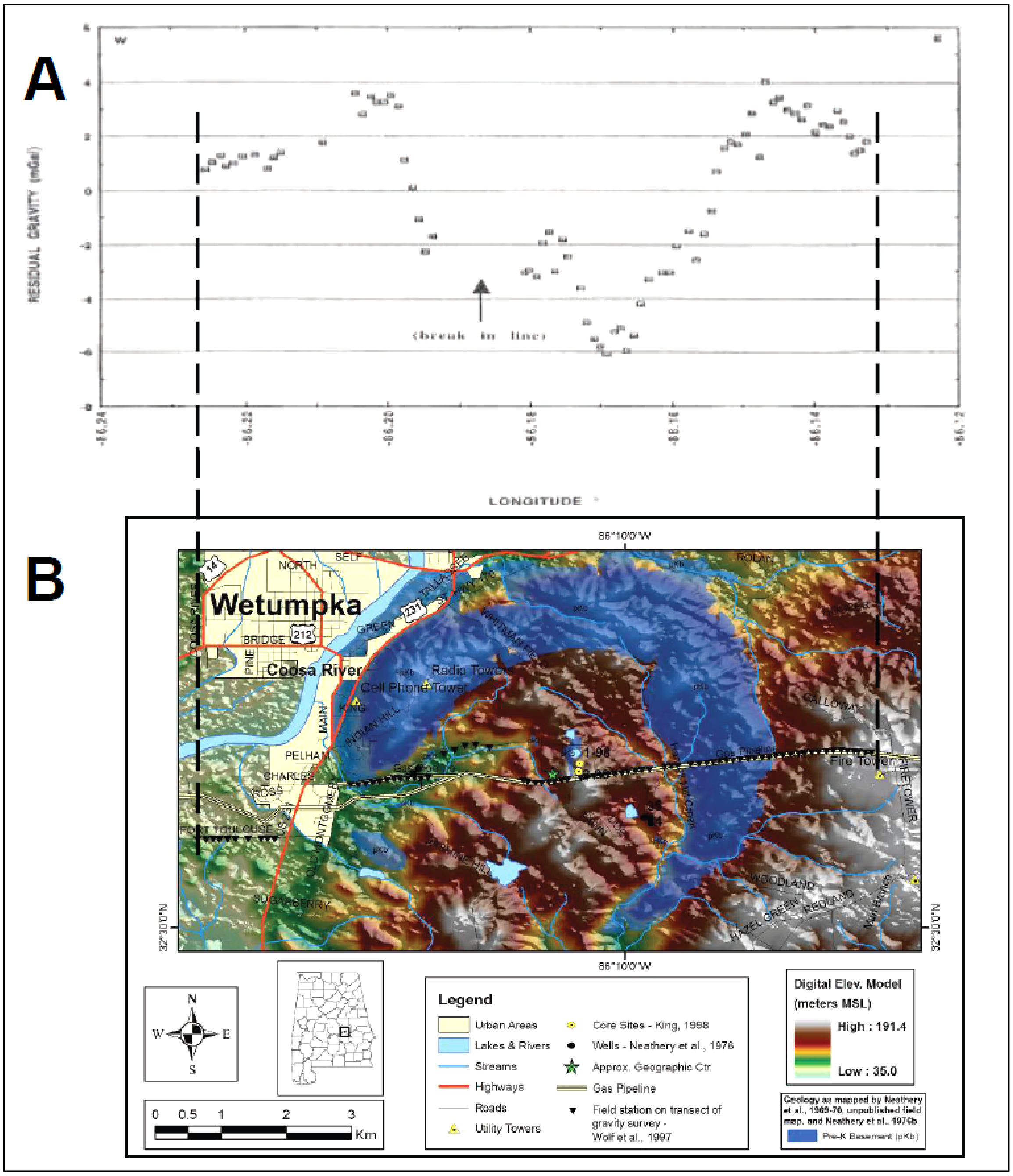

Figure 5: West to east residual gravity profile of Wetumpka (data from Wolf et al., 1997). The break in line (arrow) is a portion where unusual data points were purposely omitted to avoid confusion with readers. Taken from Johnson (2007).

To verify the origin of the Wetumpka structure as an impact crater, King et al. (2002) used in-kind support from Vulcan Materials Company to conduct core-drilling operations near Wetumpka's geographic center. Drill-core samples were produced from two core holes, Schroeder (98-01) and Reeves (98-02), named after the respective property owners. The investigation of these drill cores confirmed the impact-structure interpretation upon discovery of shocked minerals and a meteoritic chemical signature (King et al., 2002).

Based on field observations, King (1998) proposed that the broken formations located in the interior of the impact crater should be classified as a new stratigraphic unit in the Alabama coastal plain stratigraphy, which he designated as Wetumpka Mélange. This new unit was described as containing three facies. One of these facies, the "monomict megablock breccia" comprises chaotically oriented blocks. Grain sizes in this facies range from clay-sized particles within matrix to blocks that are many meters across. According to King (1998), this facies possibly developed as a result of slumping from transient crater walls within a few seconds after impact.

King (1998) also describes soft-sediment deformation features and steeply inclined Tuscaloosa sediments that are injected by clastic dikes as his "clastic-dike injected deformed-strata facies." This second facies possibly formed as a result of Tuscaloosa sediments temporarily behaving as a plastic medium. A plastic medium is defined as a substance that requires that yield stress be exceeded before it will plastically flow (Kearney, 1996). Melosh (1989) describes a mechanism by which rock and sediment may behave as a plastic fluid. He suggests that central peaks in complex craters may undergo several oscillations before shear stress, which derives oscillatory motion, falls below material cohesion strength, causing the central peak to freeze. Hydrodynamic flow continues until all stresses fall below cohesion strength of a material. At Wetumpka, the position of this dike-injected and deformed facies is between monomict megablock breccia and the centrally located polymict megaconglomerate facies (Nelson, 2000).

In 2000, Anne Nelson produced a new geologic map of the Wetumpka impact structure. Also described in her research were small and large-scale structural details characteristic to the crystalline rim, the surficial crater fill, and the region surrounding the structure.

As evidence emerged, confirming the event as a shallow marine-target impact, investigations shifted towards understanding the nature of the crater filling material. King et al. (2006) published a paper reconstructing the impact event as a means to understand the influence of target properties such as the unconsolidated shallow seabed, and especially the role of water on the cratering processes. Because it is a marine impact, water pushed away from the impact and then rushing back into the crater would have mixed the sediments on the crater floor.

In 2007, Reuben Johnson studied the stratigraphy of the crater-filling materials by analyzing core drilled from the crater's center (Schroeder and Reeves core holes, 98-01 and 98-02, respectively; Johnson, 2007). He documented an intercalated stratigraphy of sedimentary megabreccia and polymict megabreccia containing crystalline and Upper Cretaceous clasts. Polymict megabreccia is a mixed, sedimentary and crystalline breccia that contains shocked material with an impactite sand matrix. A 100 m-layer of slump and potential resurge deposits consisting entirely of sedimentary mega-blocks, which overlie a unit containing impact breccia, crystalline mega-blocks, and sedimentary mega-blocks.

With new NASA funding in 2009, four additional core holes: 09-01, 09-02, 09-03, and 09-04 were drilled to depths of 88, 23.5, 90, and 218m, respectively (Figure 6). These core holes were drilled in different areas of the crater to better understand physical relationships that might reveal information about the physical processes during excavation and modification of Wetumpka, including their relative timing. Preliminary interpretations by King et al. (2010), proposed that 09-01 contains an overturned crystalline flap, 09-02 has an interval of polymict breccia with both sedimentary and metamorphic blocks, 09-03 contains a resurge of chalky sediments containing ejecta lying upon sedimentary target blocks, and 09-04 contains a preserved slumped, overturned assemblage of Upper Cretaceous units, which are interpreted to be an overturned sedimentary flap, which lies on top of a thick section of impactite sands. Markin (in progress), previously studied these drill-cores of wells 09-03 and 09-04.

King and Ormö (2011) presented preliminary results from these new core drillings, which complemented the two core drillings performed in 1998 at the crater center (i.e., Schroeder and Reeves core holes). All in all, the new NASA-funded well drilling between the central area and the impact structure’s rim revealed thick sequences of slumped and debris-flow-like sediments. These findings supported the idea that Wetumpka is a shallow-marine impact structure that experienced early modification mass movements. The findings also showed that this impact structure experienced collapse and slumping of parts of the sedimentary target sequence as a result of marine resurge processes.

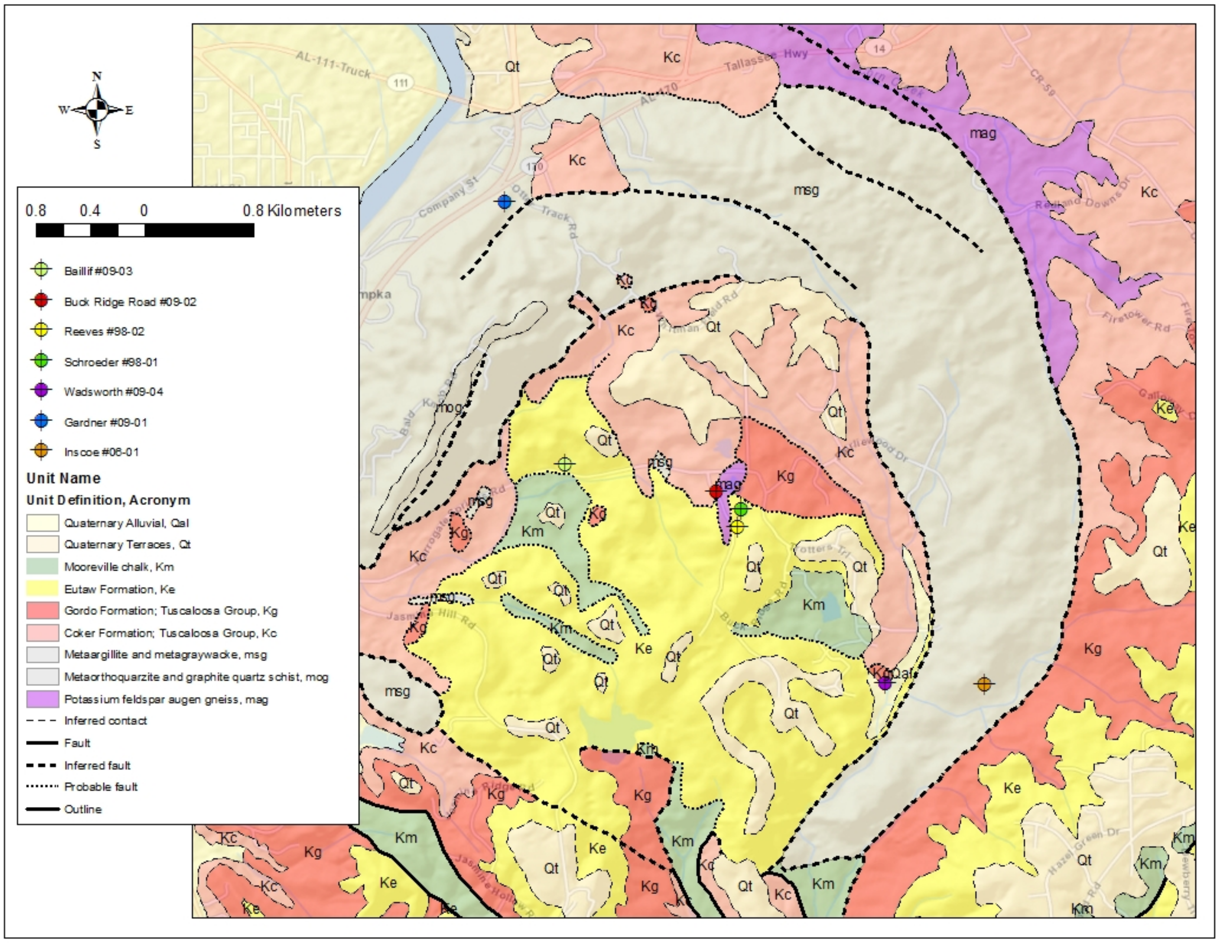

Figure 6: Geologic map with drill-core locations in Wetumpka impact structure.

In 2009-2011, James Markin (in progress) studied and described the lithofacies general stratigraphy of drill cores 09-03 and 09-04. Markin interpreted the Mooreville chalk resurge interval into four stratigraphic divisions in core-hole 09-03: lower resurge, mid-resurge, upper resurge, and uppermost resurge. Markin also interpreted the mode of entrapment of these resurge facies as a local extensional zone within a megaslump sequence. This extensional zone is interpreted as a half-graben structure (Markin, in progress). In this interpretation, resurge deposits are preserved due to post-impact subsidence-derived grabens or half-graben structures analogous to similar structures at

Chesapeake Bay crater (Poag et al., 2004). Drill core 09-04 penetrated a depth of 217.7 m near the southeastern portion of the rim. Markin noted a “fining-downward” sequence in the upper Tuscaloosa interval and a fining-upward sequence in the lower Tuscaloosa interval. The upper ~ 60 m is interpreted as a segment of slumped, overturned sedimentary section that was formerly on the rim (Markin, in progress). A section of Eutaw Formation sediments lies between the upper and lower Tuscaloosa in this drill-core.

Rodesney (2014) studied the 152 m of impactite sands below the upper ~ 60 m of overturned flap sediments in drill core 09-04. Fining-upward trends were detected in eight intervals of the 43 samples taken in the lower portion of the drill core. These fining-upward trends are interpreted as the result of an aqueous settling process (Rodesney, 2014). This settling process followed rim blocks sliding into a pool of recharged water inside the transient crater. Rodesney also noted that framework grains within the loosely consolidated sands do not originate from a single target unit and provide evidence that they are derived from a mixture of mainly sedimentary target units.

METHODOLOGY

The purpose of this study is to examine new outcrops and shallow drill cores and build upon results and interpretations of King et al. (2002; 2003; 2006), Johnson (2007), King and Ormö (2011), Markin (in progress), and Rodesney (2014) by field mapping, and petrographic and drill-core analysis, and outcrop photography and mapping. This project has produced a shallow geologic cross section of half of the crater (i.e., a half-transect). The area of the crater chosen for the cross section has the most new surface exposures available and there are associated drill cores. Samples were taken from exposures and made into petrographic thin sections, and separated with heavy liquid for heavy-mineral categorization. The upper part of drill core 98-01 was re-described and drill core 09-02 was studied for the first time to provide more information about the physical relationship between crater filling units in the geographic center of the crater to refine the cross section. The log of drill-core 09-03 (Markin, in progress) was used in the half-transect as well.

Geological half-transect methods

A Light Detection and Ranging (LiDAR) dataset with ~ 2 m resolution was provided by the Elmore County Revenue Commissioner's office in Wetumpka, Alabama, and used to produce a digital elevation model (DEM) of the impact structure (Tabares Rodenas, 2012). A published geologic map made by Neathery et al. (1976) was digitized and placed over the LiDAR-based DEM (Figure 7). Using spatial analyst tools in

ArcGIS, a topographic profile was made for the half-transect to be studied. Surface geological data and related shallow core-drilling results were synthesized and used to generate a shallow geologic cross section (i.e., the geological half-transect.)

Field mapping and outcrop description methods

The geological transect begins in the northwestern crystalline rim. The transect follows the Alabama Power electric line cut southeast to Harrogate Springs Road, then east along Harrogate Springs Road to the intersection of Buck Ridge Road, and finally south on Buck Ridge Road to the intersection of the El Paso natural gas pipeline, which is the geographic center of the structure (Figure 7).

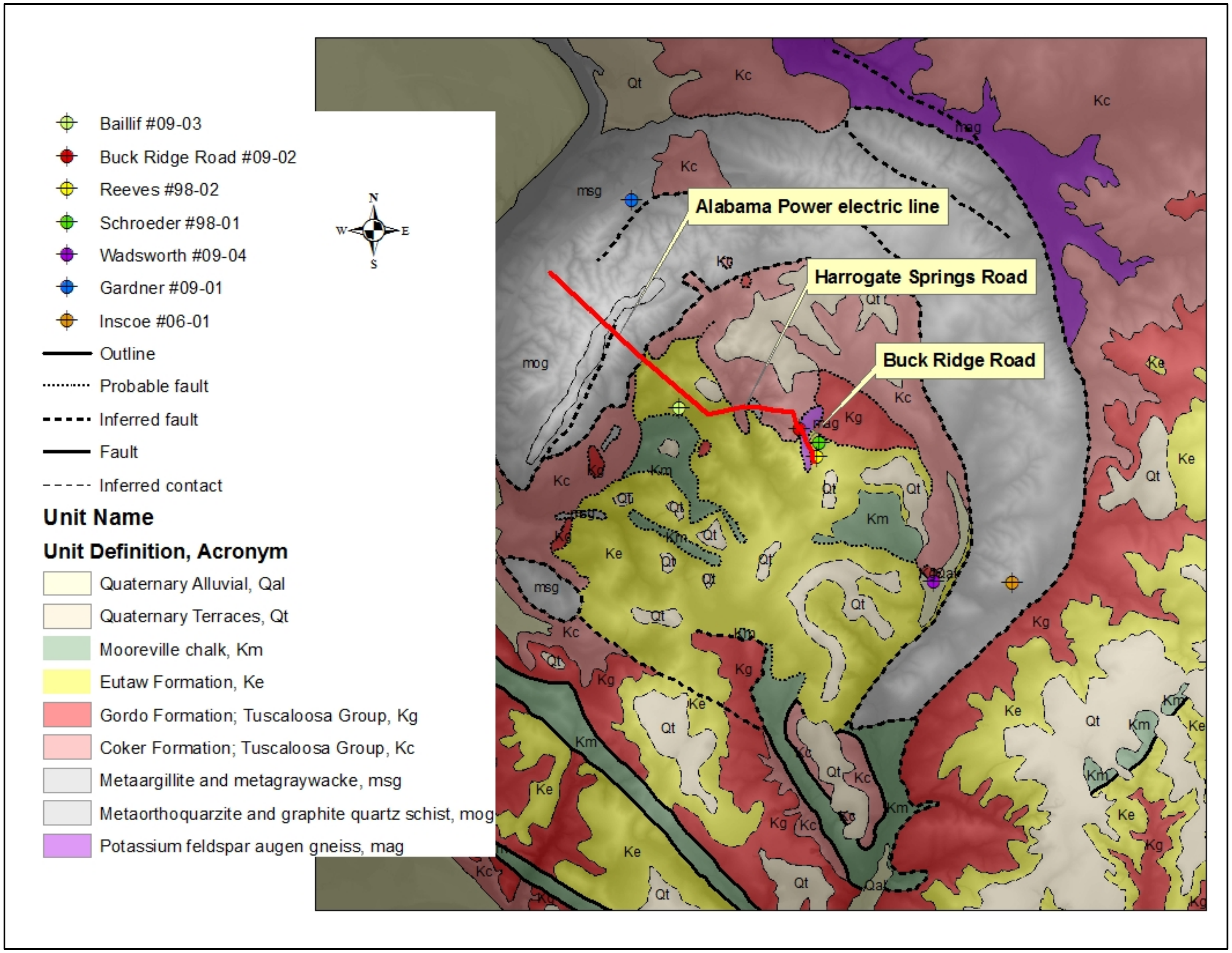

Figure 7: LiDAR-based DEM with digitized geologic map from Neathery et al. (1976). Geologic half-transect line is marked (red). Also, locations of key shallow core holes are marked.

Exposures on the Alabama Power electric line were covered with thick forest vegetation and soil, which tended to hamper detailed field investigation. However, many outcrops were found nearby streams. The largest exposure on the electric line is locally known as “The Cliffs.” This exposure is also the largest single outcrop within the Wetumpka impact crater. New exposures along Harrogate Springs Road and Buck Ridge Road were made available by the Elmore County Highway Commission, which sent work crews to clean the new exposures.

Specific procedures were followed at each exposure. GPS latitude and longitude coordinates along with field notes and strike and dip measurements were recorded. Next, geologic structures were described, including foliation, lineation, folds, fractures, joints, faults, bedding orientation, and soft-sediment deformation features. Contacts between crater-rim and crater-fill units were described if directly observable. Also, contacts between different crater-filling units were described. Identity of rock units within the crater rim and crater fill were determined with respect to known Piedmont crystalline rock units (i.e., Emuckfaw Group or Kowaliga Gneiss), and Upper Cretaceous Coastal Plain units (i.e., Tuscaloosa Group, Eutaw Formation, and Mooreville Chalk.) Field photographs were taken with an 8 megapixel iPhone 5S camera and a Canon T3i.

Samples were collected at some exposures for thin section characterization. Twenty thin sections from the crater-fill material were studied for mineral constituents. Units described and sampled are located in Appendix I.

Photographic investigation of The Cliffs

The Cliffs span ~ 120 m and have ~ 15 m of erosional relief. This feature formed as a relatively recent event as a result of sapping, a geological process of groundwater erosion. It is situated at the interior base of the northwestern quadrant of the crystalline rim. Structures in the outcrop are important for understanding the early modification stage of the crater's development. The DJI Phantom 2 Vision +© drone was used to gain a unique eye-level perspective of bedding and other structures at The Cliffs. The drone was operated by two people, one steering with a remote control, and the other operating the on-board camera with a handheld computer tablet. The drone utilizes a 14 megapixel camera mounted on a gimbal to stabilize the camera for high quality photography (Figure 8).

Figure 8: Photograph of the DJI Phantom 2 Vision +© drone used for aerial photography. One user flies the drone with the remote (top of picture), while the other controls the on-board camera with a handheld tablet (bottom left).

Petrographic methods

The process of inferring sandstone provenance has been well established by Folk (1980), Dickinson (1985), Ingersoll (1988), and others. Detrital modes calculated from point counts of framework grains within sandstone can be used to infer transport mechanisms, climate, and depositional environment of sandstones. For example, Rodesney (2014) used these techniques to interpret Wetumpka impactite sands.

Twenty thin sections were created for this study. Nine samples were collected from the Eutaw Formation, six were collected from the Tuscaloosa Group, and five were collected from the unit known as impactite sand. Each sample was collected and sent to National Petrographic Services in Houston for epoxy impregnation and thin-section production.

Careful documentation of mineralogy and textural aspects of each thin-section is important for this study. Utilizing a 0.2-mm step grid, 300 total point counts were recorded per slide utilizing the Gazzi-Dickinson point-counting method (Ingersoll et al., 1984).

Heavy-mineral characterization

Heavy-mineral fractions in sediments are composed commonly of diverse mineral species, in which each grain conveys its own history (Morton, 1985; Mange and Maurer, 1992). Samples were collected for a heavy-mineral characterization study from four units cropping out in the crater interior: Tuscaloosa Group; Eutaw Formation; impactite sand; and the central breccia unit. These four units were chosen based on their physical relationship to one another in the crater and to provide a representative assemblage of the most prominent heavy minerals in the upper portion of the post impact stratigraphy. Preparation and characterization techniques were taken from Mange and Maurer (1992).

Preparation of samples. The following is a sequence of treatments preceding heavy-mineral separation:

1. Disaggregation of coherent sediments, to liberate individual grains;
2. Removal of organic substances;
3. Sieving to extract required grain sizes.

The disaggregation of each sample was done very carefully using a mortar and pestle. Individual grains were taken care to be preserved. After disaggregation, each sample was agitated with a mechanical shaker for 15 minutes. In order, sieve pans used were coarse (1ϕ), medium-fine (4ϕ), and silt. Target grain size for separation was medium-fine sand, 4ϕ, or 0.0625 mm. For the next step, 30 grams of medium-fine grain said were used for separation. Usually, fine-to-medium grained sands yield the optimum heavy mineral assemblages (Mange and Maurer, 1992).

Concentration of heavy minerals is performed by means of high-density liquids. This study used tetrabromoethane (acetylene tetrabromide) that has a density of 2.96 g/cm^3 at 20°C. All separations were carried out in a fume hood (Figure 9) and followed the procedures outlined in Mange and Maurer (1992).

Figure 9: Photograph of the heavy-mineral extraction set up used in this study.

After heavy-mineral separation, a Frantz Isodynamic Magnetic Separator was used to separate heavy minerals by density. Magnetic separation of heavy mineral grains depends on the magnetic susceptibility of the minerals to be separated. Further separation of heavy minerals is helpful with identification. The Frantz separator (Figure 10) incorporates an electromagnet with two elongate pole pieces arranged so that the space between the poles is much wider on one side than the other. A vibrating metal chute parallels the pole pieces. Mineral particles are introduced into the upper end of the cute and slide toward the lower end. Those with higher magnetic susceptibility move toward the side of the chute where the pole gap is narrow and the magnetic flux is greatest. The separator is mounted so that it can be rotated both in the direction of grain movement (slope) and in the direction normal to the direction of grain movement (tilt). The way in which mineral particles separate as the move along the length of the chute depends on the tilt of the chute, the amperage applied to the electromagnet, and the slope and rate of the feed to the chute. At the lower end of the chute the particles are separated into two streams, one consisting of grains of higher susceptibility than that corresponding to the amperage setting used, the other consisting of grains of lower susceptibility. There is much variation in magnetic susceptibility of minerals of a given species. It is common to set the Frantz separator slope at 20°, the tilt at 25°. The following steps were used:

1. Using a side slope of 20° and a tilt of 25°, each sample was first run at a setting of 0.4 amperes. The magnetic (labeled A in Table 1) and nonmagnetic fraction were retained and labeled.
2. The nonmagnetic fraction from Step 1 was run at a setting of 0.8 amperes. The magnetic (labeled B in Table 1) and nonmagnetic fraction was collected and labeled.
3. The nonmagnetic fraction from Step 2 was run at a setting of 1.2 amperes. The magnetic (labeled C in Table 1) and nonmagnetic fraction (labeled D in Table 1) was collected and labeled.
4. Refer to Table 1 for a listing of those heavy minerals which are magnetic at 0.4, 0.8, and 1.2 amperes.

Figure 10: Photograph of the Frantz Isodynamic Magnetic Separator used for heavy mineral separation.

Table 1: Minerals that are magnetic at various amperages using a side slope of 20° and a tilt of 25° (Hess, 1966).

Magnetic at 0.4	**Magnetic at 0.8**	**Magnetic at 1.2**	**Nonmagnetic at 1.2**
Garnet	Biotite	Muscovite	Zircon
Ilmenite	Hornblende	Spinel	Rutile
Chromite	Hypersthene	Enstatite	Titanite
Chloritoid	Augite	Tourmaline	Leucoxene
Olivine	Actinolite	Clinozoisite	Apatite
	Staurolite	Diopside	Corundum
	Epidote	Tremolite	Baryte
	Chlorite		Fluorite
			Sillimanite
			Kyanite
A	**B**	**C**	**D**

Each magnetic fraction was sent to National Petrographic Services for mounting and polishing. Observations of the most common heavy minerals were made from the prepared thin-sections. No grain counting was performed. The entire slide from each lithologic unit was examined to provide supplementary data for petrographic analysis of each unit. Quantities of each heavy mineral fraction are expressed in weight percentages.

Core-logging

In 2009, drill core 09-02 was extracted in segments of a maximum 5 ft (1.52 m) length, referred to a “core sections,” using water-based, rotary core-drilling. During core-section retrievals or active drilling, the short segment length resulted in minimal loss of drill core (personal communication, King’s field notes, 2009). Following extraction, the drill-core was boxed and preliminary notes were taken on the core. All preliminary logging was measured in decimal feet. The total depth of 09-02 was 23.3 m (76.5 ft).

Drilling of the 09-02 core hole began beside the road side outcrop, polymict impact breccia located at N latitude, 32.31434, and W longitude, -86.10488, on the state right of way on Buck Ridge Road. Ground-level elevation for the well of 122 m (400 ft) was collected from a topographic map. This well location is situated beside the central breccia unit and targeted the unknowable central peak. Drill core 09-02 was not oriented in the field. Field recorded depths of core sections are assumed to be correct. Drill core 09-02 was curated for aesthetic purposes for photography. This drill core needs further cleaning to remove mud coating from the upper 4.8 m (15.7 ft).

Drill core 09-02 was logged using field recorded notes, a hand lens, a magnifying glass, and a measuring tape. Depths were changed to metric units. Notes for observations were recorded in notebooks and build upon original field notes. Each core box was photographed, and some drill-core features were documented with selective photography. Photographs of core boxes are found in the Appendix IV (Figures A3-A10).

Units and features were measured and noted for this study. The purpose of measuring and documenting the units in this core were for comparison to drill core 98-01, (located at N latitude, 32.312208, and W longitude, -86.102216), which is 192 m (630 ft) from drill-core 09-02 at a recorded elevation of 132 m (433 ft). By comparing the two drill cores, and incorporating known outcrops in the vicinity of these two wells, a shallow, detailed correlation can be made about the physical relationships between sedimentary and proximal ejecta units in the central area of the crater.

Drill-core 98-01 was originally logged by Johnson (2007). In 2007, little was known about the impactite sand unit. So, these units were not distinguished in Johnson's (2007) core log. The first 32 m (105 ft) of the drill-hole was not cored; by re-examining the upper 80 m, new interpretations were made about the physical relationships between impactite sand, Tuscaloosa, and Eutaw units to include in this study.

After 09-02 and 98-01 were logged, they were imported into SedLog 3.0. This program provided a way for scaling the logged core into a more manageable size. Once the core was entered into SedLog, they were exported to and digitized with color and symbol in Adobe® Illustrator CS©. Using scale, the elevation of each drill rig was accounted for to properly align each drill core to one another for proper correlation between the two drill-cores.

Drill-core 09-03 was logged by Markin (in progress) from 2009-2011. The location of 09-03 is N latitude, 32.52595, and W longitude, -86.18655 at an elevation of

86.3 m (283 ft) within the “chalk meadow,” termed for the area next to and directly southeast of The Cliffs. Total depth of the drill-core is 90 m (296 ft). In Markin’s drill-core analyses, he examined a 24.5 m (80.4 ft) thick section of resurge-deposited chalk in the upper part of 09-03. He also documented the internal details of the resurge chalk using CT technology to expose the internal organization of these deposits (Markin and King, 2012).

Review of the core-log shows the upper 6 m of 09-03 to be comprised of tan chalk similar to the more chalky beds of the Mooreville Chalk. Below the tan chalk is an 18.5 m thick green-grey, glauconitic mud and calcareous, sandy shale. Underlying the green-grey unit is a section of 65.6 m (215.2 ft) of tan-brown medium to coarse sand (i.e., Eutaw megablocks).

Creating a geologic half transect, cross section

A geologic cross section of half of the crater was created by incorporating the previously mentioned topographic half transect, outcrop descriptions, and logged research cores 09-02 and 98-01, as well as interpretations of 09-03 made by Markin (in progress). All other information included in the geologic half-transect is available from field mapping. Below what is available on the surface, scientific interpretations were made to correlate structures and units.

RESULTS

Field mapping and outcrop description

The following field mapping and outcrop description results will follow the southeasterly direction of this project's half-transect starting in the northwestern crystalline rim. Based upon previous work from Tabares Rodenas (2012), the border rim terrain was described using drill core 09-01.

Along the Alabama Power electric line, and the highest point on the crater rim, is "Bald Knob." Here, saprolitic crystalline rim rocks strike northeast and dip ~ 70° northwest. Moving southeast along the Alabama Power electric line, crystalline blocks of the intra-crater terrain begins at some point with lower elevation (as shown on geological maps of Neathery et al., 1976). In outcrop, pebble to boulder-sized clasts made of biotite-muscovite-quartz schist that is iron oxide stained (Figure 11 Figure 12) occur within Eutaw sediments. Clasts contain garnet and are interpreted to be related to the basal Josie Leg Member of the Emuckfaw Group lithology. Exposures such as these are highly weathered with little to no internal bedding structure. Continuing southeast along the electric line cut, the boundary between the crystalline block terrain and Eutaw megablocks is an inferred boundary where exposures of Eutaw Formation are established.

Figure 11: Photograph of boulder-sized clast (above hoe-pick) within the Eutaw Formation near the contact between the inferred boundary of the crystalline crater rim and intra-crater terrain within the zone named ‘crystalline blocks.’ Hoe-pick (~ 65 cm) for scale.

Figure 12: Photograph of 5-cm sized breccia clasts within biotite-muscovite-quartz schist. Location of this photo is near inferred contact zone of the crystalline rim and intra-crater terrain within the zone named ‘crystalline blocks.’ Scraper tool (~ 25 cm) for scale.

Exposure at The Cliffs is located on and near the electric line cut. This exposure shows large units of Tuscaloosa Group, less abundant units of Eutaw Formation, and marginal impactite sand. Units appear internally deformed, showing faults and folds that are related to impact stress and/or mass-movement mechanisms. Structural measurements were necessary to understand the complex structure of this portion of the crater. In The Cliffs, available contacts between units and bedding planes were measured using a Brunton Compass and a DJI Phantom 2 Vision +© drone was used to attain a unique eye level perspective to supplement collected field measurements. Figure 13 shows a mosaic of photographs taken, as well as drawn-in bedding orientations and fold axes. Boundaries between blocks are delineated by iron-oxide cemented sand layers that may have adjacent flattened clay layering, or variously oriented sedimentary layers juxtaposed with one another. Stations 1 – 26 delineate locations of measurements (Figure 14) taken at specified coordinates (Appendix II; Table A4).

The major structure observed in this exposure is interpreted as an asymmetric, northwest-southeast plunging parasitic antiform (Figure 15). On a stereonet, poles to bedding planes as well as axial planes and hinge lines for fold axes were calculated for each of the measurements taken (Figure 16 and Figure 17). On the western and eastern limbs of this major antiform are synclines that strike roughly parallel to the fold axis of the antiform. After developing a structural map, a bisecting cross-sections, labeled “A-A’” was made to better understand the significance of this large exposure.

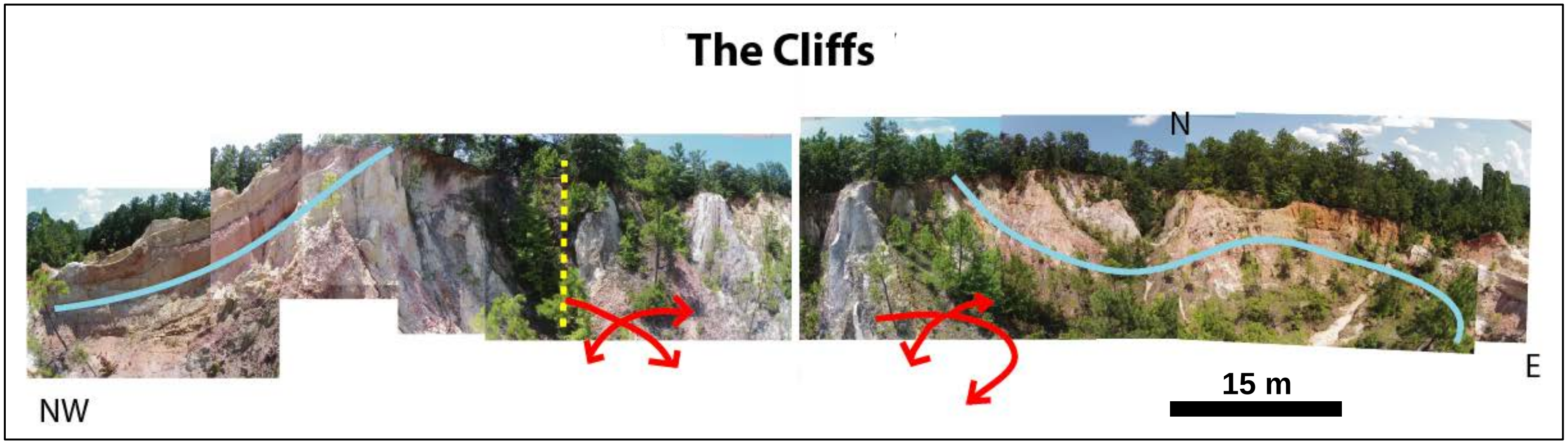

Figure 13: Asymmetrical folding of The Cliffs shown in two photo mosaics. Blue line is a correlated overbank bed. Yellow line is the axial plane of the major antiformal fold. Red line symbol is approximate hinge of asymmetrical fold. Vergence (paleo-slump direction) is to the north. Plunge direction is southeast. Photos taken with a DJI Phantom 2 Vision +© drone.

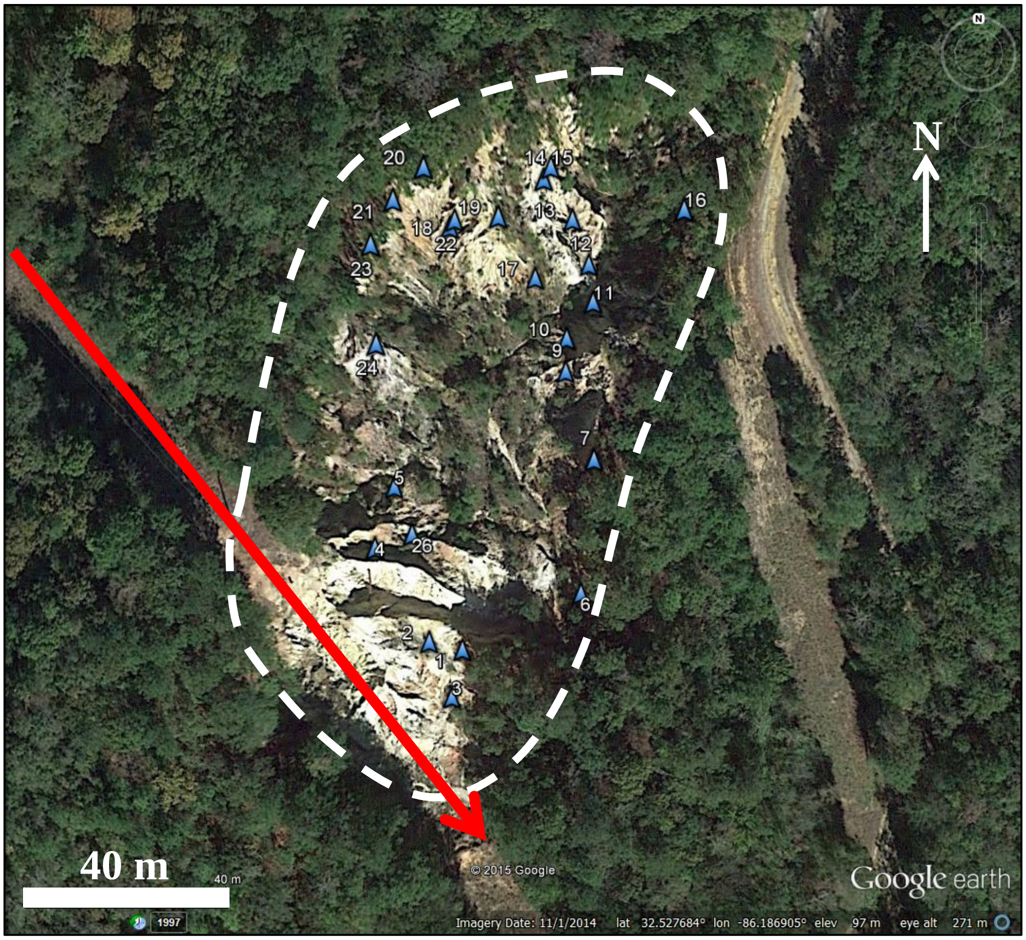

Figure 14: Locations of stations of measurement at The Cliffs. Stations are numbered and marked with blue arrows. The location of the Alabama Power electric line cut is marked with a red arrow. The Cliffs are outlined with a white dotted line.

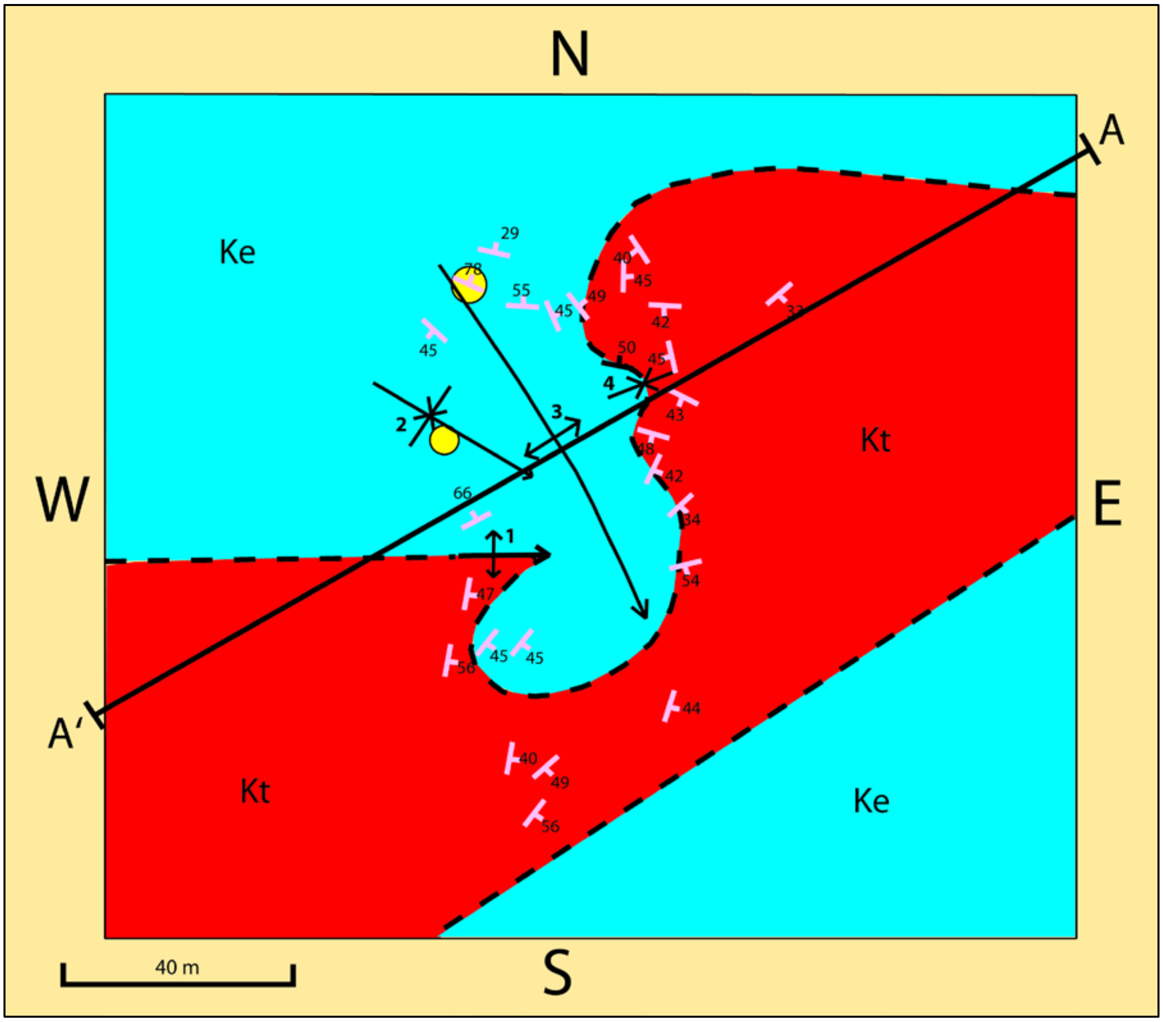

Figure 15: Structural map of The Cliffs area. Red is Tuscaloosa Group (Kt). Blue is Eutaw Formation (Ke). Yellow is impactite sand exposures. Major structural features (i.e. anticlines and synclines) are indicated and numbered 1 - 4. Cross-section line is marked "A-A'." Note that stratigraphy is upside down (older Kt lies on top of younger Ke).

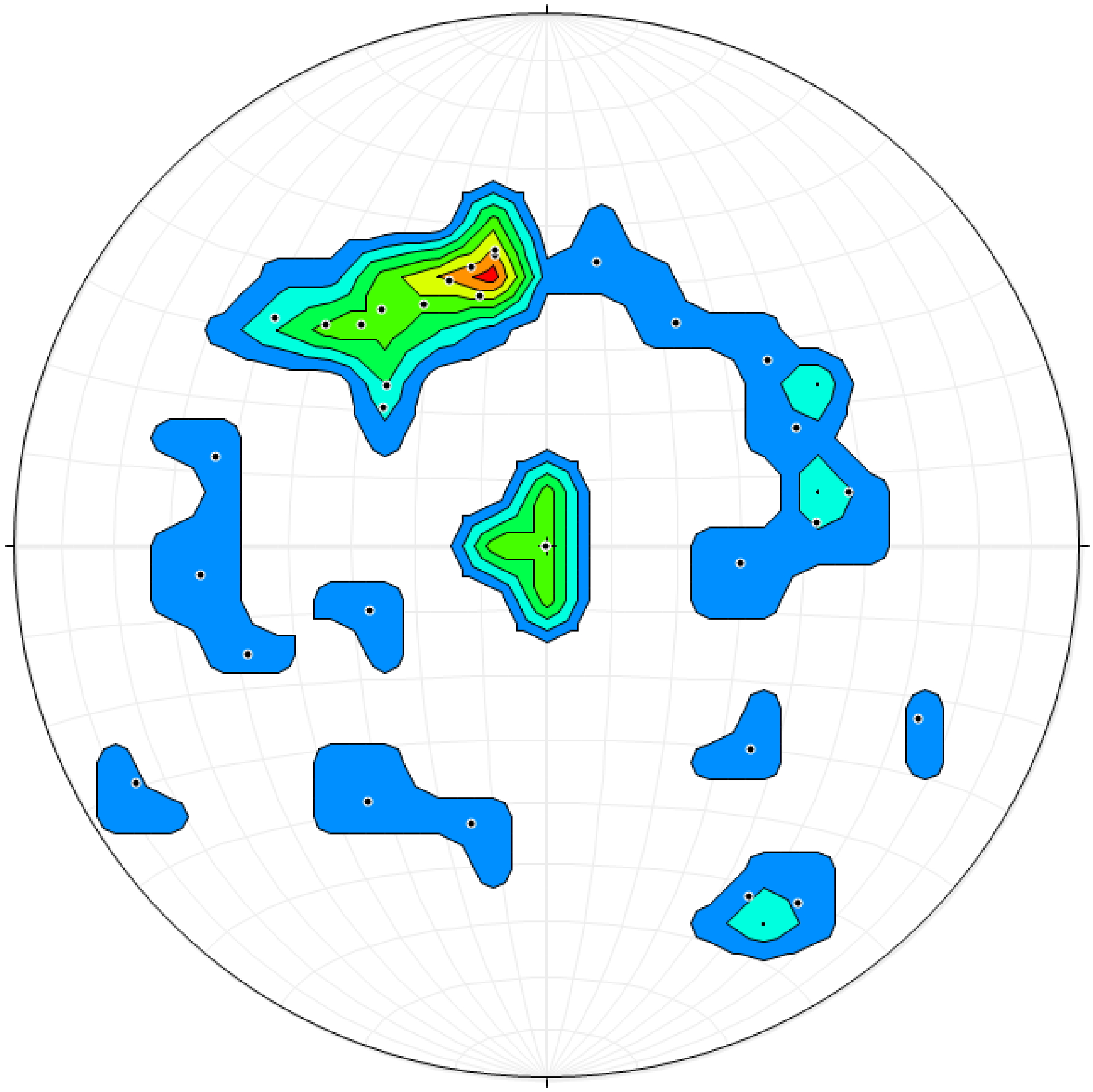

Figure 16: Stereonet showing calculated poles to measured bedding planes at The Cliffs. Poles (black dots) are contoured with 1% area.

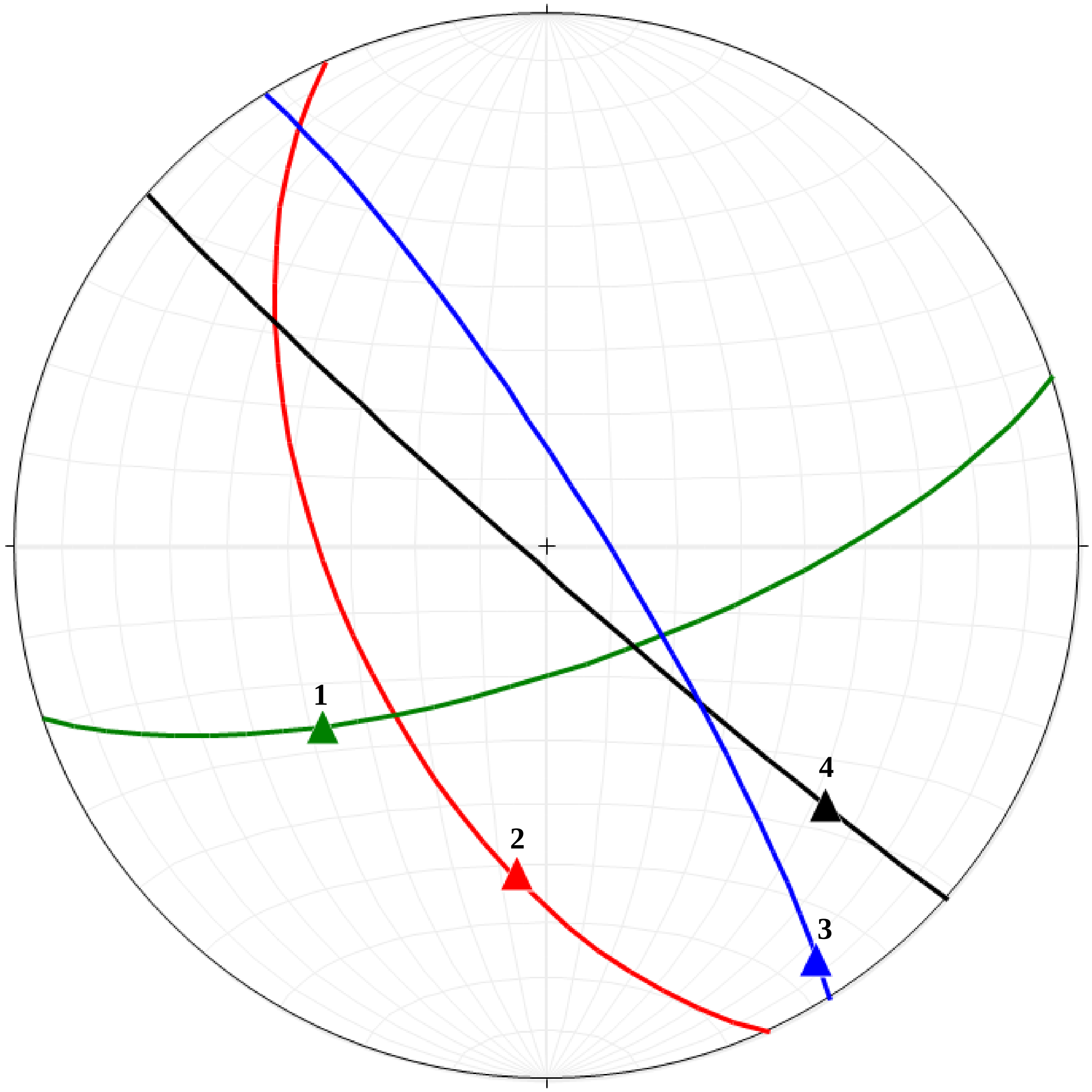

Figure 17: Stereonet showing calculated axial planes and hinge lines for the fold axes (triangles) for each structure at The Cliffs. Colored and numbered hinge lines (triangles) correspond to Figure 15 and show a primary south-southeast plunge.

The cross-section transect “A-A’” bisects The Cliffs northeast to southwest, perpendicular to each major structural feature (Figure 18). Units on the northeastern and southwestern portion of the cross-section are Tuscaloosa Group. The Eutaw Formation occurs in the topographic low area. Because of ground-water sapping, the majority of the antiform is eroded away exposing the “older” Eutaw Formation. Regional pre-impact stratigraphy is known to have younger Eutaw Formation overlying older Tuscaloosa Group. Because Eutaw underlies Tuscaloosa at The Cliffs, it is clear that this section is overturned. Drill-core 09-04 (located southeast of The Cliffs at N latitude, 32.5105, and W longitude -86.16145, Figure 6) also encountered overturned flap stratigraphy. These occurrences are interpreted to be a transported portion of the southern overturned rim flap that was created post-impact.

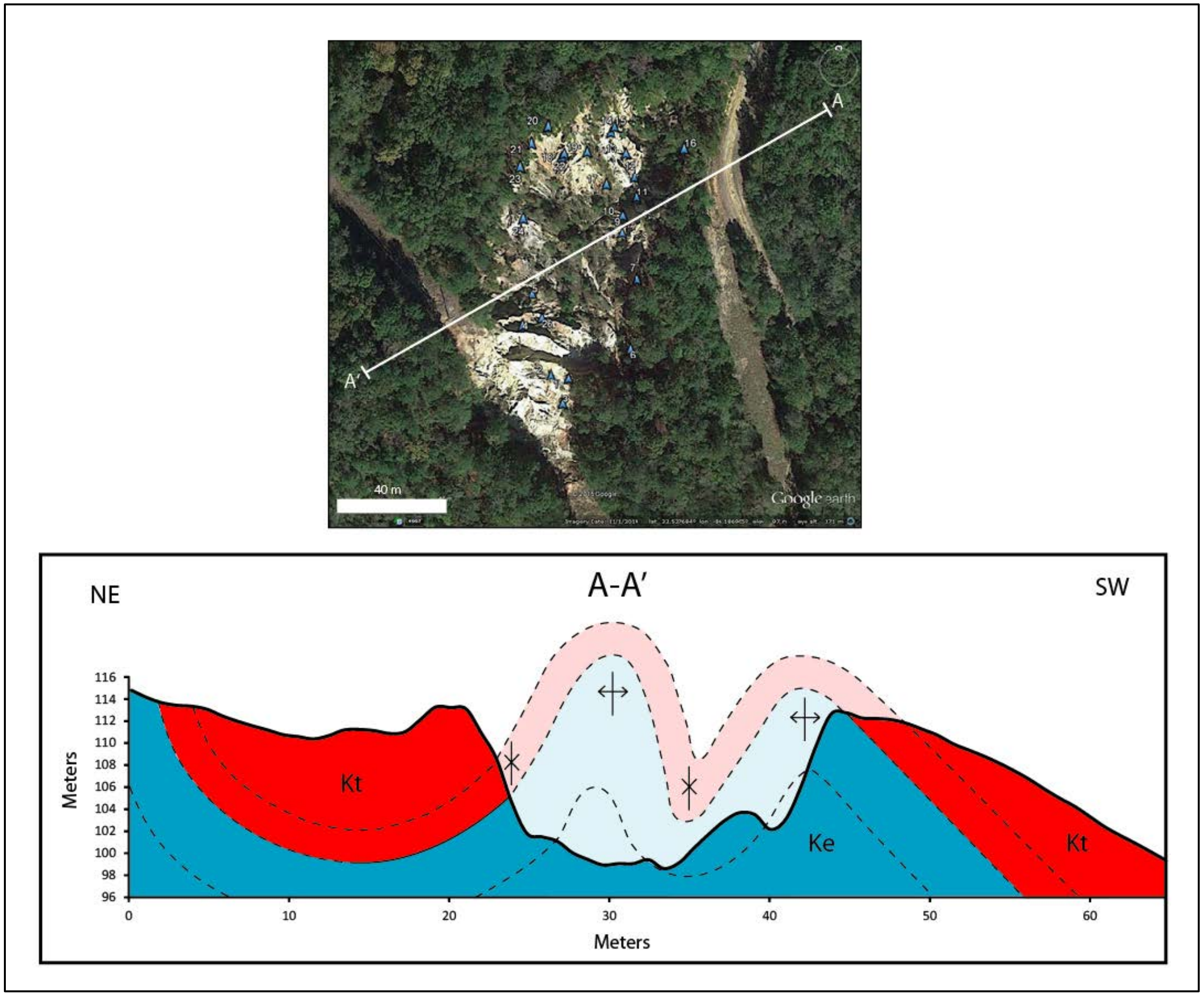

Figure 18: Cross-section showing key structural features at The Cliffs area along a topographic profile. The direction of this cross-section is northeast to southwest, looking down plunge (i.e. southeast). See A-A' in Figure 15. Dotted lines indicated inferred boundaries. Numbered fold hinges correspond to Figures 15 and 17.

The parasitic nature of structures in The Cliffs is due to a combination of events. Primary plunge to the south-southeast is a result of the lateral spreading of the detached, now non-existent, southwestern rim. Overturned packages of sediments laterally spreading to the northwestern crater wall would have theoretically piled up against the harder crystalline rim. Lateral spreads occur on gentle slopes, especially where a stronger upper layer of rock is undergoing extension and moves above an underlying softer, weaker layer (Highland and Bobrowsky, 2008). Multiple episodes of lateral spreading and soft sediment deformation due to weakened underlying units help explain the parasitic nature of the antiform. But, if the trans-crater slide were to come directly from the southwest, the fold axis of these anticlines would be plunging west-east. The north verging, southeast plunging nature of The Cliffs structure better supports a hypothesis that the trans-crater slide traveled in an arcuate west to north to east fashion around the northwestern crater wall (Figure 19).

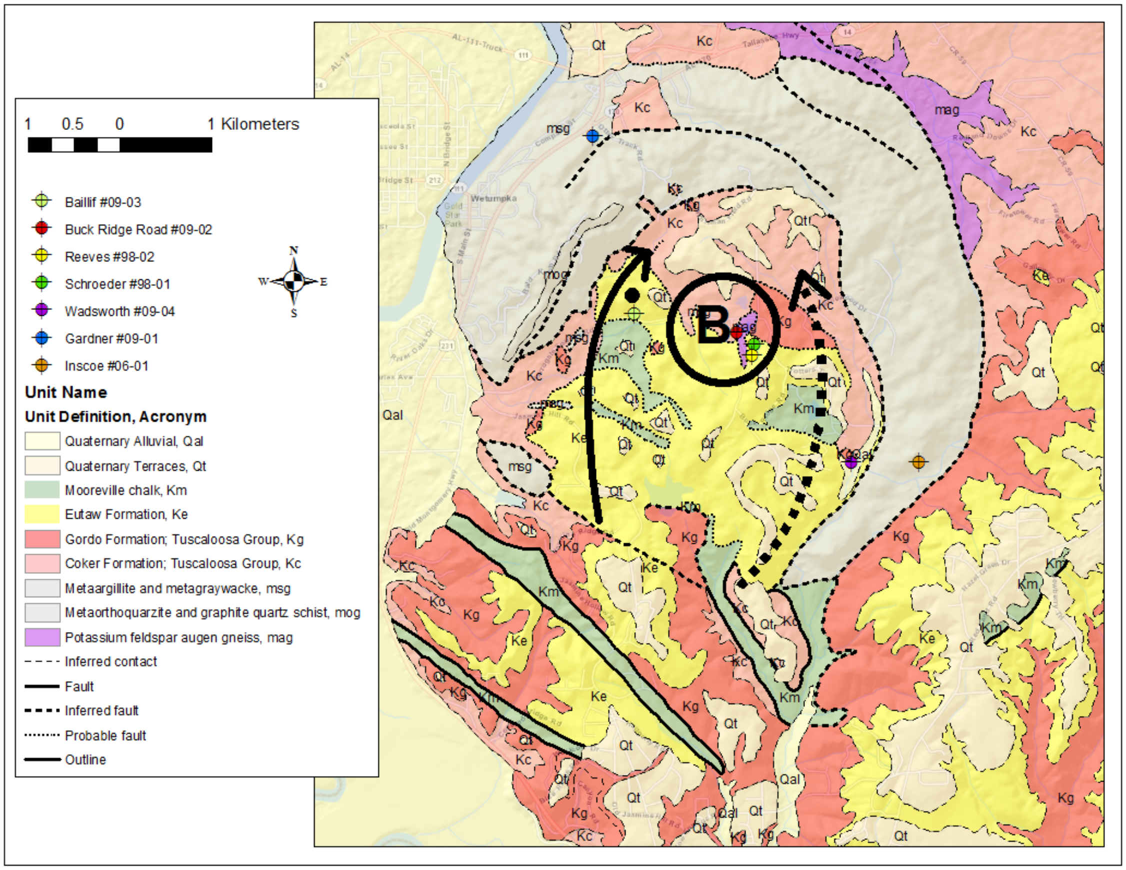

Figure 19: Illustration of the direction of transient crater slide (TCS). TCS is diverted by the developing central bulge (labeled 'B'). The Cliffs area is marked by a black dot.

The Mooreville Chalk overlies the Eutaw Formation at the southeastern extent of The Cliffs. This “chalk” unit is composed of calcareous, clayey, silty marl and is characterized by white, caliche nodules, which are result of dissolution of microfossil calcite in the rock and precipitation during evaporation (King and Ormö, 2011). This marl is mapped as Mooreville Chalk, but is not the same Mooreville as in the chalk outcrop belt of central Alabama. It is composed of ~ 20-30% fossil plankton, including foraminifera, ostracodes, diatoms, radiolarians, and coccoliths (King, 1987). Some megafossils, such as oysters, cephalopods, and shark teeth have been found as well (King and Ormö, 2011). U.S. Geological Survey studies on the paleontology of the Mooreville Chalk from surface exposures at drill-core 09-03 (depth ~ 0.3 m) reported partially melted dinoflagellates (King and Petruny, 2009). In this instance, dinoflagellates would have been suspended in the water mass and deposited after onset of the energetic water movements of the oceanic resurge (King and Ormö, 2011). King et al. (2013) reported sand-sized schist fragments of target origin in the chalk from within the crater.

Drill-core 09-03 was drilled ~ 200 m east of The Cliffs in the chalk meadow. In 2011, Markin proposed that the chalk meadow to be a half-graben structure that has structurally-preserved a mostly complete interval of resurge facies. This interpretation helps explain the relationship between the Eutaw and Tuscaloosa units to the north and west. The units seen in The Cliffs were not penetrated during coring of the 90-m-deep 09-03 drill-core (King and Ormö, 2011). Noting this, a possible explanation for Markin's proposed half-graben structure is that the large sequence of units at The Cliffs first spread laterally, northwest to meet the crater wall. Then, through compressional folding seen in The Cliffs, the Mooreville Chalk was deposited in the half-graben by a tsunami resurge late in the early modification stage (Figure 20).

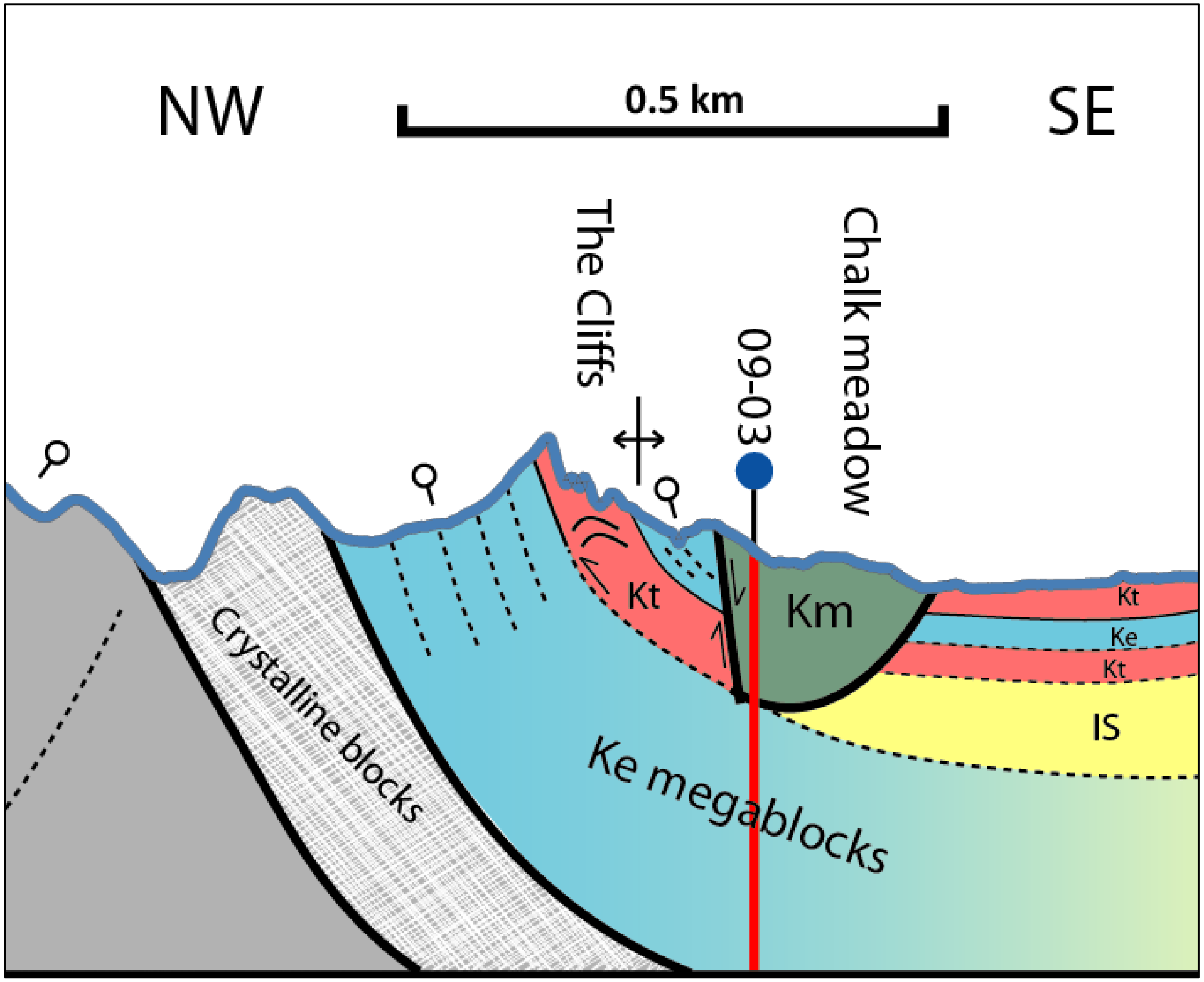

Figure 20: Cross-section showing extensional half-graben with green-colored Mooreville Chalk (Km) preserved as a resurge facies from oceanic tsunami resurge caused by compressional folding at The Cliffs. Vertical units are in meters, horizontal units are in kilometers. Kt is Tuscaloosa Group (red). Ke is Eutaw Formation (blue). Yellow is impactite sand. Tadpoles mark the direction of dip.

Harrogate Springs Road outcrop #1 (HSR-1) is the first outcrop encountered on Harrogate Springs Road, going east toward the junction with Buck Ridge Road. HSR-1 is shown in Figure 21 (located at N latitude 32.525938, and W longitude -86.180846). HSR-1 is interpreted as a tilted or possibly folded unit of Tuscaloosa Group sediments. At ground level, Tuscaloosa Group red-colored, fining upward fluvial sequences occurs with intruded tan-colored, structureless impactite sand. The Tuscaloosa strata are steeply inclined. At station 27 (Appendix II; Table A4), the strike of this inclination is N 5°W, dipping 30° northwest.

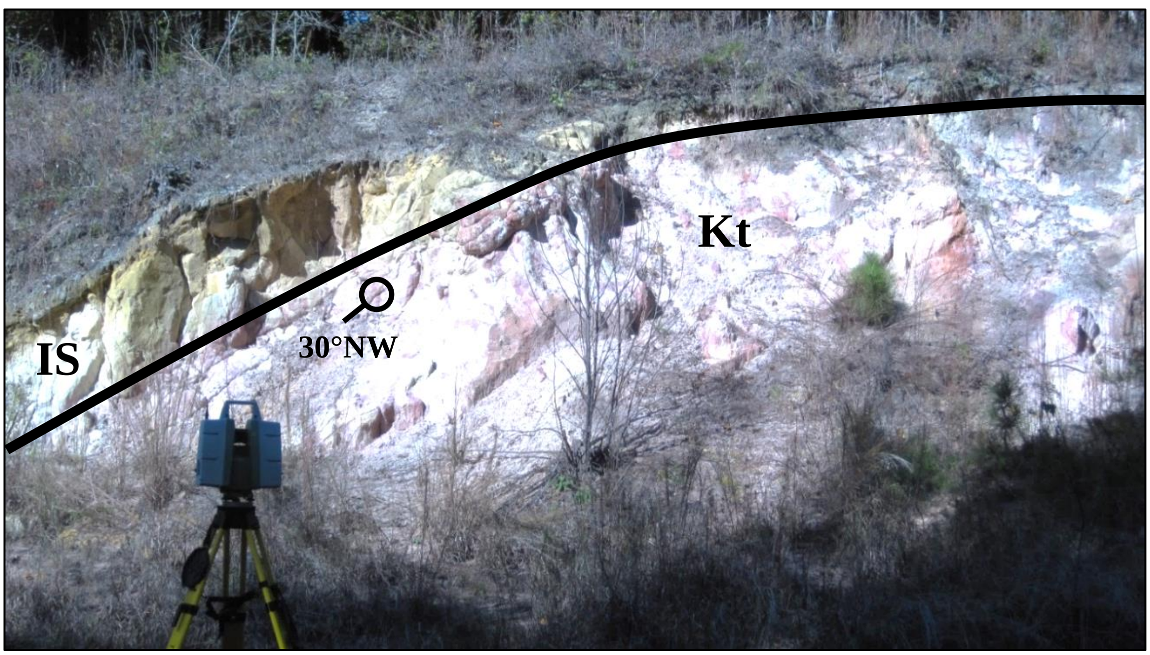

Figure 21: Photograph of HSR-1 outcrop (station 27). Tuscaloosa Group (Kt) sedimentary layers are marked as is the contact with impactite sands (IS). Ground-based LiDAR instrument for scale (~ 5.5 ft tall). Photo looking north. Tadpole marks the direction of dip.

Petrographic analysis of the Tuscaloosa Group from this outcrop show that it is a poorly sorted, subrounded, quartz sandstone with hematite matrix. Heavy mineralogy includes staurolite with quartz inclusions (Figure 22). Impactite sand petrology from this locality shows no feldspar content and a clay matrix. Details of petrographic point counts and heavy-mineral analyses are given in the Appendix I (Table A2 and A3).

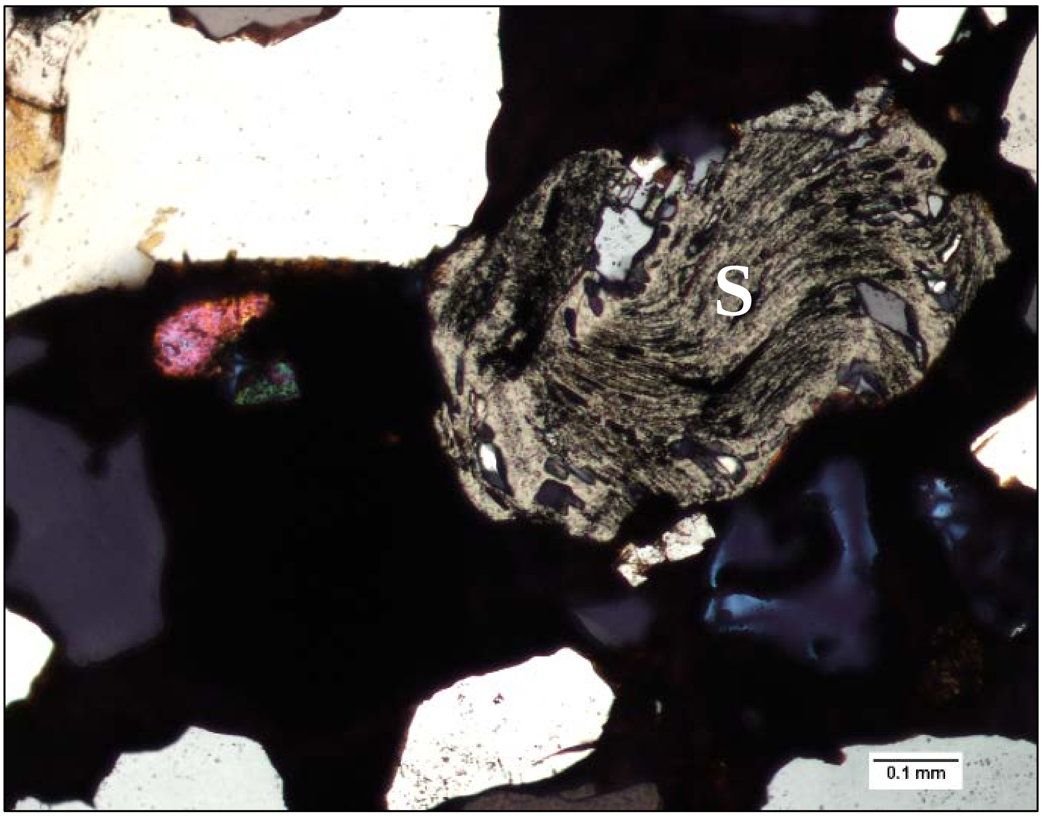

Figure 22: Thin-section photomicrograph showing staurolite (S) with quartz inclusions from the Tuscaloosa Group at HSR-1. Thin section 1765-14. Photomicrograph was taken in cross-polarized light (xpl).

Harrogate Springs Road outcrop #2 (HSR-2) is the second outcrop going east on Harrogate Springs Road toward the junction with Buck Ridge Road. This outcrop is ~ 80 m in length and exposes mass-movement units of the overturned rim sequence (i.e. Tuscaloosa-Eutaw-Tuscaloosa) plus impactite-sand injection dikes.

The majority of the outcrop displays deformed units of Tuscaloosa Group and Eutaw Formation sediments. Impactite sand cross-cut both the Tuscaloosa and Eutaw. Clasts of both units are found within one another as well as within impactite sand injection dikes. This supports the hypothesis that impactite sand intruded into and mixed with overlying units such as the transported Tuscaloosa and Eutaw layers.

In lateral spreads, softer, weaker, underlying units squeeze upward into fractures that divide laterally extending layers into blocks (Highland and Bobrowsky, 2008). The upper, more stable, layer (i.e., overturned rim sequence) extended along a weaker underlying unit (i.e., impactite sand) that flowed following liquefaction or plastic deformation. Specifically, when dilation cracks opened in the transported units, fragments of other layers in transport were injected before the dilated cracks closed.

On the east end of HSR-2, Eutaw and Tuscaloosa units are juxtaposed at a high angle. The interpreted structure is a shallowly plunging synclinal fold (plunge measured 38°NE; Appendix II; Table A4). The left and right limbs of these folds were measured as N20°E/45° SE and N20°E/45°SW, respectively (Figure 23; Appendix II; Table A4). Impactite sand intrudes between what would be the contact between the Tuscaloosa and Eutaw. In this intrusion, fist-sized Tuscaloosa clasts are included with no apparent orientation. This observation supports the hypothesis of impactite sand dikes intruding into overlying units. These clastic dikes appear to have formed contemporaneously during the sliding event of the overturned flap back into the crater interior. Petrographic analysis of this clastic dike shows that the matrix is moderately sorted, angular quartzose sandstone (thin section no. 1765-9; Appendix I; Table A2 and A3). Some euhedral micas appeared to be frayed on the ends (Figure 24), which is a characteristic of Wetumpka's impactite sands (Rodesney, 2014).

The west end of HSR-2 is predominantly composed of Tuscaloosa Group, an impactite sand dike, and minor Eutaw Formation sediments. Impactite sand is intruded in the same fashion as on the eastern side of HSR-2; however, no clasts of Tuscaloosa or Eutaw were found in the dike. Instead, small, fist-sized clasts of grey, mica-bearing impact breccia are found within the Tuscaloosa at this location (Figure 25). These are suggested to be part of the proximal ejecta that landed on the overturned crater rim, and then were mixed into a transported unit of the Tuscaloosa Group.

Below the major Tuscaloosa unit in HSR-2 are smaller units of Eutaw Formation (Figure 26). These small exposures are interpreted to be parts of the underlying Eutaw Formation, which is associated with the synclinal fold on the east side of HSR-2. This hypothesis is consistent with a "trans-crater slide," during the early modification stage. Clastic impactite sand dikes are, again, contemporary to the trans-crater slide and suggest that the underlying impactite sand was squeezed up into the overlying Tuscaloosa and Eutaw.

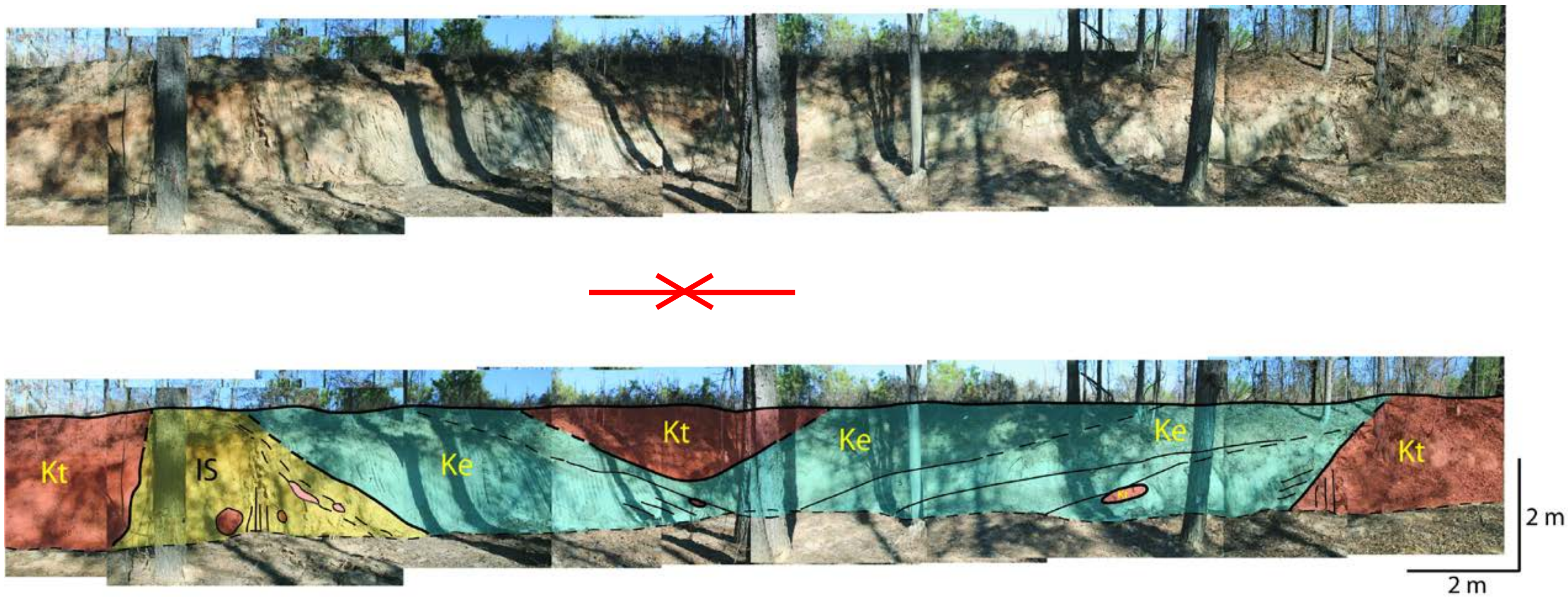

Figure 23: Photomosaics showing the eastern end of HSR-2. Upper photo: unmarked mosaic of the eastern end of HSR-2. Lower photo: marked and colored mosaic of the eastern end of HSR-2. Note synclinal fold (red arrows) with Tuscaloosa Group (Kt) overlying and underlying Eutaw Formation (Ke). Injected impactite sand (IS) is on the left with Tuscaloosa clasts completely enclosed within the unit suggesting an intrusive and interactive element to the impactite sand. Red is Kt; Blue is Ke; Yellow is IS; boundaries and bedding are marked with black lines.

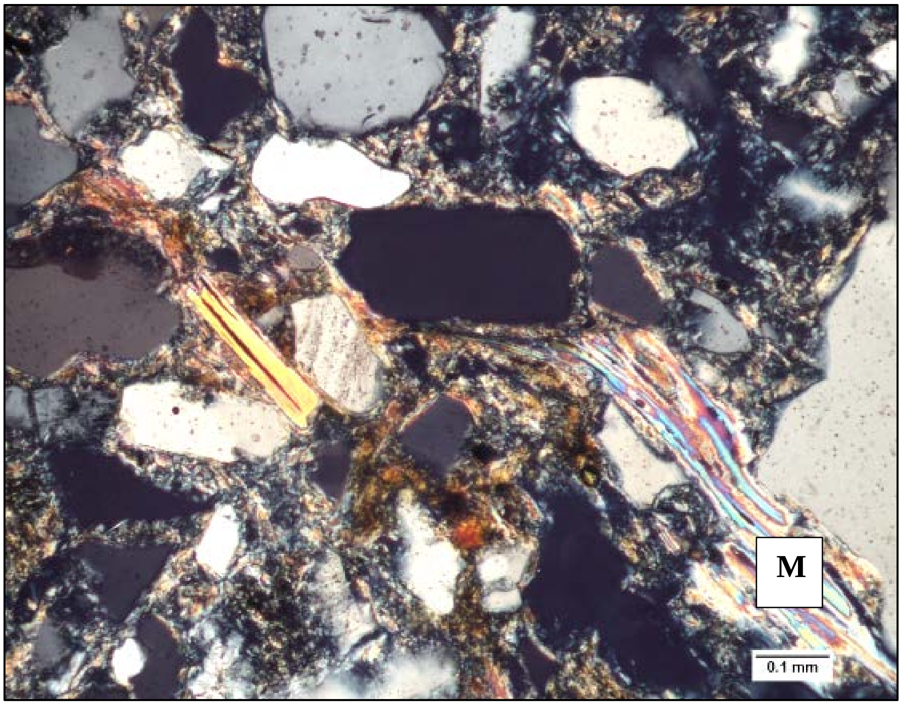

Figure 24: Photomicrograph showing impactite sand from HSR-2. Thin section number 1765-9. Note frayed mica (M) with minor mica occurrence in matrix. Photomicrograph taken in cross-polarized light (xpl).

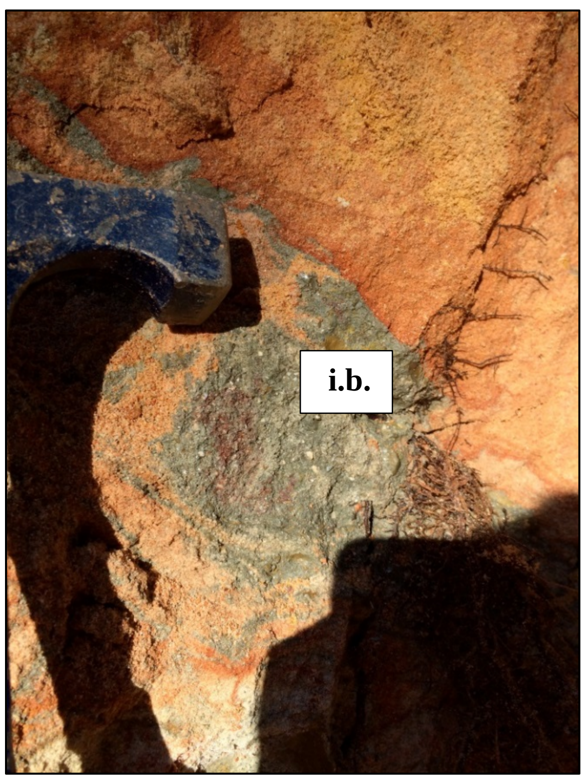

Figure 25: Outcrop photograph showing fist-sized clast of impact breccia (i.b.) within the Tuscaloosa Group at HSR-2. Hammer head (~ 8 cm) for scale.

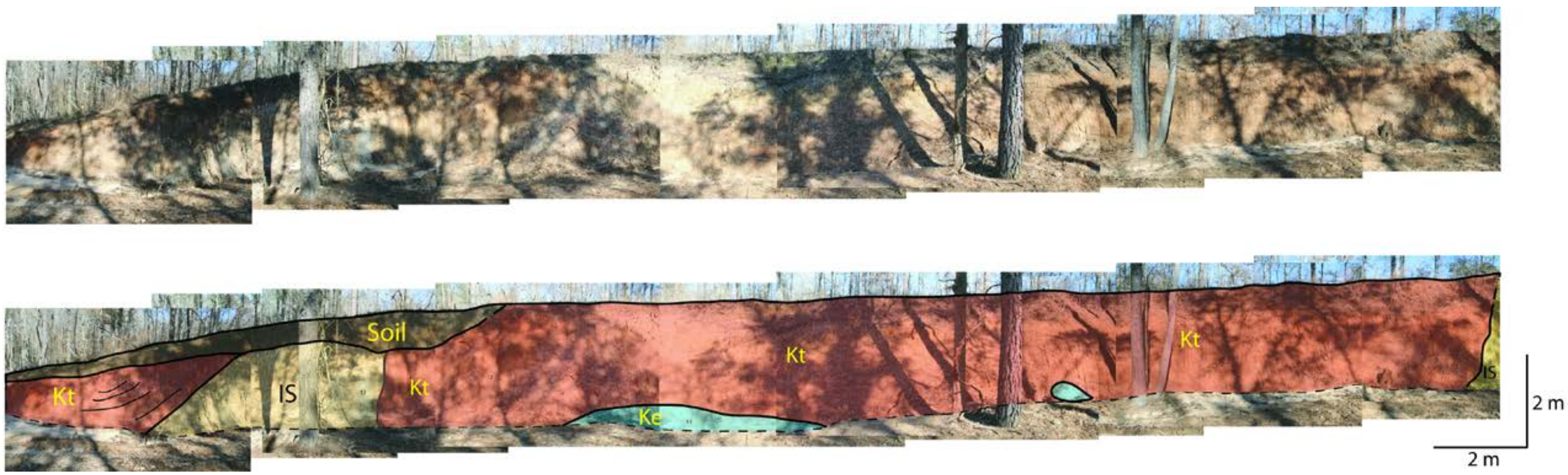

Figure 26: Photomosaic showing the western end of HSR-2. Upper photo: unmarked mosaic of the western end of HSR-2. Lower photo: marked and colored mosaic of the western end of HSR-2. Note Tuscaloosa Group (Kt) overlying small portions of Eutaw Formation (Ke). Injected impactite sand (IS) is on the left bounded by the Tuscaloosa Group suggesting an intrusive element to the impactite sand. Red is Kt; blue is Ke; yellow is IS; brown is soil; boundaries and bedding are marked with black lines.

The Buck Ridge Road portion of the half-transect includes exposures of the central breccia unit (CBU) (see Figure 38). In the main outcrop, central breccia unit extends for ~ 60 m on the east side and is ~ 2 m tall. It is exposed as matrix-supported, polymict impact breccia. It contains weathered clasts and blocks of metamorphic and sedimentary rock. At the base of this outcrop, drill-core 09-02 was drilled through the surficial polymict impact breccia. At an elevation of 122 m (400 ft), this drill-core revealed the top 5 m (16.4 ft) to be the same unit as outcropped on Buck Ridge Road.

Gravity-driven slumping is the mechanism King and Ormö (2011) to account for emplacement of the whole of the surficial shock-bearing deposits (Morrow and King, 2007) (i.e. central breccia unit) (King et al., in press). The central breccia unit may have moved into place as proximal ejecta that was rafted by the trans-crater slide or may have fallen back into the crater from some other part of the rim. The latter may be slightly favored because of its central position, which may have been protected from erosion by the trans-crater slide as it parted around the rising central bulge (see Figure 19).

Petrographic Analysis

Thin-section analysis of the Tuscaloosa Group, Eutaw Formation, and impactite sands provides a means of understanding the mineralogy of each unit. Using standard point-counting method, heavy and accessory minerals were included in point counts. On both heavy mineral thin-sections and cut samples, a diverse collection of minerals were revealed, including: magnetite, staurolite, tourmaline, heavily-fractured kyanite, orthopyroxene (i.e., hypersthene), detrital and euhedral zircon, and rutile. Details of petrographic analyses are given in the Appendix I (Tables A2 and A3).

Point counting data revealed an apparently similar mineralogy as Markin (in progress) and Rodesney (2014) (Figure 27, Figure 28, Figure 29). All samples were dominated by monocrystalline quartz (Qm). Secondary minerals were commonly polycrystalline quartz (Qp), mica (M), and weathered mica, clay, and hematite making up the matrix (Mtx) of all three units. Accessory minerals such as heavy and opaque minerals were classified as "other." Detrital and euhedral zircon were common in samples from each unit.

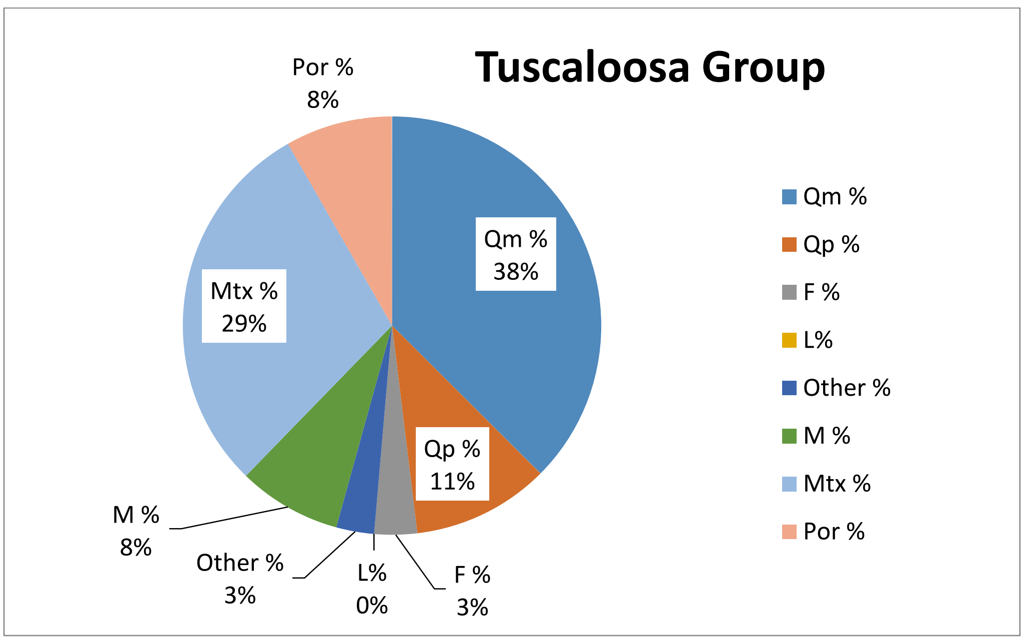

Figure 27: A pie diagram showing average point counts reduced to percentages for the Tuscaloosa Group samples (7 samples) collected from HSR-1 and HSR-2. Qm is monocrystalline quartz, Qp is polycrystalline quartz, F is feldspar, L is lithic fragments, Other is accessory minerals and opaque minerals, M is mica, Mtx is matrix, Por is porosity.

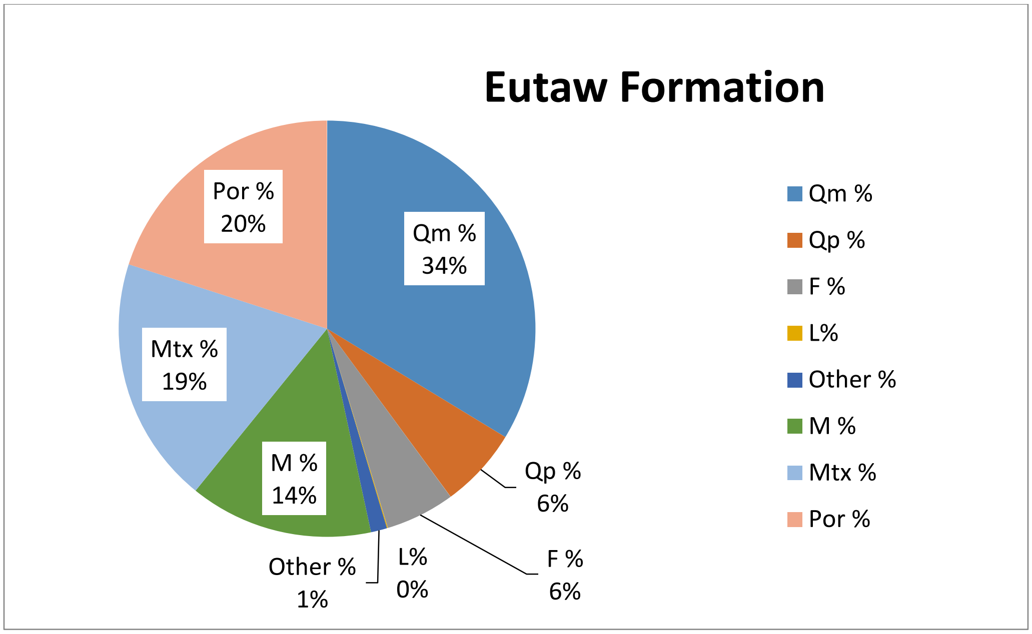

Figure 28: A pie diagram showing average point counts reduced to percentages for the Eutaw Formation samples (9 samples) collected from HSR-1 and HSR-2. Qm is monocrystalline quartz, Qp is polycrystalline quartz, F is feldspar, L is lithic fragments, Other is accessory minerals and opaque minerals, M is mica, Mtx is matrix, Por is porosity.

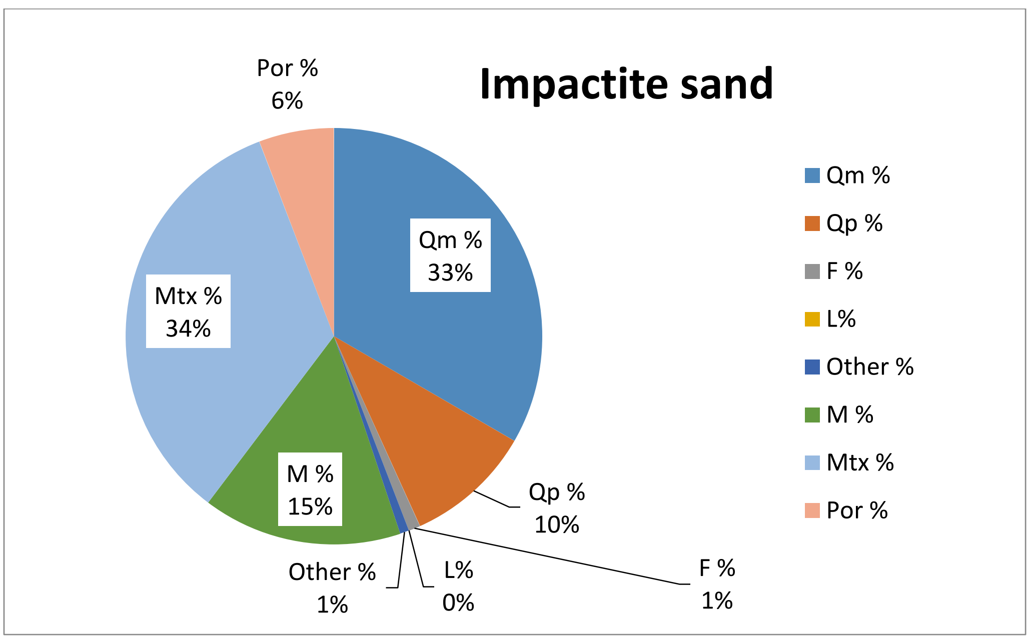

Figure 29: A pie diagram showing average point counts reduced to percentages for impactite sand samples (4 samples) collected from HSR-1 and HSR-2. Qm is monocrystalline quartz, Qp is polycrystalline quartz, F is feldspar, L is lithic fragments, Other is accessory minerals and opaque minerals, M is mica, Mtx is matrix, Por is porosity.

At Wetumpka, the Tuscaloosa Group was mottled silty to sandy, poorly sorted, subrounded quartzose sandstone. This unit was dominated by monocrystalline quartz, muscovite, and iron-oxide matrix. This matrix was mainly made of highly weathered quartz and muscovite. The Eutaw Formation was slightly more argillaceous than the Tuscaloosa. Matrix material was weathered, like the Tuscaloosa, but was more clay-rich. Weathered muscovite and quartz were commonly present within the matrix. Weathered feldspar was also common within the matrix. Grains appeared subangular to angular and moderately sorted. The impactite sand unit was a poorly sorted quartzose sandstone with weathered and euhedral muscovite within the matrix. Euhedral muscovite grains were commonly bent around quartz grains.

Accessory minerals were more common in the central breccia unit, followed by the Tuscaloosa Group, Eutaw Formation, and impactite sand. Weight percentages were calculated to assess the relative abundance of heavy mineral fractions of each sample (Figure 30). Furthermore, weight percentages of each magnetic fraction were calculated to assess the relative abundance of heavy minerals within a given magnetic fraction (Figure 31). Magnetic fractionation helped separate popular minerals; however it was common to find minerals from high magnetic fractions in lower magnetic fractions, and vice-versa. This is probably due to larger or smaller grains having affinity towards one particular magnetic fraction during the separation process. Knowing this, the percentage of each magnetic fraction within a sample is not accurate to determine the relative abundance of one fractional suite of heavy minerals compared to another fractional suite.

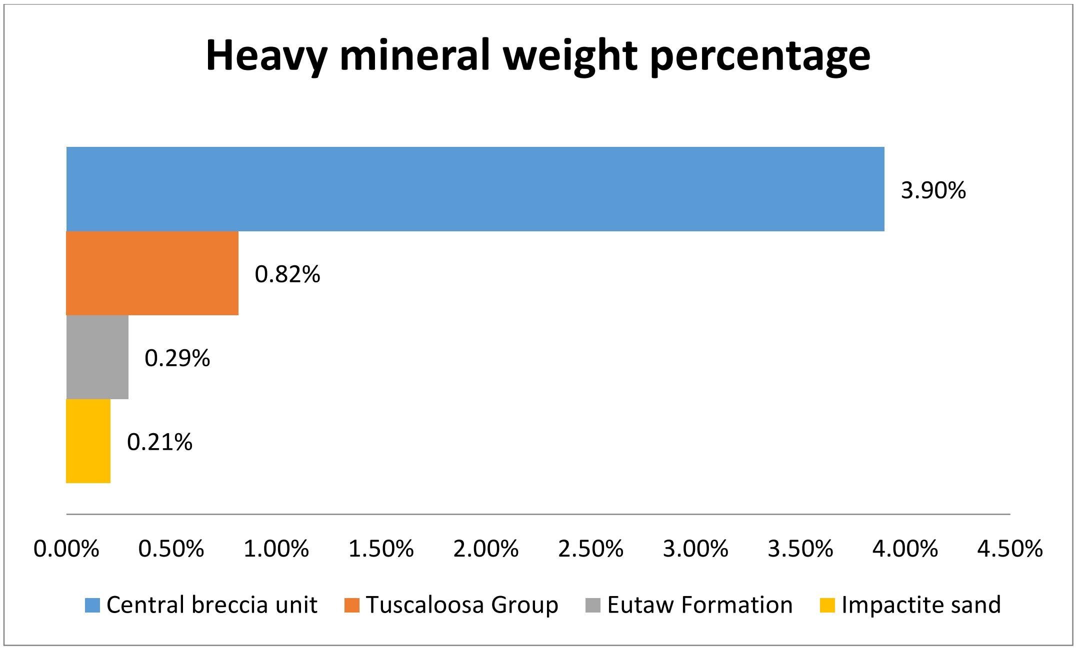

Figure 30: Bar graph showing heavy-mineral weight percentages for units discussed in text.

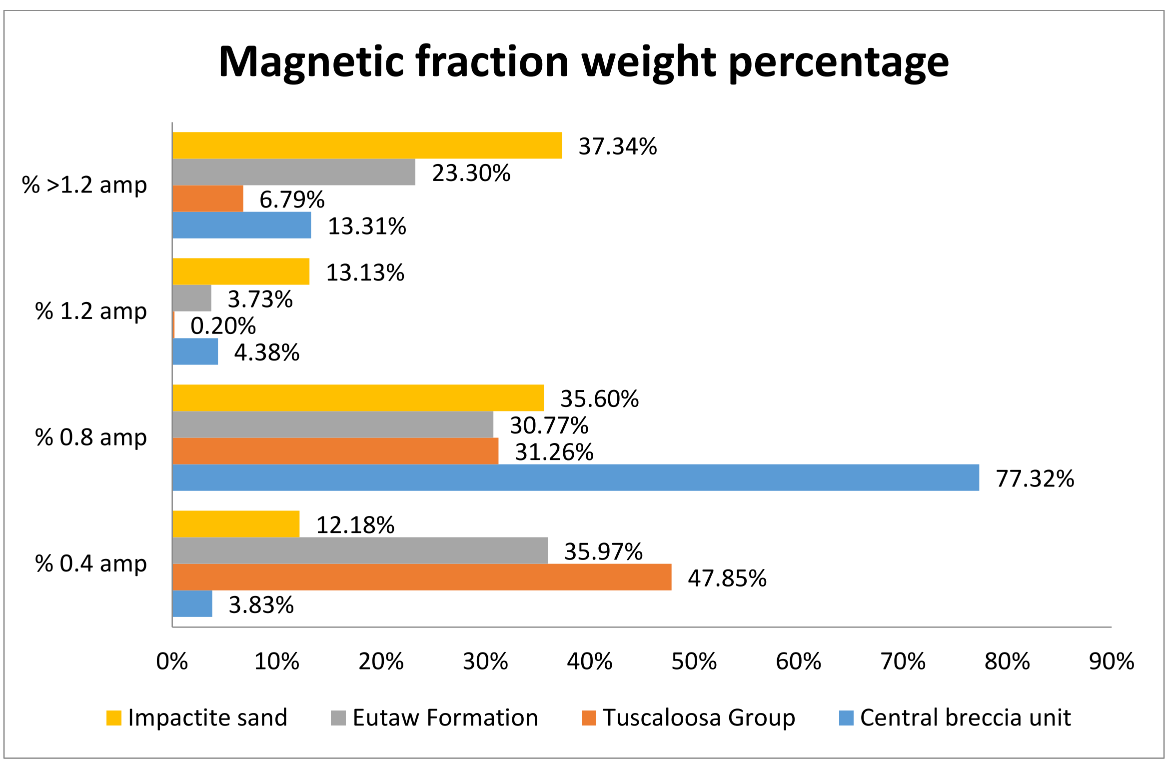

Figure 31: Bar graph showing magnetic fraction weight percentages for units discussed in text.

The following heavy-mineral assemblages are listed in the order of general abundance, with the exception of magnetite. The central breccia unit is dominated by staurolite, hypersthene, tourmaline, and kyanite along with biotite, muscovite, magnetite, and zircon. Mineral assemblages in the Tuscaloosa Group also include staurolite, hypersthene, and kyanite along with rutile, magnetite, and zircon. Mineral assemblages in the Eutaw Formation contain staurolite, kyanite, zircon, and rutile along with muscovite and magnetite. The impactite sand heavy-mineral assemblage includes abundant rutile, kyanite, zircon, tourmaline, and staurolite along with muscovite and magnetite. In each sedimentary formation, the most abundant heavy minerals, excluding magnetite, were staurolite and kyanite. Units and frequently encountered grains, occupying > 30% of their magnetically separated fraction are presented in Table 2. Zircons were minimal in each unit. Heavy mineral grains from the Tuscaloosa 'C' fraction were too few to be mounted by National Petrographic Service; however weight percentages for this fraction and all other sample fractions are located in Figure 31.

Table 2: Most common heavy minerals from each separated unit and respective magnetic fraction.

	A **0.4 amp**	**B** **0.8 amp**	**C** **1.2 amp**	**D** **>1.2 amp**
Central breccia unit	Magnetite	Staurolite Hypersthene Biotite	Tourmaline Muscovite	Kyanite Zircon
Tuscaloosa Group	Magnetite	Staurolite Hypersthene	No minerals in thin-section	Kyanite Rutile Zircon
Eutaw Formation	Magnetite	Staurolite	Muscovite	Kyanite Zircon Rutile
Impactite sand	Magnetite	Staurolite	Tourmaline Muscovite	Rutile Kyanite Zircon

Roundness and angularity of each popular heavy-mineral component were similar between the four samples. Staurolite and hypersthene were typically more rounded than kyanite and rutile crystals which exhibited more angularity along with magnetite. Tourmaline was typically subangular.

To further understand the implications of each heavy mineral phase, more time is needed to quantify and analyze samples from Wetumpka. Most common minerals presented in this thesis are to be treated as general overview for heavy mineral suits encountered in the intra-crater units. There is good evidence presented here that the metamorphic basement contributed to the sands in some way. Heavy minerals are more abundant in the central breccia unit, followed by the Tuscaloosa Group, Eutaw Formation, and then impactite sand. Knowing this, it is hypothesized that catastrophically rafted proximal ejecta (i.e., central breccia unit) were derived more from the metamorphic basement, which contributed to the different heavy mineralogy.

Drill-core logging results

The purpose of measuring and documenting the units in drill-core 09-02 and 98-01 was for comparison, whereas incorporating the ~ 2 m surficial polymict impact breccia outcrop on Buck Ridge Road, to illustrate a shallow, detailed correlation between each element due to their close proximity, whereby physical relationships between the sedimentary and proximal ejecta units in the central area of the crater can be understood. Notes from drill-core 09-02 can be seen in Appendix III (Table 5). Original 98-01 drill-core interpretations were made by Johnson (2007).

Drill-core 09-02. The upper portion of this core, below 0.457 m, is sheared polymict impact breccia schist blocks, similar in lithology to what is found in outcrop on Buck Ridge Road. Below schist blocks, in order, are sections of saprolitic gneiss, injection type impactite sand, Kowaliga Gneiss, Tuscaloosa Group, impactite sand, Tuscaloosa Group, impactite sand, suevitic impact breccia, Eutaw Formation, Tuscaloosa Group, and finally impactite sand to the end of the core. Table 3 shows the depth transitions and thicknesses of the lithologies encountered.

Table 3: A simple table showing lithologies, depth transitions, and thicknesses in meters for drill-core 09-02.

Drill-core 09-02			
From (m)	**To (m)**	**Thickness (m)**	**Lithology**
0	0.457	*0.457*	Not cored
0.457	4.90	*4.44*	Schist blocks
4.90	5.16	*0.26*	Gneiss blocks
5.16	6.25	*1.09*	Impactite sand
6.25	10.47	*4.22*	Gneiss blocks
10.47	10.91	*44.20*	Tuscaloosa Group
10.91	11.73	*82.30*	Mixed interval (Tuscaloosa/impactite sand)
11.77	13.43	*1.66*	Impactite sand
13.43	13.63	*0.20*	Tuscaloosa Group
13.63	13.93	*0.30*	Impactite sand
13.93	14.14	*0.21*	Impact breccia
14.14	14.44	*0.30*	Tuscaloosa Group
14.44	14.71	*0.30*	Impactite sand
14.71	17.22	*2.51*	Impact breccia
17.22	18.75	*1.53*	Eutaw Formation
18.75	20.95	*2.20*	Tuscaloosa Group
20.95	23.31	*2.36*	Impactite sand

Drill-core 98-01. Originally, Johnson (2007) interpreted large amounts of the upper 80 m of this drill-core to be Tuscaloosa Group. By revisiting the core, portions of units originally called Tuscaloosa, are now known to be impactite sand. Table 4 shows the depth transitions and thicknesses of the lithologies encountered.

Table 4: A simple table showing re-classified lithologies, depth transitions, and thicknesses in meters for drill-core 98-01. Original core-logging was done by Johnson (2007).

Drill-core 98-01			
From (m)	**To (m)**	**Thickness (m)**	**Lithology**
0	31.94	*31.94*	Not cored
31.94	33.07	*1.13*	Tuscaloosa Group
33.07	34.35	*1.28*	Not recovered
34.35	34.64	*0.29*	Tuscaloosa Group
34.64	35.94	*1.30*	Not recovered
35.94	36.20	*0.26*	Impactite sand
36.20	37.49	*1.29*	Not recovered
37.49	39.17	*1.68*	Impactite sand
39.17	41.33	*2.16*	Tuscaloosa Group
41.33	42.21	*0.88*	Not recovered
42.21	44.90	*2.69*	Tuscaloosa Group
44.90	45.38	*0.48*	Impactite sand
45.38	53.54	*8.16*	Tuscaloosa Group
53.54	53.77	*0.23*	Impactite Sand
53.77	54.32	*0.55*	Tuscaloosa Group
54.32	54.41	*0.09*	Impactite sand
54.41	66.52	*12.11*	Not cored; King's drilling notes document: "mica in water; sand and clay; gray clay chips coming up."
66.52	72.85	*6.33*	Eutaw Formation
72.85	72.95	*0.10*	Impactite sand
72.95	73.06	*0.11*	Tuscaloosa Group
73.06	73.41	*0.35*	Impactite sand
73.41	74.05	*0.64*	Not recovered
74.05	75.47	*1.42*	Impactite sand
75.47	80.01	*4.54*	Tuscaloosa Group

Tuscaloosa Group megablocks dominated the upper ~ 54 m of 98-01. Impactite sand was encountered in an incoherent, alternating fashion within the upper Tuscaloosa megablock, and these occurrences were not extensively thick (< 2 m). A 6.33 m thick section of Eutaw Formation was logged at a depth of 66.52 m. Thereafter, the same sequencing of Tuscaloosa and impactite sand see in the upper ~ 54 m is encountered to a depth of 80.01 m. Refer to Johnson (2007) for a complete drill-core log of 98-01.

Drill-core comparison. Figure 32 shows the correlation between drill-core 09-02 and 98-01. The overlap between 09-02 and 98-01 is ~ 1.65 m. Drill-core 09-02 has impactite sand at the bottom of the drill-hole (23.31 m), which overlaps with a 11.28 m thick section of Tuscaloosa Group at 31.94 m depth in drill-core 98-01.

The close proximity of both of these drill-cores shows the relationship between units in the center of the crater. Impactite sand occurs within schist, Kowaliga Gneiss, impact breccia, Tuscaloosa Group, and Eutaw Formation megablocks located at the geographic center of the crater. No distinctive overturned rim flap stratigraphy (i.e., Tuscaloosa-Eutaw-Tuscaloosa) is observed between the two drill-cores.

Deformation features seen in both drill-cores include impactite-sand injection dikes as well as hydraulic flow textures that occur among various lithologic boundaries. Impactite sand injections cross-cut bedding planes and deform surrounding lithologies intrusively. These injections are emplaced through sediment mixing and contemporary liquefied clastic injections occurring in a combination of directions through weak and fractured block layers. Intrusive impactite sand units have different sorting and grain size than surrounding units (Figure 33 and Figure 34). Flow textures are developed between units in contact with impactite sand (Figure 35 and Figure 36). These physical relationships are interpreted to be related to the reduced strength of overlying units, post-impact, and the aqueous nature of the impactite sand unit. Shearing in the polymict impact breccia schist (Figure 37) in drill-core 09-02 is interpreted to be resultant of mass wasting processes whereby units are internally deformed by sliding past one another on susceptible bedding planes.

Crystalline breccia lying above Tuscaloosa and Eutaw block sequences in 09-02 are interpreted as proximal ejecta from the excavation stage. Ejecta above these sedimentary block sequences in the center of the crater are indicative of the mass movement of material from outside to inside the crater.

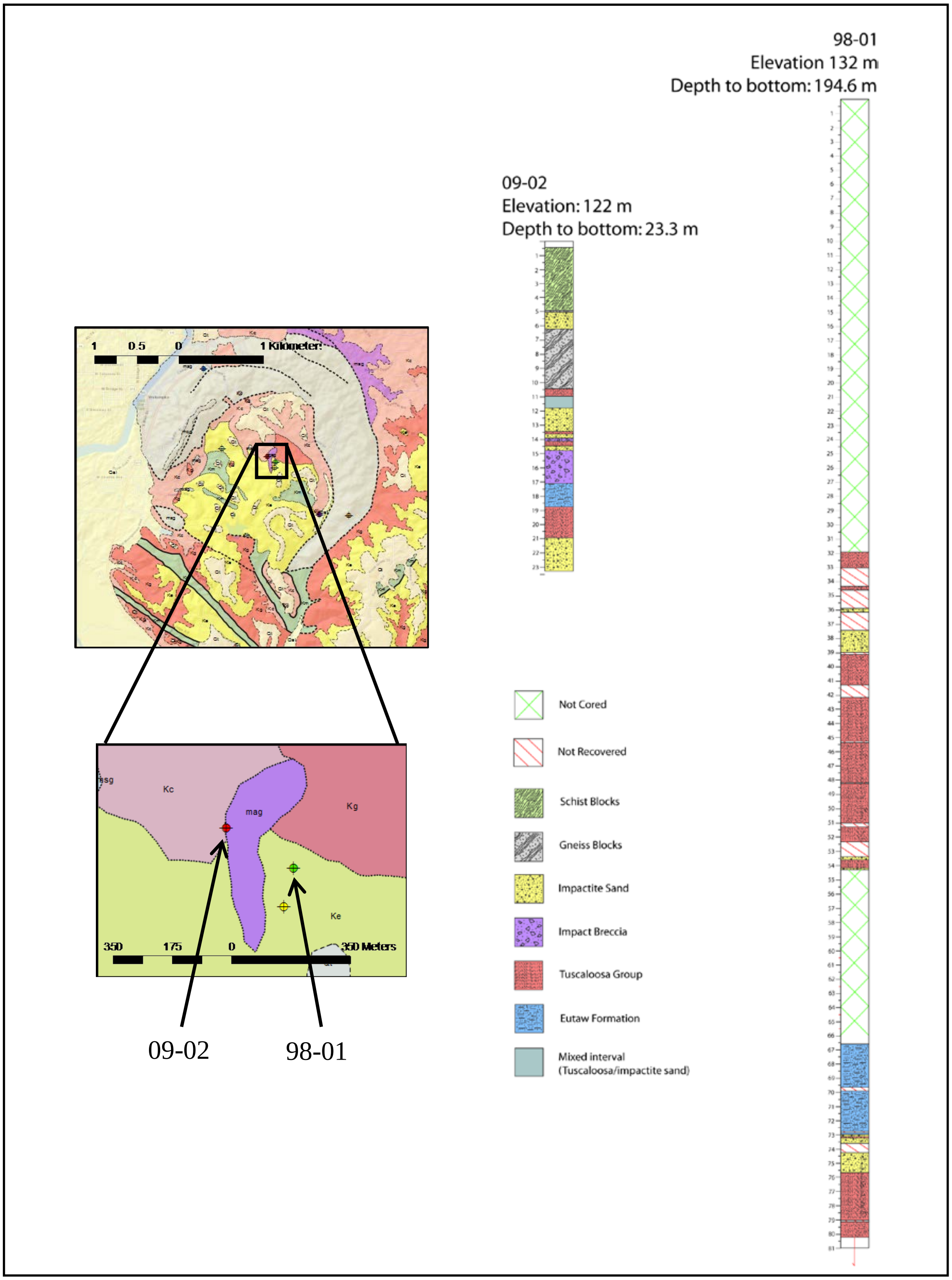

Figure 32: Correlation of drill-cores 09-02 and 98-01. Drill-cores are positioned according to the elevation of the top of each core-hole. There is no lithic datum. Difference in elevation is 10 m. Inset geologic map of Wetumpka shows drill-core locations.

Figure 33: Short section of drill-core 09-02. Depth is 5 m. Note fine grained impactite sand injection (left) cross cutting weathered gneiss (right). Centimeter scale on left.

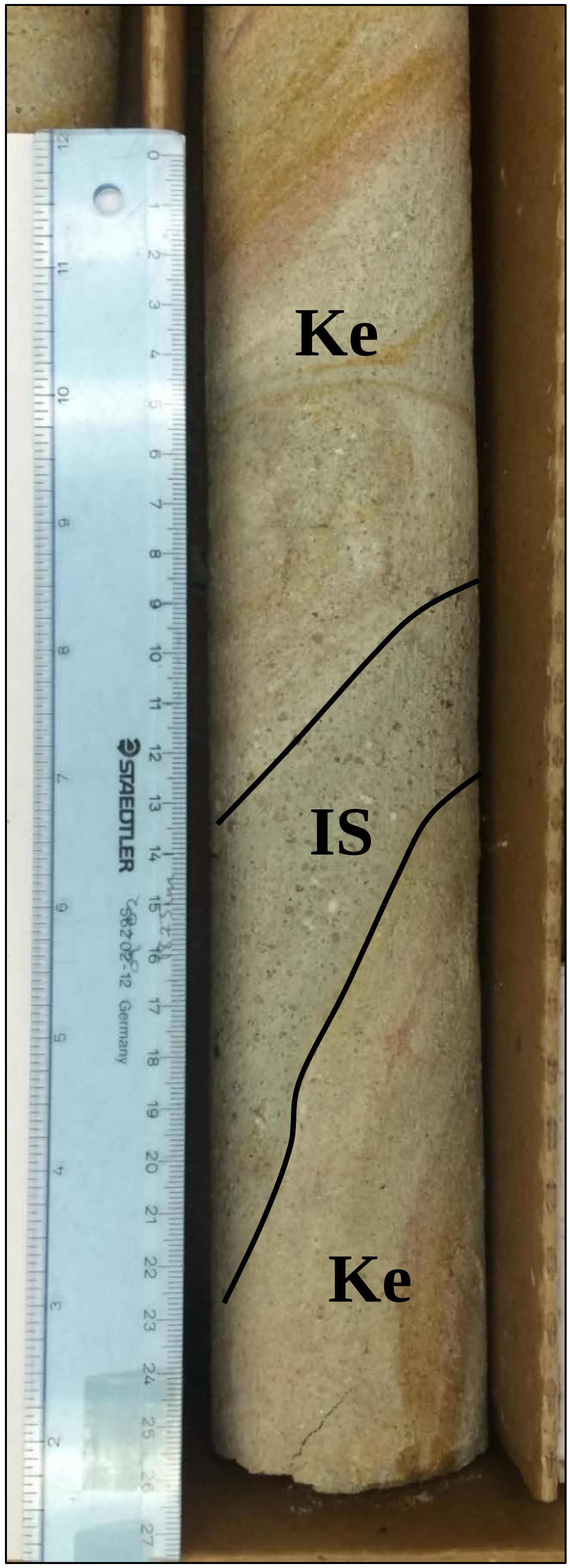

Figure 34: Short section of drill-core 09-02. Depth is 18.23 m. Note the fine-grained Eutaw Formation unit (Ke) surrounding impactite-sand injection (IS). Eutaw sands appear to be folded and deformed to accommodate the dike injection. Scale is in cm and inches on the left.

Figure 35: Short section of drill-core 09-02. Depth is 11.77 m. Note flow textured structures within coarser grained impactite sand (left). Scale is in cm and inches on the left.

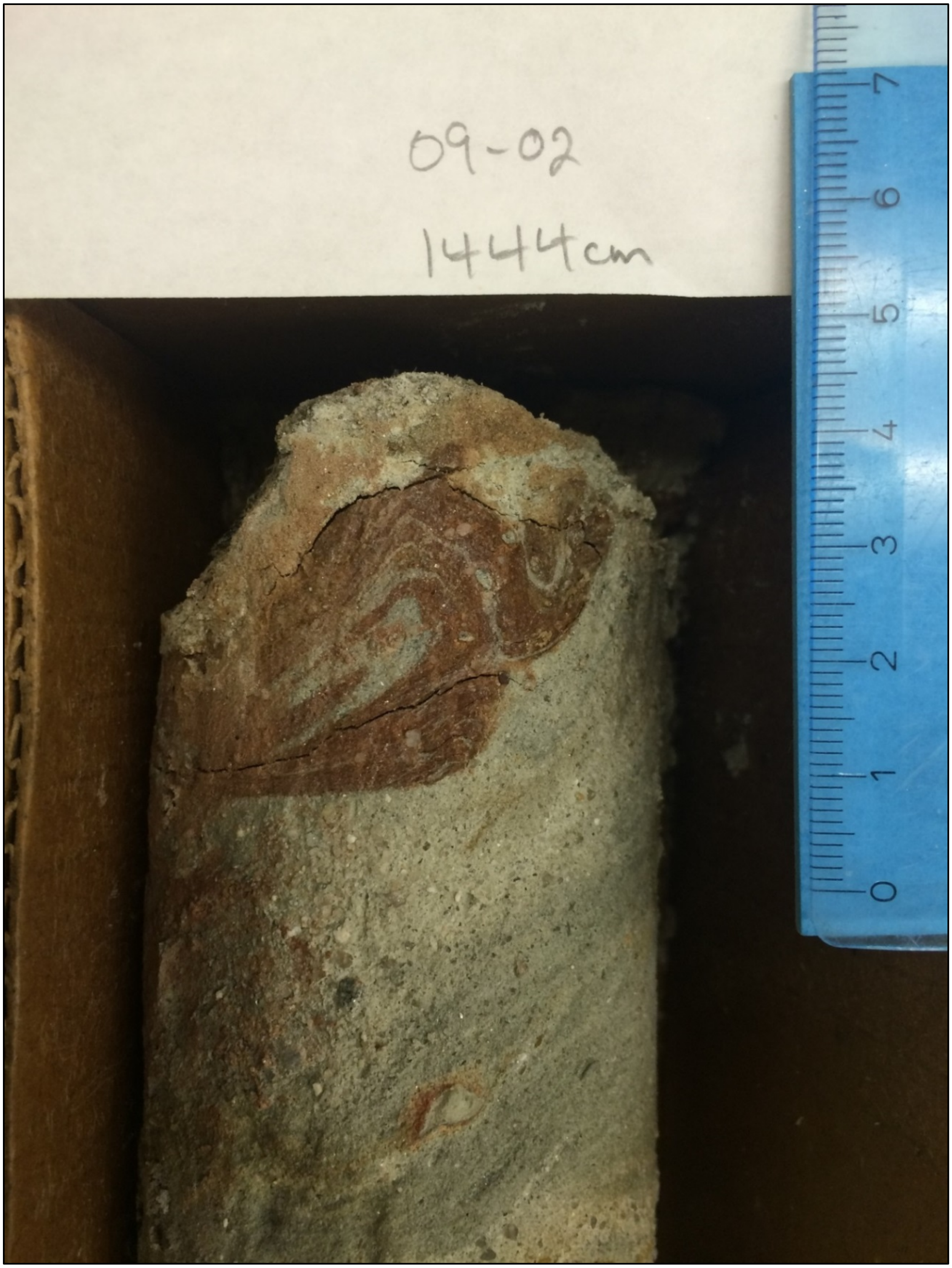

Figure 36: Short section of drill-core 09-02. Depth is 1444 cm (14.44 m). Note deformed Tuscaloosa clay overbank clast (red) above impactite sand. Scale is in cm and inches on the right.

Figure 37: Short section of drill-core 09-02. Depth is 2.14 m. Saprolitic, foliated muscovite schist. Note small inconsistent phacoids in foliation dipping at 80°; direction of dip unknown. Scale is in cm on the left.

Geologic half-transect

The data gathered from field mapping, outcrop description, and drill-core study and comparison provide sufficient clues for which a geologic half transect is made (Figure 38). This section will relate each unit and structure to one another as they occur, from northwest to southeast, along the half-transect. This half-transect starts in the northwestern crystalline rim and ends near the geographic center of the crater.

The northwestern end of the half-transect is entirely crystalline rim. Outcrops such as Station 30 (Appendix II; Table A4), located in the most northwestern end of the half-transect, expose massive, northwest dipping, biotite-muscovite-quartz schist. Moving southeast on the half-transect, rim rocks maintain dip direction but become increasingly weathered and saprolitic.

Crystalline blocks are first encountered at points of lower elevation beyond Bald Knob. Crystalline block exposures are composed of biotite-muscovite-quartz schist clasts within Eutaw Formation sediments. Clasts are pebble to boulder-sized and contain garnet. These clasts are interpreted to be related to the basal Josie Leg Member of the Emuckfaw Group lithology. Clasts and bedding in the crystalline block terrain are incoherently oriented.

To the southeast, along the electric line cut, the boundary between the crystalline block terrain and Eutaw megablocks is an inferred boundary where exposures of Eutaw Formation are established. These megablocks dip in a southeast-southwest direction (Station 33 and 34; Appendix II; Table A4).

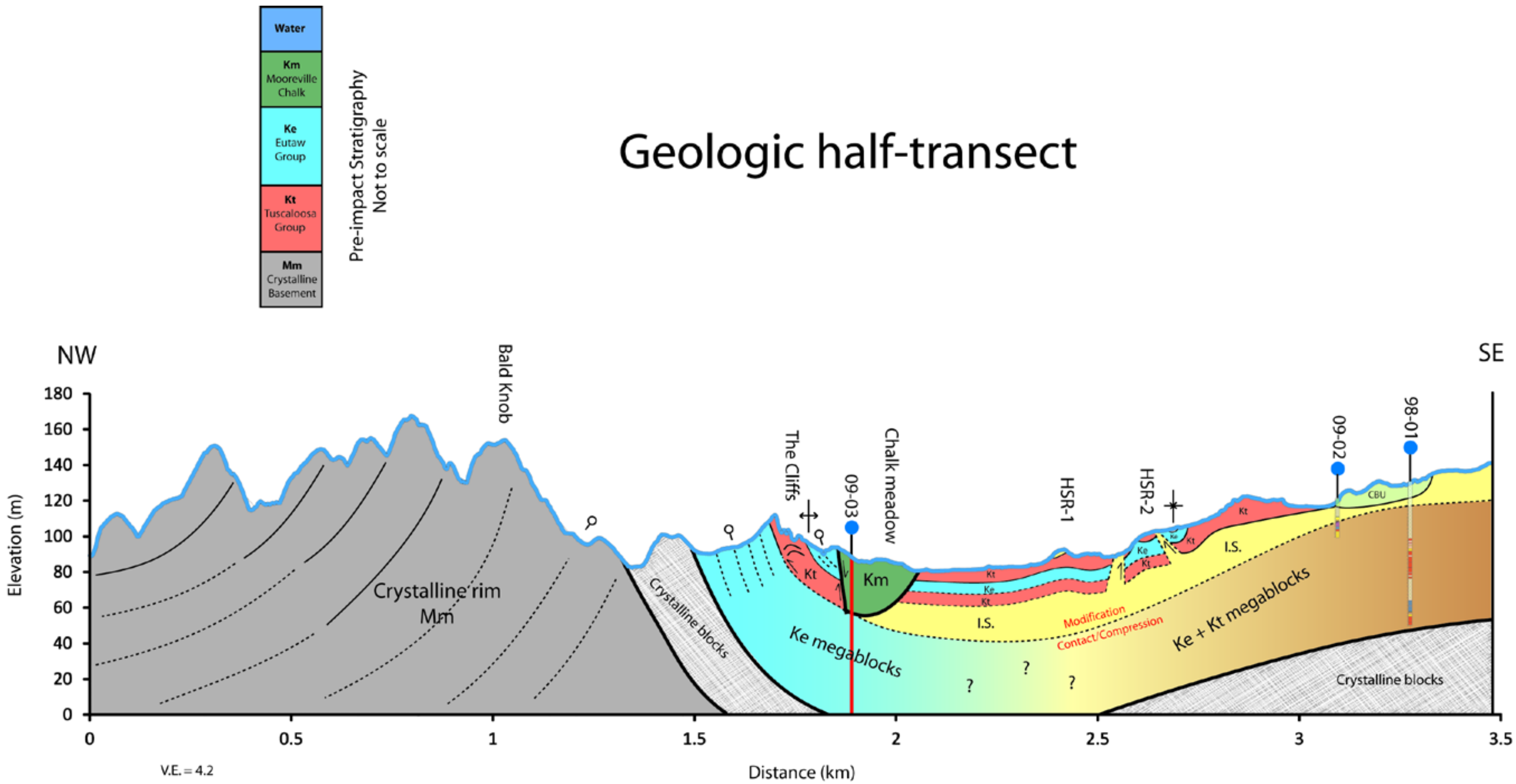

Figure 38: Interpretative geologic half-transect of Wetumpka impact structure, as described in text. Structures and dip directions are indicated with arrows and tadpoles, respectively.

The Cliffs is an exposure showing large units of overturned Tuscaloosa Group and Eutaw Formation, with marginal impactite sand. Units are internally deformed and extensively eroded exposing Eutaw sediments below the Tuscaloosa Group in a southeasterly plunging parasitic antiform. In the half-transect, plunging Tuscaloosa Group folds are marked to the northwest of southeasterly dipping Eutaw sediments.

Southeast of The Cliffs, redeposited Mooreville Chalk exists in a half-graben structure. Information about the depth of the Mooreville Chalk in the chalk meadow is documented in core-log 09-03 created by Markin (in progress). The depth at which the redeposited Mooreville extends is 24.5 m. Below this depth, Eutaw megablocks were drilled to a depth of 90 m. The position of the half-graben chalk meadow with respect to The Cliffs is related to extensional down faulting at the base of the laterally spreading trans-crater slide that compressionally thrust itself against the base of the northwestern crater wall where the slide ceased movement. Highland and Bobrowsky (2008) note that in rock spreads, solid ground extends and fractures, pulling away from stable ground, moving over weaker layers. The extensional half-graben suggested by Markin (in progress) is demonstrated better with constraints about on the overall structure seen at The Cliffs as well as information about laterally spreading, mass movement, mechanisms.

East of the chalk meadow on Harrogate Springs Road is Tuscaloosa Group sediments followed by HSR-1. At this outcrop, steeply inclined (30°NW; see Figure 21) Tuscaloosa sedimentary megablocks fine upward and are juxtaposed on the western side of the outcrop by structureless impactite sand.

At the east end of Harrogate Springs Road toward the junction with Buck Ridge Road is HSR-2. This outcrop exposes deformed units of Tuscaloosa and Eutaw sediments. Clastic impactite sand dikes cross-cut both units and are exposed at ground level. The eastern end of HSR-2 exhibits a shallow, northeast plunging synclinal fold with Tuscaloosa occurring above Eutaw sediments. The overturned rim sequence is shown very clearly in HSR-2. Underlying Eutaw unit thicknesses are unknown, but speculations can be made based on what is shown at HSR-2.

The Buck Ridge Road outcrop to the south of the junction with Harrogate Springs Road exposes the central breccia unit near the geographic center of the crater. Drill-cores 09-02 and 98-01 are 10 m apart and located in this area of the crater as well. By incorporating the Buck Ridge outcrop and hanging the drill-cores on their true elevation on the half-transect, the shallow subsurface in the center of the crater is put into perspective. From top to bottom, drill-core 09-02 showed slumped blocks of schist, Kowaliga Gneiss, Tuscaloosa Group, impact breccia, and Eutaw Formation. Thin impactite sand units occur between and below these blocks. Drill-core 98-01 was dominated by slumped Tuscaloosa and Eutaw sedimentary megablocks with thin sections of impactite sand.

Inferred boundaries between overlying impactite sand and underlying Eutaw and Tuscaloosa megablocks is drawn based on the relationships between both drill cores. This inferred boundary is used in the northwestern portion of the half-transect to account for thicker impactite sand units (> 20 m) in the “moat” of the crater that were documented in drill-core 09-04 (Rodesney, 2014).

DISCUSSION

This thesis focuses on the systematic analysis of crater-filling sediments by conducting field work to produce a geologic cross section (half-transect) through the northwestern interior of Wetumpka impact structure. Thus, the timing of impact-related events and mega- and microscopic features will be related to understand the dynamics of the syn- and post-impact modification events. In addition, Wetumpka will be compared to other terrestrial impact craters to establish analogous features. Interpretations of results will overlap to some extent because one interpretation may depend partly on aspects of others.

The following is a discussion of the proposed sequence of events for the Wetumpka impact structure based on data collected. Because of the target and paleogeography, these events are unique to other impacts. Figure 39 illustrates a simplified conceptual model described in this section showing different sedimentary processes active at different stages of Wetumpka impact crater sedimentation.

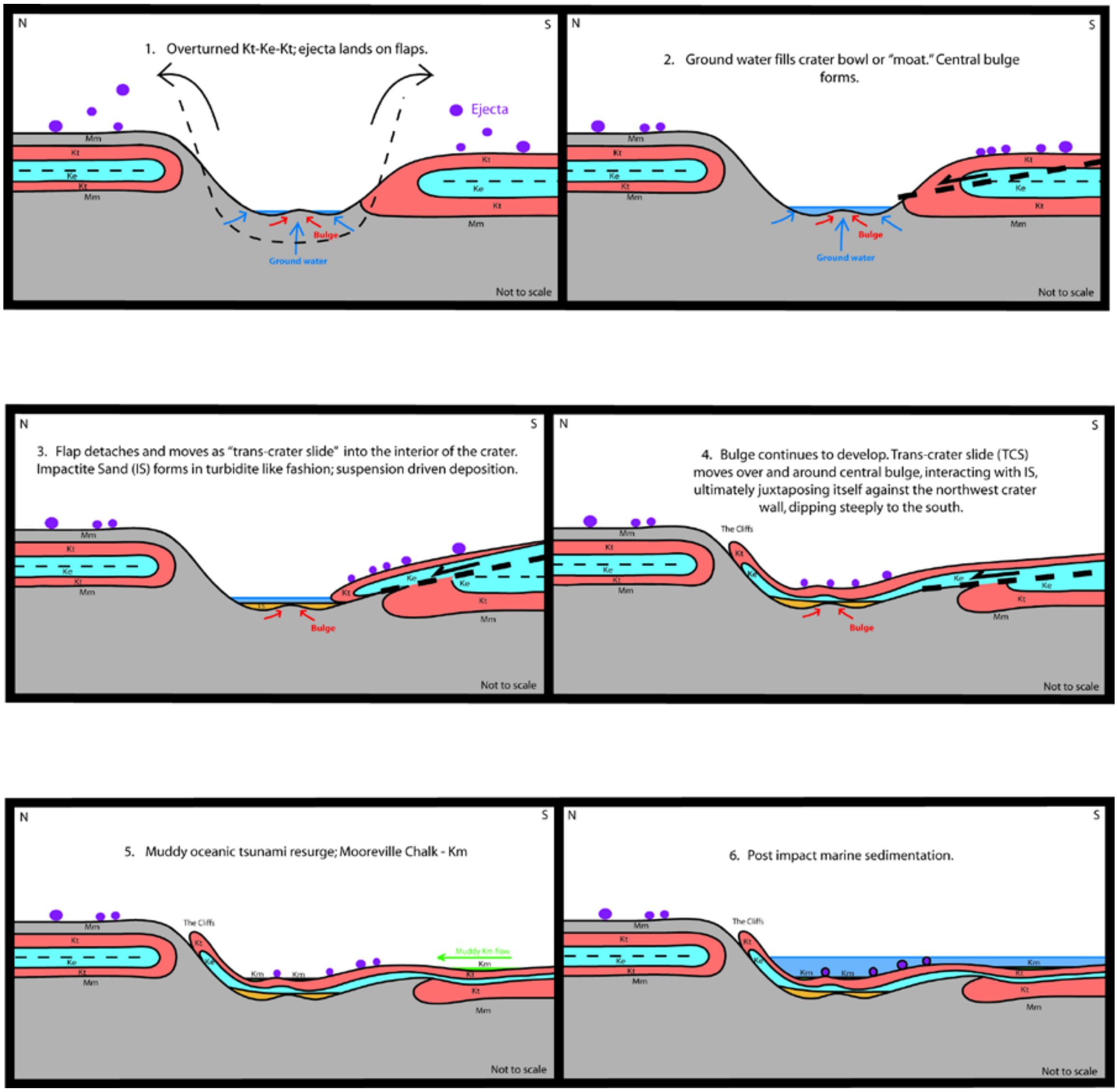

Figure 39: Simplified conceptual model showing different sedimentary processes active at different stages in cross sections, as explained in the text. Not to scale. North is left, south is right.

Wetumpka is characterized by a wide, horseshoe-shaped crystalline rim, an interior region of broken and disturbed sedimentary formations, and an exterior terrain on the south and southwest composed of structurally disturbed, sedimentary target formations (King et al., 2002; 2003; King and Ormö, 2011). A semi-complex crater is one that is on the "boundary" between a simple and a complex crater. Wetumpka's basement has been studied to determine its extent, but no "textbook" central peak has been found to make it as a classic complex crater.

To reconstruct the Wetumpka impact scenario, it is assumed the water layer was excavated in the contact and compression stage along with the sediment and crystalline rocks at Wetumpka, owing to a paleowater depth that was significantly less than the diameter of the impactor (Ormö et al., 2002).

After brief contact and compression, the excavation stage begins and creates overturned rim flaps on all edges of the crater rim (Figure 41). In the marine environment, a fresh crater's rim is ephemeral and would be rapidly reduced by the removal of the water layer under the overturned flap, and by dewatering and compaction of sediments (Figure 39.1). Shallow excavation flow prior to crystalline flap deposition would also generate slightly lower fresh crater rim than would be expected with a dry target (King et al., 2006).

The sedimentary thickness over the crystalline basement should have been slightly less on the northern side than on the southern side due to the previously mentioned slope of the offshore shelf and slightly greater water depth (King et al., 2006). Therefore, in the northern portion of the target, the sedimentary rock units formed less volume of the rim than on the south. In the southern target area, the sedimentary units probably made up significantly more of the overturned flap because they were thicker. Ejecta flying out of the crater after rim formation will land on top of the overturned rim flap around the entire crater. Overturned flap stratigraphy, in the northern rim, from top to bottom, would have been Mm-Kt-Ke-Kt-Mm, with Eutaw sediments doubled in thickness. In the southern rim, flap stratigraphy from top to bottom would have been Kt-Ke-Kt. Again, Eutaw sediments are doubled in thickness. In research well 09-04, the documented stratigraphy is consistent with the overturned flap sequence of Kt-Ke-Kt (Markin, in progress).

During the later portion of the excavation stage, ground-water recharge began to fill the crater bowl (Figure 39.2 and Figure 41). Evidence for groundwater filling the crater bowl is documented from drill core 09-04. Rodesney (2014) found a series of fining-upward sequences in the impactite sands. Impactite sands must have formed in the way a turbidity flow forms: settling into water. Sands that formed the impactite sands are related to Tuscaloosa and Eutaw sedimentary blocks that slumped into the water filled crater. The fining-upward sequence in impactite sands in 09-04 suggests that crater-filling water was present and was a factor in the early modification of the crater interior. No shocked grains are found in this impactite sand, suggesting that this material probably did not come from the basement (Rodesney, 2014).

At Wetumpka, a semi-complex crater shape formed and a small central “bulge” develops. The “bulge” rises simultaneously with the formation of the overturned flap and ejecta excavation (Figure 41). The term “bulge” is used to make the distinct notion that Wetumpka does not have a clearly defined central peak, as is characteristic of true complex craters. One line of evidence is seen in 09-04 where the impactite sand sequence is much thicker (> 20 m) than the (~ 1.7 m) impactite sand sequence in 09-02. Drill-core 09-04 is located in what would be the “moat” of the crater interior, while 09-02 is above the area where the central bulge is thought to have been located. Thinner impactite sand above the central bulge suggests there was coeval growth of the central bulge because there was no time to erode 10s of meters of impactite sand off the crater center prior to emplacement of overlying units.

In the target south, detachment of the unstable, water-saturated sedimentary rim starts the process of gravity sliding of these south-southwestern rim sediments back into the crater interior as a giant “trans-crater slide” (TCS). A TCS would theoretically move this collapsed portion of the rim to the north-northeast. The upper 90 m of drill-core 09-04 displayed this displaced, overturned rim sequence (Markin, in progress). Due to the influence of pore water on sedimentary layers of the southern rim, the southern sector of the fresh crater rim would have collapsed almost immediately (Figure 41) (King et al., 2006). Blocks of crystalline rock occur today near the crater center (i.e., the central breccia unit) are interpreted to be fragments of crystalline ejecta that were catastrophically rafted on top of the sliding rim flap and/or were gravity-driven into the crater interior separately.

The TCS moved the southern overturned rim flap into the crater because of a presumed detachment fault (Figure 39.3). Blocks of the TCS retained their coherent sequential structure, while others are internally deformed and/or broken. This is seen in the intra-crater terrain where units do not sustain original thickness and are chaotically oriented and fractured (i.e., The Cliffs and Harrogate Springs Road). Mass-wasting mechanisms such as lateral spreads coincide with what is seen in the crater interior. Solid ground detached, extended, fractured, pulling away from stable ground and moved over weaker layers (i.e. impactite sand unit) (Highland and Bobrowsky, 2008). The southern rim is the only breach in the morphology of the crater today. Outside this breached area, the geology is described as “disturbed,” and referred to as the “extrastructure terrain” (King and Ormö, 2011). The structural disturbance of this area (i.e., numerous NW-SE faults) is attributed to basal effects the breaching of the rim and subsequent basal slide into the interior of the crater. In this terrain, large blocks of target rocks have been rotated, slumped, and disturbed without evidence of substantial lateral transport. In this terrain, sets of extensional horst-and-graben structures have developed with a general strike tangential to the crater rim (King et al., 2003). These kinds of relationships are encountered in various places throughout the extrastructure (or disturbed) terrain (King and Ormö, 2011) (Figure 40).

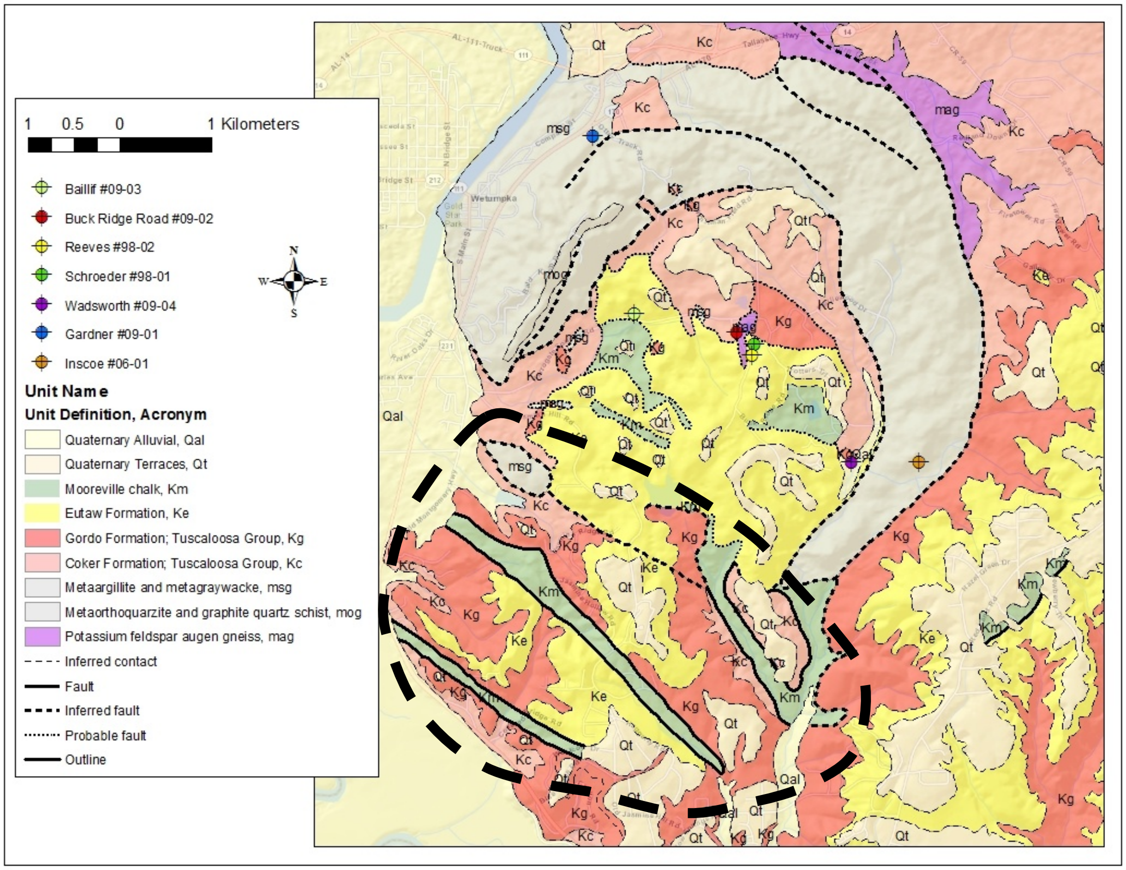

Figure 40: Geologic map of Wetumpka impact structure. Note the missing southern rim and in its place (left) the "extra-structure" terrain (outlined with dashed black line).

This terrain is different from the Wetumpka surficial unit, which occurs only within the confines of the crystalline rim, principally because this extrastructure terrain lacks the impactite sands. In addition, the redeposited Mooreville Chalk (i.e., the uppermost target unit) is more abundant in the exterior terrain versus inside the crater bowl. The exterior disturbed terrain is an integral part of the impact structure. The overall shape of the Wetumpka impact structure is more like an inverted baseball cap (versus the “inverted sombrero” shape from the Chesapeake Bay impact structure where the disturbed terrain is a 360° rim around the crater; Horton et al., 2006) (King and Ormö, 2011).

Because Wetumpka is believed to be a “semi-complex” crater, on the boundary between a simple and a complex crater, the TCS is obstructed by the rising “bulge” in the center of the crater. The bulge is suggested to be a relatively minor oscillatory rebound of the center of the crater due to the target’s rheological properties (Melosh, 1989). The TCS would has been diverted to the northwestern portion of the crater wall by the central bulge (see Figure 19), whereby moving east in an arcuate pattern, ultimately developing the southeastern plunging, asymmetric folds seen at The Cliffs. At The Cliffs, Harrogate Springs Road, and drill-core 09-02 and 98-01, the Tuscaloosa Group overlies the Eutaw Formation. This is consistent with post impact, overturned flap stratigraphy, suggesting that during early modification the TCS moved as a semi-coherent slide (i.e., stratigraphy can still be discerned). This discernable stratigraphy is different than the incoherent slumped megablocks that are developed during contact and compression (see Figure 38).

During this “flap-slide,” impactite sand that formed through intra-crater groundwater recharge (and still lies below the slide) comes in contact with the TCS and is squeezed upward into fractures, dividing the extending layer into blocks (Figure 41). In outcrop at The Cliffs and on Harrogate Springs Road, impactite sand dikes cross-cut and separate intra-crater units. The cross-cutting injection dike relationships that exist between the impactite sand and slide-related Tuscaloosa and Eutaw Formations is thought to be developed because the strength and stiffness of these overlying units were reduced, ultimately acting as a liquefaction-type injection in and between overlying TCS units that were deformed or pulled apart during the massive slide.

As the TCS met the northwestern crater wall and ends its movement (Figure 39.4). At The Cliffs, a northerly vergence of sediments can be seen. Structurally, the feature is a parasitic, southeasterly plunging antiform. The vergence, plunge, and parasitic nature of The Cliffs suggest the direction of movement of the TCS to be in an arcuate fashion from west to north to east (see Figure 19).

As modification of the crater continued, muddy Mooreville Chalk (Km) flowed into the crater by way of a resurge tsunami (King and Ormö, 2011). At the southeastern extent of The Cliffs, the resedimented Mooreville Chalk overlies the Eutaw Formation. The suggested half-graben structure preserved a mostly complete interval of resurge facies (Markin, in progress), due to compressional folding and thrusting documented at The Cliffs as a result of the culmination of the TCS at the northwestern crater wall which opened an extensional graben to preserve this resurge facies (Figure 39.5). Units seen in The Cliffs were not penetrated in a similar arrangement during coring of the 90-m-deep 09-03 drill-core (King and Ormö, 2011). Marine sedimentation followed (Figure 39.6).

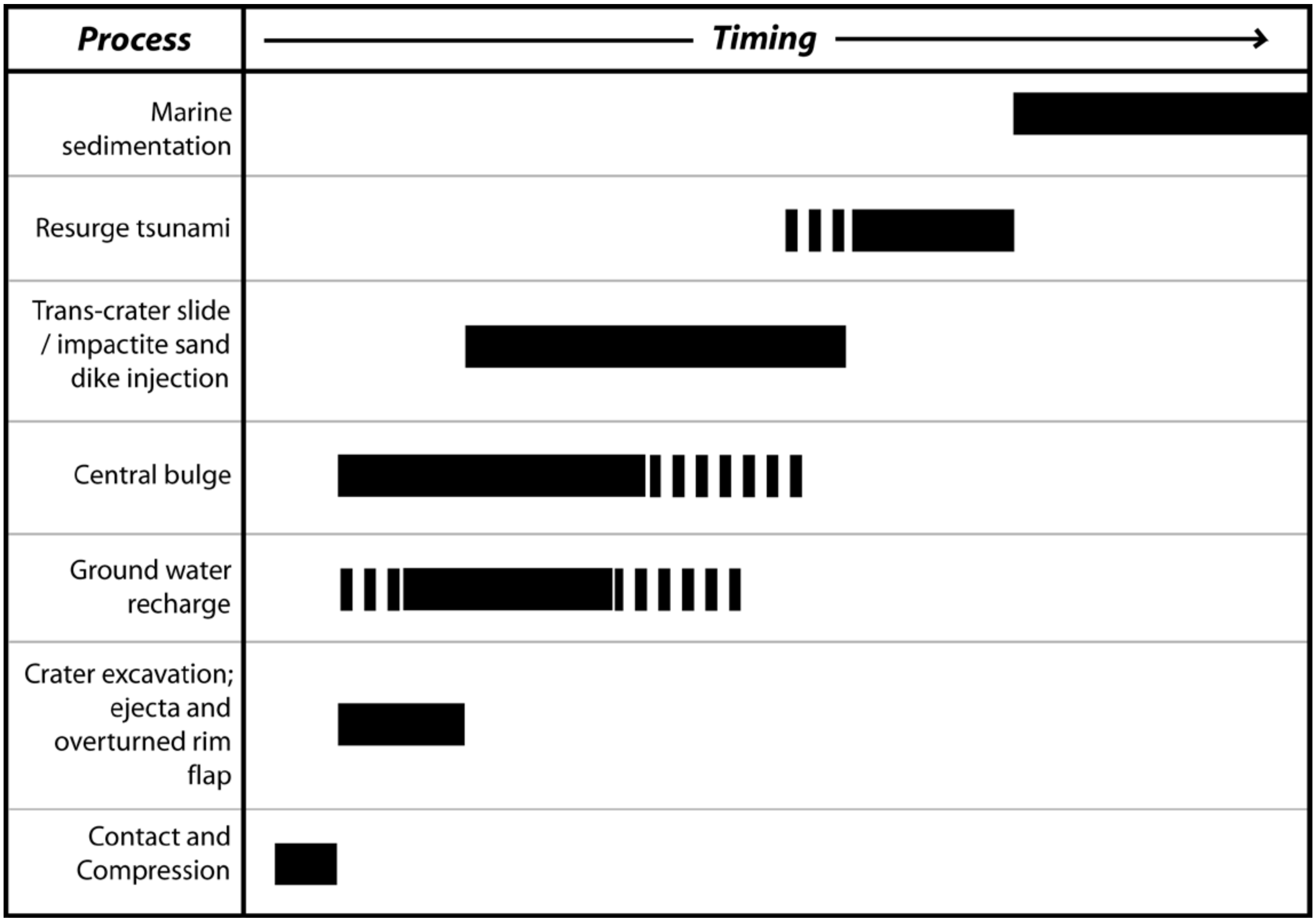

Figure 41: Critical moment diagram illustrating the timing of each major process that occurred during the early modification stage at Wetumpka impact structure, as discussed in text. Solid and dashed lines indicate the length of each process with respect to one another.

Comparison to other marine impact structures

Marine impact craters of comparable geological settings, e.g., Gardnos, Kärdla, Lockne, Chesapeake Bay, and Ritland, preserve several hundred meters of crater-filling sedimentary successions that record local depositional history and related sedimentary processes. Sedimentary processes in these craters depend on one another according to the crater size, target lithology, and sea-water depth (Azad et al., 2015).

The 2.7-diameter Ritland and 6 km-diameter Gardnos bolides struck comparable targets, i.e., the granitic/gneissic sub-Cambrian peneplain, overlain by a marine sedimentary succession. The Early/Middle Cambrian paleogeographic setting of Scandinavia suggests the existence of an extensive shallow (<200 m water depth) epicontinental sea in the Ritland and Gardnos areas (Hallam, 1981; Nielsen and Schovsbo, 2011). The Ritland and Gardnos areas were probably located seaward of a wave-dominated shore face, in inner shelf areas of the Early Cambrian epicontinental sea (Nielsen and Schovsbo, 2011). Outside of the Ritland impact structure, a thin (0-30 cm thick) layer of basal conglomerate has been found overlying the sub-Cambrian peneplain, probably deposited from reworking of weathering products of the Precambrian basement rocks (Azad et al., 2015). This Lower Cambrian basal conglomerate and overlying 10-20 m of silty shale (Setså, 2011) were the pre-impact marine sediments in the Ritland area. Numerical modeling of the Ritland impact structure (Shuvalov et al., 2012), related distribution of the ejecta layers (Setså, 2011), and the studied sedimentary signatures within the crater infill (Azad et al., 2012) suggest that the paleo-water depth at Ritland impact target site was 100 m or less (Azad et al., 2015).

The Gardnos impact structure is deeply eroded (Kalleson et al., 2008) compared to Ritland; no pre-impact successions have been found within the vicinity of the Gardnos structure. The presence of minor, partly deformed sedimentary clasts and relatively high carbon content (typically 0.2-1.0 wt. % carbon) within the impactites (Gilmour et al., 2003) suggests a partially consolidated to unconsolidated organic rich pre-impact sedimentary cover of a few tens of meters overlying the sub-Cambrian peneplain at the Gardnos site (Kalleson et al., 2008). The sedimentary signatures in the Gardnos succession, absence of well-developed resurge deposits, presence of minor amounts of pre-impact sedimentary clasts and carbon-rich impactites suggest a paleo-water depth at the Gardnos site to be less than the calculated rim height of 240 m (Kalleson et al., 2008).

The 4-km diameter Kärdla and 7.5-km diameter Lockne craters were formed in a comparable Ordovician epicontinental sea setting (Lindström et al., 1992). The pre-impact target stratigraphy of Kärdla consists of 120 m thick, poorly consolidated Early Cambrian siliciclastic rock succession overlain by 22 m of lithified Ordovician limestone and sandstone. Precambrian basement of migmitized amphibolites, gneisses and granites (Suuroja et al., 2002) underlies this site. The presence of algal oil shale and the pre-impact Ordovician limestone suggests a water depth of ~50 m at the Kärdla impact site (Suuroja et al., 2002).

At Lockne, the Proterozoic crystalline basement was overlain by 30 m of unconsolidated dark clay (Sturkell et al., 2013) and 50 m Ordovician limestones. Based on numerical modeling (Ormö et al., 2002; Shuvalov et al., 2005) and geological observations (Lindström et al., 2005a), the paleo-water depth at Lockne target site was suggested as ~500 m.

The complex, 90-km diameter Chesapeake Bay impact structure (CBIS) formed on the mid-continental shelf of a passive margin, with a thick (~700-800 m) pile of pre-impact sediment covering Proterozoic and Paleozoic igneous and metamorphic rocks (Poag et al., 2004). The near-shore to shelf setting of the CBIS impact target surface reflects water depth varying from a few tens of meters in the inner-shore area to about 300 m to the shelf area (Horton et al., 2005).

Comparable order of sedimentary processes, e.g., rock-avalanches, slides and slumps, debris and density flow, turbidity and suspension deposition are observed in the Gardnos, Kärdla, Lockne, Chesapeake Bay, and Ritland impact craters, despite their differences in crater size, target composition, and sea water depth. Azad et al. (2015) compares each of these craters, concluding that sedimentary processes in each crater resulted in qualitatively rather similar crater-infilling successions. Rock avalanches dominate where the target site is crystalline and has a shallow water depth, as seen in the Ritland and Gardnos cases. Target sites with low-strength, thick sedimentary cover and water depth comparable or less than the impactor size (Kärdla and Chesapeake Bay) resulted in large scale collapse of the rim and ejecta flap generating repeated rock avalanches, slides and slumps. Bolide impact into deeper water in Lockne resulted in subdued collapse of the transient seafloor cavity but was accompanied by contemporaneous powerful resurges. The thickness and composition of these deposits were controlled by impactor size, target composition, and water depth (Azad et al., 2015).

Mass flows, such as, debris- and density-flow, dominated in the early post-impact stage, generated by the resurge of sea water and largely influenced by the target composition and water depth. Impact on crystalline target with a shallow sea cover may result in formation of well-developed, elevated crater rim reducing instantaneous, powerful resurge of sea water, as observed in Gardnos and Ritland. The debris flow events in these craters were probably limited and transformed into density flows, as water gradually seeped through and breached the crater rims. Relatively weaker rim/brim development in the sedimentary target sites (Kärdla, Lockne and Chesapeake Bay) allowed for instantaneous, powerful resurge generating multiple large-scale debris flows (Azad et al., 2015).

Turbidites are commonly observed at the waning stage of the resurge during the early post-impact stage as the crater cavity approaches more stable conditions. Resurge turbidites have been commonly observed in the Kärdla and Lockne craters. Ritland and Gardnos turbidites are, dominantly derived from later slope-failure and reworking of the impact-derived debris. The Chesapeake Bay crater-filling sandstones may either represent resurge turbidites or derive from later slope-failure. Late post-impact sedimentation is mostly suspension deposition dominated in all craters and was largely controlled by their regional geological settings (Azad et al., 2015).

Wetumpka may be much like the Ritland and Gardnos impacts where rock avalanches dominated in the early modification. The crystalline block terrain as well as in the sedimentary megablock terrain are much like the rock avalanches documented at Ritland and Gardnos. Both terrains are derived from contact and compression and precede the later modification events. The northern portion of the crater had shallower water depth compared to the southern portion. Lockne and Chesapeake Bay, being deeper water marine impacts, had thicker sedimentary cover in the pre-impact stratigraphy, which is more akin to the southern portion of Wetumpka. In all three cases, the areas with thicker sedimentary resulted in large scale collapse of the crater rim. Powerful, large-scale debris flow resurge into the crater interior is documented in Kärdla and Chesapeake Bay impact structures, much like Wetumpka's crater interior that was subjected to resurge after the southern rim collapsed. Turbidites are seen in Wetumpka and documented as impactite sand (Rodesney, 2014). These are similar Ritland and Gardnos turbidites that are derived from reworked impact-derived debris. In the case of Wetumpka, the reworked impact-derived debris is derived from the target Tuscaloosa Group and Eutaw Formation, which were involved in rim-slope failures.

CONCLUSIONS

Field analyses, outcrop and drill-core description, petrographic analyses, and previous studies provides practical information to understand the shallow intra-crater terrain at Wetumpka, as well as the sequence of events active during post-impact modification.

- The overturned rim flap developed during the excavation stage and the stratigraphic sequence of this flap was Tuscaloosa-Eutaw-Tuscaloosa on the southern side of the crater.
- A trans-crater slide (TCS) moved the southern overturned rim flap into the crater due to a presumed detachment across the exterior disturbed terrain.
- In drill-core 09-02 and 98-01, outcrops on Harrogate Springs Road and The Cliffs document the overturned flap stratigraphy of the trans-crater slide.
- Large units of the trans-crater slide retained their coherent sedimentary features, whereas other units were internally deformed and/or broken. This is seen in the intra-crater terrain where units do not sustain original thickness and are chaotically oriented and fractured (i.e., The Cliffs and Harrogate Springs Road).
- Petrographic investigation of Tuscaloosa Group, Eutaw Formation, and impactite sand units from Harrogate Spring Road respectively show unique mineralogical makeup that helps establish their identity.

- Mass-wasting mechanisms such as lateral spreads (described elsewhere) coincide with what is seen in the crater interior. Overturned rim flap units were extended and fractured while moving over weaker, impactite sand, layers that squeezed upward into fractures that divided the extending TCS layer into blocks.
- Impactite sand from drill-core 09-04 exhibited fining-upward sequences suggesting turbidite-like deposition within the crater early in the modification of the crater. These impactite sands interacted with overlying TCS packages intrusively by cross-cutting transported units in areas of reduced strength as clastic dikes.
- At all areas within the crater, schist and gneiss blocks that represent proximal ejecta occur above the overturned and transported rim flap sequence. The position and location of these sequences, where they crop out, represent catastrophically rafted packages of overturned rim blocks or layers that have slid back into the crater.
- The northwestern crater wall juxtaposes the southeasterly plunging parasitic antiform known as The Cliffs. This feature exposes the overturned rim sequence and helps explain the suggested direction of travel and final emplacement of the TCS.
- Redeposited resurge tsunami sediments (i.e., the Mooreville Chalk) exist in extensional grabens and low areas in and around the crater. Evidence of this is noted from drill-core 09-03 logged by Markin (in progress) and in geologic maps that show extensional horst-and-graben structures developed with a

general strike tangential to the crater rim (King et al., 2003; Nelson, 2000; Neathery et al., 1976). These chalks represent the waning stages of post-impact modification.

The selective failure of Wetumpka's rim represents the ways target composition and water depth come into play in a marine impact. The systematic analysis of impact related events and mega- and microscopic features relate to understanding the dynamics of the syn- and post-impact modification events. This distinctive morphological feature and the details in and of itself are of great importance for establishing analogous features in marine impacts of Wetumpka-size on Earth and perhaps Mars as well.

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APPENDIX

I. Thin-section data

Table A1: List of thin-sectioned samples. The prefacing number 1765 is given to identify the house number from which each sample was collected from. Likewise, the prefacing letters correspond to locations. HSR is Harrogate Springs Road. BE is Baillif Eutaw. C is Cliffs.

Thin section #	**Lithology being investigated**
1765-1	Eutaw Formation
1765-2	Eutaw Formation
1765-3	Tuscaloosa Group
1765-4	Eutaw Formation
1765-5	Eutaw Formation
1765-6	Eutaw Formation
1765-7	Eutaw Formation
1765-8	Impactite sand
1765-9 (Figure 24)	Impactite sand
1765-10	Tuscaloosa Group
1765-11	Eutaw Formation
1765-12	Tuscaloosa Group
1765-13	Impactite sand
1765-14 (Figure 22)	Tuscaloosa Group
1765-15	Impactite sand
HSR-1	Tuscaloosa Group
HSR-2	Impactite sand
BE-1	Eutaw Formation
BE-2	Eutaw Formation
C-1	Tuscaloosa Group

Table A2: Data from thin-section petrography of outcrop interior crater-filling units. N is points counted, Qm is monocrystalline quartz, Qp is polycrystalline quartz, F is feldspar, L is lithic fragments, Other is accessory minerals and opaque minerals, M is mica, Mtx is matrix, Por is porosity. Ke is Eutaw Formation. Kt is Tuscaloosa Group. IS is impactite sand.

Sample	Unit	N	Qm	Qp	F	L	Other	M	Mtx	Por	Sum	Description
1765-1	Ke	300	94	8	17	0	3	57	0	121	300	Angular-subangular, poorly sorted micaceous quartz sandstone
1765-2	Ke	300	107	25	50	0	1	77	0	40	300	Very angular-angular, poorly sorted micaceous quartz sandstone
1765-3	Kt	300	66	21	28	0	1	65	117	2	300	Very angular, poorly sorted micaceous quartz sandstone
1765-4	Ke	300	112	14	3	1	13	19	107	31	300	Angular sorted micaceous quartz sandstone
1765-5	Ke	300	119	14	2	1	4	37	102	21	300	Angular sorted micaceous quartz sandstone
1765-6	Ke	100	21	5	1	0	0	29	44	0	100	Highly weathered, poorly sorted micaceous quartz sandstone
1765-7	Ke	300	108	44	4	0	1	30	65	48	300	Moderately sorted, quartz rich sandstone
1765-8	IS	300	61	38	3	0	3	54	129	12	300	Very poorly sorted, micaceous sandstone
1765-9	IS	300	128	32	2	0	1	35	69	33	300	Angular, moderately quartz sandstone
1765-10	Kt	300	102	32	6	0	31	27	86	16	300	Subangular, poorly sorted micaceous quartz sandstone
1765-11	Ke	300	75	17	5	0	4	30	37	132	300	Angular-subangular, poorly sorted quartz sandstone
1765-12	Kt	300	101	77	12	0	5	46	25	34	300	Poorly sorted, micaceous quartz sandstone
1765-13	IS	160	57	19	3	0	2	42	16	21	160	Moderately sorted, micaceous quartz sandstone
1765-14	Kt	160	77	20	3	0	2	0	58	0	160	Poorly sorted quartz sandstone with hematite matrix
1765-15	IS	160	66	14	0	0	1	0	79	0	160	Matrix supported quartz sandstone
HSR-1	Kt	300	81	3	0	0	10	4	107	95	300	Subangular to angular, poorly sorted quartz clay stone
HSR-2	IS	300	81	16	3	0	1	64	132	3	300	Poorly sorted micaceous matrix supported quartz sandstone
BE-1	Ke	300	100	8	20	0	4	16	38	114	300	Subangular, poorly sorted quartz sandstone
BE-2	Ke	300	132	23	41	0	4	31	36	33	300	Angular-subangular, poorly sorted micaceous quartz sandstone
C-1	Kt	160	96	11	4	0	1	1	46	1	160	Very poorly sorted hematite matrix quartz sandstone

Table A3: Calculated percentage and averaged values from point counted thin section samples. N is points counted, Qm is monocrystalline quartz, Qp is polycrystalline quartz, F is feldspar, L is lithic fragments, Other is accessory minerals and opaque minerals, M is mica, Mtx is matrix, Por is porosity. Ke is Eutaw Formation. Kt is Tuscaloosa Group. IS is impactite sand.

Sample	Type	N	Qm%	Qp%	F%	L%	Other%	M%	Mtx%	Por%	Sum
1765-1	Ke	300	31.3%	2.7%	5.7%	0.0%	1.0%	19.0%	0.0%	40.3%	100.0%
1765-2	Ke	300	35.7%	8.3%	16.7%	0.0%	0.3%	25.7%	0.0%	13.3%	100.0%
1765-3	Kt	300	22.0%	7.0%	9.3%	0.0%	0.3%	21.7%	39.0%	0.7%	100.0%
1765-4	Ke	300	37.3%	4.7%	1.0%	0.3%	4.3%	6.3%	35.7%	10.3%	100.0%
1765-5	Ke	300	39.7%	4.7%	0.7%	0.3%	1.3%	12.3%	34.0%	7.0%	100.0%
1765-6	Ke	100	21.0%	5.0%	1.0%	0.0%	0.0%	29.0%	44.0%	0.0%	100.0%
1765-7	Ke	300	36.0%	14.7%	1.3%	0.0%	0.3%	10.0%	21.7%	16.0%	100.0%
1765-8	IS	300	20.3%	12.7%	1.0%	0.0%	1.0%	18.0%	43.0%	4.0%	100.0%
1765-9	IS	300	42.7%	10.7%	0.7%	0.0%	0.3%	11.7%	23.0%	11.0%	100.0%
1765-10	Kt	300	34.0%	10.7%	2.0%	0.0%	10.3%	9.0%	28.7%	5.3%	100.0%
1765-11	Ke	300	25.0%	5.7%	1.7%	0.0%	1.3%	10.0%	12.3%	44.0%	100.0%
1765-12	Kt	300	33.7%	25.7%	4.0%	0.0%	1.7%	15.3%	8.3%	11.3%	100.0%
1765-13	IS	160	35.6%	11.9%	1.9%	0.0%	1.3%	26.3%	10.0%	13.1%	100.0%
1765-14	Kt	160	48.1%	12.5%	1.9%	0.0%	1.3%	0.0%	36.3%	0.0%	100.0%
1765-15	IS	160	41.3%	8.8%	0.0%	0.0%	0.6%	0.0%	49.4%	0.0%	100.0%
HSR-1	Kt	300	27.0%	1.0%	0.0%	0.0%	3.3%	1.3%	35.7%	31.7%	100.0%
HSR-2	IS	300	27.0%	5.3%	1.0%	0.0%	0.3%	21.3%	44.0%	1.0%	100.0%
BE-1	Ke	300	33.3%	2.7%	6.7%	0.0%	1.3%	5.3%	12.7%	38.0%	100.0%
BE-2	Ke	300	44.0%	7.7%	13.7%	0.0%	1.3%	10.3%	12.0%	11.0%	100.0%
C-1	Kt	160	60.0%	6.9%	2.5%	0.0%	0.6%	0.6%	28.8%	0.6%	100.0%

Averages	Qm%	Qp%	F%	L%	Other%	M%	Mtx%	Por%	Sum
Kt	37.47%	10.35%	2.82%	0.00%	2.60%	6.85%	32.29%	7.09%	100.00%
Ke	33.70%	6.22%	5.37%	0.07%	1.26%	14.22%	19.15%	20.00%	100.00%
IS	33.38%	10.14%	1.14%	0.00%	0.73%	19.31%	30.00%	7.28%	100.00%

II. Structural data

Table A4: Stations, strike and dip measurements, and GPS readings in decimal degrees.

Station	Strike	Dip	N Latitude	W Longitude	Notes
1	N 45°E	49° SE	32.527341	-86.187010	Figure 14
2	N 75°E	40° SE	32.527355	-86.187078	Figure 14
3	N 40°E	56° SE	32.527252	-86.187034	Figure 14
4	N 80°E	46° SE	32.527519	-86.187184	Figure 14
5	N 80°E	47° SE	32.527623	-86.187151	Figure 14
6	N 70°E	44° SE	32.527433	-86.186762	Figure 14
7	N 15°E	54° SE	32.527669	-86.186743	Figure 14
8	N 45°E	35° SE	32.527746	-86.186763	Figure 14
9	N 63°E	42° SE	32.527824	-86.186797	Figure 14
10	N 10°W	48° SW	32.527879	-86.186796	Figure 14
11	N 25°W	43° SW	32.527940	-86.186743	Figure 14
12	N 80°W	45° SW	32.528011	-86.186749	Figure 14
13	N 5°W	42° SW	32.528081	-86.186785	Figure 14
14	N 60°W	40° SW	32.528138	-86.186845	Figure 14
15	N 75°E	45° SE	32.528157	-86.186831	Figure 14
16	N 40°E	33° SE	32.528077	-86.186573	Figure 14
17	N 20°W	50° NE	32.527988	-86.186860	Figure 14
18	N 5°W	55° NE	32.528067	-86.187034	Figure 14
19	N 55°W	49° NE	32.528072	-86.186935	Figure 14
20	N 20°W	29° NE	32.528146	-86.187080	Figure 14
21	N 30°W	78° NE	32.528096	-86.187141	Figure 14
22	N 75°W	45° NE	32.528077	-86.187024	Figure 14
23	N 40°W	45° SW	32.528024	-86.187186	Figure 14
24	N 25°E	66° NW	32.527766	-86.187180	Figure 14
25	N 55°E	45° SE	32.527541	-86.187113	Figure 14
26	N 50°E	45° SE	32.527566	-86.187106	Figure 14
27	N 5°E	30° NW	32.525938	-86.180846	Figure 21
28	N 55°E	71° NW	32.533122	-86.194338	Crystalline Rim
29	N 60°E	65° NW	32.532481	-86.195340	Crystalline Rim
30	N 45°E	45° NW	32.528126	-86.204439	Crystalline Rim
31	N 20°E	45° SE	No reading	No reading	HSR-2 fold arm
32	N 20°E	45° SW	No reading	No reading	HSR-2 fold arm
33	N 65°E	50° SE	No reading	No reading	Behind The Cliffs
34	N 80°W	60° SW	No reading	No reading	Behind The Cliffs

III. Drill-core description (09-02)

Table A5: Drill-core notes for well 09-02

Drill-core 09-02		
From (m)	**To (m)**	**Notes**
0.457	1.98	Red-tan-light brown; saprolitic muscovite-quartz-minor garnet breccia; muscovite foliations exhibit some S-C fabric at 141 cm; More S-C fabric seen with larger saprolitic clasts (red in color) containing muscovite in foliation. Proper measurement is difficult to obtain because of the muddy covering on the core. Grain size is fine to very fine. Sorting is difficult to determine but it appears moderate to poor. No distinct bedding. Muscovite foliations are present throughout (mostly saprolite). **Polymict impact breccia**
1.98	3.51	Red-brown. Saprolitic muscovite-quartz (-garnet?) breccia. Shearing evident at 2.14 m as foliated muscovite (very saprolitic). Color of this section of core is redder than previous section. Foliations seem to change moving down in depth. Small inconsistent S-C phacoids at 2.14 m (Figure 37). At 2.33 m, muscovite foliation has 80° dip, but direction cannot be determined. More poorly sorted with quartz pebbles throughout the surface- could be a product of drilling. This section is very muddy on the exterior. **Polymict impact breccia**
3.51	4.39 (measured ~ 4.25 m)	Red-brown saprolitic clayey muscovite-quartz breccia. Soft schist fragments with varying foliation included. Quartz pebbles ~ 1 cm (largest) and smaller see in mixed throughout this section. King's field notes mention that this may be from Tuscaloosa Group (Kt). Only the upper part to ~ 3.80 m of the core contains the largest of the quartz pebbles. Below ~ 3.80 m, quartz pebbles become smaller and less abundant. Sorting is poor. Grain size is the same as the above section. **Polymict impact breccia**
4.39	4.66 (measured 4.70 m)	4.39 m to 4.70 m is material from 3.51 m to 4.39 m. This material dropped back into the hole. Same rock as above. No noticeable structures; just fall back gunk; same mineralogy. **Polymict impact breccia**
4.66 (4.70 cm)	4.90	Upper 20 cm is from previous pull. Brown-tan saprolitic clayey muscovite-quartz breccia. Quartz clasts are ~ 0.3 cm and poorly sorted. Looks to be the same Impact Schist. Lower 40 cm transitions to saprolitic schist (brown) with garnets. Some S-C fabric seen at ~ 4.90 m but is difficult to measure. Muscovite foliations are very distinct but original direction cannot be determined. **Polymict impact breccia**
4.90		Impact Schist stops and transitions for 10 cm (to 5.16 m) to weathered gneiss. Quartz-biotite-muscovite-feldspar gneiss. **Kowaliga Gneiss**
5.16		Fine grained injection type deposit cross cuts the weathered gneiss and has a distinct boundary perpendicular to the gneiss foliation (Figure 33). After this small feature, weathered (slightly saprolitic) gneiss begins again. **Impactite sand (injection)**
6.25		Gneiss loses saprolitic texture. **Kowaliga Gneiss**

6.50		Massive gneiss. No dominant foliation directions seen. Most of the core is not intact. King's field notes describe a 1.4ft (42.6 cm) loss of core. **Kowaliga Gneiss**
7.32	8.08	Fractured gneiss. Fractures contain feldspar and quartz. **Kowaliga Gneiss**
8.08	9.60	Augen (Feldspar clasts) gneiss. "V" folds dipping ~ 48°, direction unknown. At 9.40 m (Figure A1) **-** banded gneiss continues to 10.47 m. **Kowaliga Gneiss**
10.27	10.47	Banded gneiss transitions to clayey greenish-brown color sand. **Kowaliga Gneiss**
10.47	10.91	Brown-tan-red colored sandstone. Poorly sorted. **Tuscaloosa Group (channel overbank)**
10.91	11.74 (measured 11.27 m	Cross-bedded brown-tan and white-grey sandstones. Bedding is inclined 66° at 11.00 m. On the reverse side of this section, there is what appears to be saprolitic muscovite-quartz-garnet schist. Foliations are dipping in the same fashion as the cross beds. Quartz clasts ~ 0.2 cm are distributed throughout making this sand poorly sorted. The grey-white sandstone beds appear to be impactite sand. This section to 11.98 cm is very deformed and coarse. The color is mainly tan-brown with grey-white. This is probably a sort of "mixing" zone between Tuscaloosa Group and impactite sand with impact breccia schist. **Mixed interval (Tuscaloosa/impactite sand)**
11.77	11.98	This section is 82 cm in length contrary to King's notes saying ~ 20 cm. At what would be 20 cm above 32.3 ft (11.98 m), the boundary between the above mixed Tuscaloosa-impactite sand-schist unit and impactite sand exists. 3 cm of coarse clay nodules show up, and below that is moderate-poorly sorted white-grey sand. 1-1.5 cm clasts of grey sand appear in the IS. These are clay clasts. This core smells like sulfur. Flow structures with greenish clay at the same level. These flow structures have finer grained material than the surrounding impactite sand (Figure 35). **Impactite sand**
11.98	12.66	Poorly sorted, grey impactite sand. Quartz pebbles ~ 0.2 cm; no apparent bedding. **Impactite sand**
		Impactite sand
13.29	13.43	**Impactite sand**
13.43	13.63	Tuscaloosa Group clay overbank. Red-brown in color. Impactite sand injection at 13.57 m; probably a small side of an injection crossing into the Tuscaloosa. Some pebbles on the outside surface of the Tuscaloosa. **Tuscaloosa Group (clay overbank)**
13.63	13.93	Poorly sorted, **Impactite sand**
13.93	14.14	Breccia. This is grey to dark grey in color; very poorly sorted. Large ~ 2 cm weathered gneiss clasts surrounded by grey-green fine grained schist texture. Impactite sand components in the matrix of surround sands. Impactite sand injection at 13.97 m. This is possibly a boundary mixing portion from the above impactite sand. **Impact breccia**
14.14	14.44	Tuscaloosa Group clay overbank. Red-brown in color. Cross beds with white grey sand beds (like laminations and very thin). Base has a flow feature (Figure 36) that looks like an overturned flap ~ 3 cm in size. **Tuscaloosa Group (clay overbank)**
14.44	14.71	Impactite sand with many flow textures. This clay, flow like, impactite

		sand looks exactly like the end of box 4 (11.77 m). Smells like sulfur; grey-green clay flowing in and around poorly sorted impactite sand. **Impactite sand**
14.71	15.18	King's field notes describe this texture as "suevite" or "suevitic." Possible altered glass in this portion. Clasts are white and reach 3.5 cm in size. Other clasts have gneiss texture and foliations vary and are inconsistent between clasts. This breccia is very poorly sorted and has a range of clast sizes and colors (from grey to green to white). Some clasts have rims around them. White clasts are possibly white because of impact deformation; originally being mafic and dark but now have a bleached appearance. **Impact breccia**
	17.22	Boundary to the next unit is not well defined. **Impact breccia**
17.22	18.75	Eutaw Formation. Fine grained, sorted, yellow-grey-red sandstone. Impactite sand injection dikes appear at 18.23 m. Sands around them appear to be folded and shaped to the incoming dike. Dike at 18.43 m; appears to go vertically with the core direction. **Eutaw Formation**
18.75	20.95	Tuscaloosa Group clay transition to bedded sandstone. Tuscaloosa sandstone begins ~ 19.75 m; texture of this is flow like with red to grey beds alternating with flame, flow like features crossing the core. Clayey sand has insect burrows. Tan sand at base. **Tuscaloosa Group**
20.95	23.32	Undeformed impactite sandstone; mineralogy is quartz-feldspar-muscovite, red-tan in color. Areas of more iron staining occur--possibly due to water contact. Moderately sorted and medium to fine grained. End of core at 23.32 m. **Impactite sand**

Figure A1: Short section of drill-core 09-02. Depth is 940 cm (9.4 m). Note banded augen (feldspar clast) gneiss. "V" folds dipping 48° in an unknown direction. Up is at the top of the photograph. Scale is in cm and inches on the right side.

Figure A2: Short section of drill-core 09-02. Depth is 14.71 m – 15.18 m (49.8 ft). Note "suevitic" breccia texture. Up is the top of the photograph. Wood depth marker is in feet. Scale is in cm and inches on the right side.

IV. Core-box photographs (09-02)

All core-box photographs

Drill-core #09-02 Buck Ridge Road

Top is upper right; bottom is lower left in all boxes.

Wood depth markers are in ft.

Figure A3: Photograph of drill-core 09-02, box 1 (0.457 m – 3.51 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A4: Photograph of drill-core 09-02, box 2 (3.51 m – 5.99 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A5: Photograph of drill-core 09-02, box 3 (5.99 m – 9.60 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A6: Photograph of drill-core 09-02, box 4 (9.60 m – 11.98 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A7: Photograph of drill-core 09-02, box 5 (11.98 m – 15.16 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A8: Photograph of drill-core 09-02, box 6 (15.18 m – 18.75 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A9: Photograph of drill-core 09-02, box 7 (18.75 m – 21.79 m). Up is top right; bottom is lower left. Wood depth marker is in feet.

Figure A10: Photograph of drill-core 09-02, box 8 (21.79 m – 23.32 m). Up is top right; bottom is lower left. Wood depth marker is in feet.