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PALEOMAGNETIC ANALYSIS OF THE FLYNN CREEK AND WELLS CREEK IMPACT STRUCTURES, TENNESSEE, U.S.A.

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ABSTRACT

The Flynn Creek impact structure consists of a 3.8-km circular feature that contains deformed Ordovician through Devonian limestones and dolomites. The age of this structure is stratigraphically constrained by the Ordovician Knox Group and the overlying undeformed late Devonian through Mississippian Chattanooga Shale. Paleomagnetic samples were collected from deformed Flynn Creek Breccia, a fallback breccia from the inside of the structure. Stepwise thermal demagnetization and alternating field demagnetization of tilted limestone samples reveals a characteristic remanent magnetization (ChRM) with southeasterly declinations and moderate down inclinations, with maximum unblocking temperatures of 440°C—the ChRM resides in magnetite. The calculated pole position is 36.7°N, 131.3°E (d_p = 5.8°, d_m = 11.5°) which lies on the late Carboniferous to early Permian portion of the apparent polar wander path (APWP) for North America.

The Wells Creek impact structure consists of a 12-km circular feature that contains deformed Ordovician through Mississippian limestones and dolomites. The age of this structure is stratigraphically constrained by the Ordovician Knox Group and the overlaying undeformed Cretaceous Tuscaloosa Gravel (200Ma +/- 100Ma). Paleomagnetic samples were collected from deformed Fort Payne Limestone and Warsaw Limestone, fallback breccias from the southern rim of the structure. Stepwise thermal demagnetization and alternating field demagnetization of tilted limestone samples reveals a ChRM with southeasterly declinations and moderate down inclinations (declination = 152°, inclination = 18.5°, k = 105.7, and $\alpha 95$ = 6.5), with

maximum unblocking temperatures of 440°C—the ChRM resides in magnetite. The pole lies at 37.1°N, 127.9°E (d_p = 3.5°, d_m = 6.8°) which lies on the late Carboniferous to early Permian portion of the apparent polar wander path (APWP) for North America.

The ChRM that resides in both of these structures was imparted from the same origin and is the result of a regional remagnetization event associated with the Alleghenian Orogeny. The age of the Flynn Creek impact structure was not further constrained through paleomagnetic tests; although the Wells Creek impact structure now has an upper constraint at the late Carboniferous to early Permian. The ChRM is interpreted as a chemical remanent magnetization (CRM) imparted by the influx of heated orogenic brines into these structures and is carried in secondary magnetite formed by alteration of pyrite. Although there are other possible mechanisms for remagnetization, the lack of deep burial and evidence of alteration in petrographic study indicate that this magnetization was the result of hydrothermal fluid activity.

1. INTRODUCTION

1.1 IMPACT FORMATION

Impact structures are a ubiquitous feature on all of the interior rocky planets and many of the moons of our solar system. The process of a bolide impacting the surface of a celestial body creates distinct features both in the geomorphology and in the gravity and magnetic signatures of the rocks. The entire process
lasts only minutes but can result in longstanding effects on the geology.

The formation of an impact structure by hypervelocity bolide impact can be broken into three distinct stages: contact and compression, excavation, and modification (French, 1998). The contact and compression stage begins when the shock waves from the bolide reach the surface of the Earth. The bolide then hits the Earth, stopping almost instantly, and transferring the kinetic energy to the host rock by shock waves (Gault et al. 1968; Melosh, 1989). These shockwaves are transmitted outward and then reflected back towards the projectile (Melosh, 1989; O'Keefe and Ahrens, 1993). Once this reflected, or release, wave reaches the projectile, the shock pressures and high temperatures result in nearly complete melting and destruction of the projectile. Once this wave passes through the projectile and into the compressed target rock the contact and compression stage reaches its conclusion (French, 1998).

The excavation stage encompasses the interactions between the shock waves and the surface of Earth that physically open up the crater (Melosh, 1989; Grieve, 1991). The force of the impactor hitting the target sends shock waves into the earth and are then transmitted back into the projectile. This results in the explosion of the impactor and the excavation of the crater (French, 1998). These complex interactions will eject target rock at different speeds and distances depending on where they are located within the impact area. The result is a transient crater—a concentric depression—in the target rock (Maxwell, 1977; Grieve et al., 1977, Grieve and Cintale, 1981; Melosh, 1989). The transient crater is comprised of two zones, the ejection zone and the displaced zone. Velocities in the ejection zone can reach speeds greater that 100m/second and cause the rock to be not only ejected beyond the rim of the final crater, but also vaporized (Ward et al., 1995). These high velocities and resulting ejection and vaporization aid in the formation of a crater that is much larger that the projectile that came in contact with the ground surface (Grieve et al. 1977; Dence et al. 1977; Kieffer and Simonds, 1980). The deeper displaced zone has lower velocities during ejection and the target rock is not ejected outside of the crater but instead pushed downward and outward (French, 1998). The excavation stage ends once the transient crater has reached its maximum size.

The modification stage begins at the moment that the transient crater has reached its maximum size. This is the final stage of the cratering process and is defined by conventional processes such as gravity and rock mechanics, as the shock waves have dissipated into low pressure elastic stress waves far outside of the rim. The modification stage does not have a clear conclusion as many geologic processes, such as uplift, erosion, and sedimentation, begin to occur (French, 1998). A variety of breccias can be deposited during the modification stage and through subsequent geologic processes can be reworked, especially in shallow marine environments where fluid processes can have a greater effect on the reworking of these breccias (Warme and Kuehner, 2010). The ejected material settles and an ejecta blanket forms outside of the structure itself. Polymict fallback breccia can settle back within the crater and be reworked and deposited on top of the breccia formed inside the structure. Suevites are also polymict and are hard to completely differentiate from fallback breccias, although, they do exhibit melt like textures that are indicative of impact structures. Lastly, melt breccias are monomict breccias that form in-situ from rock units within the crater. These breccias are highly indicative of impacts because it takes a lot of heat and pressure to produce this kind of breccia and there are few other geologic processes capable of doing so (French, 1998).

Impact events also play a role in the magnetization of the target rock. It has been observed that shock related demagnetization has occurred in conjunction with large impacts; although many target rocks do contain a magnetization (Carporzen et al., 2005). The magnetization found in impact structures is generally randomly oriented and the magnetic carriers are likely secondary. When viewed as a whole (i.e. aeromagnetic survey), the addition of these randomly oriented magnetic vectors cancel out the magnetization which creates the appearance of a demagnetized structure (Carporzen et al., 2005). Another hypothesis suggests that impacts do undergo shock demagnetization. Kavkova and Kletetscha (2019) investigated the Santa Fe impact structure and determined that shock demagnetization did occur by evidence of decreased paleointensities of magnetic remanence and scattered paleodirections.

1.2 INTRODUCTION TO STUDY

Paleomagnetic investigation of the effects of an impact can lead to a greater understanding of how the mechanisms of the impacting process can alter magnetic characteristics once the crater has reached the modification stage and standard terrestrial geologic processes dominate. The craters can vary in their structures from well-formed at the surface with a concentric rim and basin or only inferred from the surrounding sedimentary deposition and deformation of the target rock—many craters have been eroded or buried since their formation. Paleomagnetic studies can help to constrain the age of the post impact processes, this is important to gain a better understanding of the bombardment history of Earth. Paleomagnetic field tests, such as conglomerate tests and tilt tests, can be used to help determine the timing of magnetization in regard to deformation associated with the impact event and can help constrain the age of the crater in the absence of other dating methods or poor stratigraphic control (Elmore and Dulin, 2007; Dulin and Elmore, 2008; Hamilton et al., 2018).

Paleomagnetic results from two known impact craters, the Flynn Creek and the Wells Creek impact structures, located in central Tennessee are presented here (Fig. 1). The Wells Creek impact structure, first identified as a possible impact structure in 1860 by Dr. James M. Safford, is 12 km in diameter and contains impact features such as a radial structure, shatter cones, and brecciation (Fig. 2). The age constraint on this structure is not well confined and is based on surrounding stratigraphy. The Flynn Creek impact structure, 3.8 km in diameter, also contains shatter cones and brecciation and is radial in structure (Fig. 3). The Flynn Creek impact was also first described by Dr. James M. Safford in 1869. The Flynn Creek age has been well confined based on surrounding stratigraphy. Conventional dating methods are sometimes difficult to use in association with impacts because the surrounding geology is often eroded and the minerology has been altered. This impact structure will be used as a proof on concept for dating impact events using paleomagnetic methods, as well as provide insight into the mechanisms for which magnetization is recorded during an impact event.

1.3 PURPOSE OF STUDY

The purpose of this study is to test if a paleomagnetic signature is localized within the deformed limestones at both the Flynn Creek and Wells Creek structures, and to test if this signature can be used to further constrain the timing of the deformation and elucidate timing of magnetic acquisition/remagnetization during impact events. Understanding the timing of impacts and constraining the age ranges for impact events can lead to a better quantification of Earth's bombardment history. Paleomagnetic signatures in carbonate rocks have been investigated within a number of impacts and have been related to mechanisms such as shock effects, heating, and chemical alteration (Carporzen et al., 2005; Dulin and Elmore, 2008; Evans et al., 2012; Kavkova and Kletetscha, 2019). These previous studies will act as guides and provide background into our study of both central Tennessee structures.

Samples were collected across a transect of the structure at Flynn Creek (Fig. 3)—with testing, this could provide a proof of concept for this method and verify the current well constrained age. The rocks sampled were all taken from the Flynn Creek

Breccia, likely a fallback breccia found throughout the center of the crater and towards the rim. At the Wells Creek structure samples were collected from deformed limestone breccia in the southern rim of the structure (Fig. 2). The samples were collected from the Fort Payne Limestone and the Warsaw Limestone, both are likely fallback breccias. The Warsaw Limestone could potentially be part of the ejecta blanket due to its location on the far outer section of the rim. These breccias were collected and tested in hopes of performing a conglomerate test on individual clasts; although the clasts were rather small so a modified conglomerate test was performed. Deformed limestones were sampled for a tilt test to help determine the timing of the magnetization in relation to the deformation. This, in conjunction with petrographic analysis, will determine the presence of an ancient magnetization, the timing of acquisition, and the magnetic minerals present within the impact structures.

Accurate age constraints on impact events can lead to a better understanding of bombardment rates during Earth's history and can help us to understand if bombardment is random or periodic (French, 1998). With nearly 70% of Earth's surface being covered with water, it is reasonable to assume that many impact events have occurred in the ocean. The ocean crust only records through the Triassic so a greater understanding of the impacts that we can study will help us to determine bombardment rates throughout geologic history. Furthermore, Earth's history can be used as an analogue for all of the inner planets in our solar system.

2. GEOLOGIC SETTING AND PREVIOUS WORK

2.1 FLYNN CREEK GEOLOGIC SETTING

The Flynn Creek structure is a 3.8km circular feature bounded by a raised rim defined by circular drainage patterns (Fig. 3). The structure is located in north central Tennessee (Fig. 1), east of Nashville, in and near Gainesboro, TN, and is comprised of deformed Ordovician through Devonian limestones and dolomites, with outcrops of the Devonian Flynn Creek Formation, which is highly brecciated, and the overlying undeformed late Devonian through Mississippian Chattanooga shale. The accepted cause of deformation is by hypervelocity impact. The presence of shatter cones in the center of the structure within the Knox Dolomite and shock metamorphic features such as planar deformation features in quartz and calcite have been observed (Roddy, 1977), which led to verification of the impact hypothesis. Field relationships and modeling indicate that the environment of deposition during the suspected time of impact was a shallow coastal marine setting, likely around 50 m in depth (Bray et al., 2019) within the Chattanooga Sea (Roddy, 1979). Roddy (1976, 1977a) determined that the impacting body would have been around 100 meters in diameter and would have been travelling around 25 km/second. The impact caused ~150 meters of rock to be brecciated and uplifted throughout the crater with up to 450 m uplifted in the center (Roddy, 1979). Sub-aqueous erosion as a result of the incursion of the Chattanooga sea during the Mississippian occurred shortly after cratering started, removing the ejecta blanket and redepositing those sediments in the center of the crater. As the sea deepened, the Chattanooga Shale was then conformably deposited over the impact structure. The uplift of the Nashville Dome, associated with sediment loading in the Appalachian Basin, caused more erosion and exposed sections of the crater (Roddy, 1979). The Nashville dome, situated between the two impacts, is surrounded by flat lying strata (Fig. 1).

2.2 WELLS CREEK GEOLOGIC SETTING

The Wells Creek structure is 12km circular feature bounded by a rim with circular drainage patterns (Fig. 2). The structure is located in north central Tennessee, north west of Nashville, in and near Cumberland City, TN (Fig. 1). It is comprised of Devonian-Mississippian limestones, dolomites, and shale within the Knox Dolomite-St. Louis Limestone, with outcrops of Fort Payne Limestone and Warsaw Limestone. The age of the structure is poorly constrained stratigraphically. It is overlaid by the Cretaceous Tuscaloosa Formation, deposited 75 Ma, constraining the impact event to 200 Ma +/- 100 Ma. The presence of shatter cones and brecciation within the structure has verified that it was formed by an impact event. The Wells Creek structure is surround by low dipping strata, located on the Western Highland Rim of the Nashville Dome. The impacting body is interpreted to be about 300 m in diameter, travelling around 15-40 km/second, and likely penetrated 2000 ft into the subsurface (Wilson and Stearns, 1968. The deposition of the impact took place on the Western Highland Rim of the Central Basin, the resulting basin from erosion of the Nashville Dome.

2.3 FLYNN CREEK STRATIGRAPHY

The stratigraphy described in this section is all involved in the impact (Fig. 4); although, only the Flynn Creek Breccia was sampled for this study. The region is heavily wooded and alluvium covers most of the outcrop associated with the impact (Ford et al., 2013)—therefore sampling from multiple formations was not accessible.

The stratigraphy of the Flynn Creek Structure is made up of Ordovician and Devonian limestone and dolomite and is overlaid by Devonian shale. The Knox Group, or Knox Dolomite, was deposited from the Upper Cambrian through the Lower Ordovician and is comprised of mainly limestone and dolomite with some calcareous and dolomitic shale. It ranges in color from yellowish-brown to various shades of gray. It is mostly fine grained but can be coarser and ranges in bedding thickness from 8 inches to 10 feet (Wilson and Stearns, 1968).

The Ordovician Stones River Group lies directly above the Knox Group and is marked by a change in lithology from limestone-dolomite to limestone to shaley-limestone sequences. The two facies found in the Stones River Group are a thick bedded limestone and a thin bedded limestone with thin shale laminations. Chert can also be found sporadically throughout the Stones River Group. The color ranges from yellowish-brown to various shades of gray. Texture ranges from very coarse to fine, it is mostly fine-grained, and the thickness ranges from 2 inches to 3 feet (Wilson and Stearns, 1968).

The Ordocivian Catheys-Leipers Formation is a limestone that is made up of three major facies: the granular phosphatic facies, the light gray colored facies, and the pale colored facies. The granular phosphatic facies is a massive-bedded and coarse-grained limestone. It is blue to gray in color and is mainly found in the lower half of the formation. The dove colored facies is found in the basal 25 feet of the formation and is more thinly bedded. It is light gray, fine grained, and brittle. Ostracods can be found here, although fossils are sparse, and it has a fairly high clay content. The pale colored facies makes up the upper half of the formation and is blue to gray in color. It ranges in thickness (3-24 feet) and has wavy surfaces. It is fine grained and very dense. Beds can be separated by shale parings (Wahlman, 1992). The basal breccia facies is poorly sorted carbonate clasts that are derived from the underlying strata. The bedded breccia facies is made up of carbonate clasts, fossil debris, quarts and chert grains. The bedding thickness ranges from 50 to 150 cm and beds are separated by shale drapes. The bedded facies contains dolomite breccia as well and tends to be more poorly sorted near the time of the structure (Schieber and Over, 2005).

The Devonian Flynn Creek Breccia is a fallback impact breccia that ranges from 50 to 175 meters thick and is comprised of carbonate limestone blocks. It is a polymict breccia with clasts sizes ranging from a few centimeters to a few meters (King et al., 2018) and is found in the center of the crater. This breccia was reworked resulting from deposition in a shallow marine environment and is likely a mix of the ejecta blanket and fallback breccia within the crater.

2.4 WELLS CREEK STRATIGRAPHY

The Wells Creek Impact Structure contains all of the stratigraphy (Fig. 4) listed here as well as the Knox Group and the Stones River Group described above in the "Flynn Creek Stratigraphy" section. Only the Fort Payne Limestone and Warsaw Limestone were collected for this study. The region in around the impact was developed as a gravel quarry and railway, destroying much of the accessible outcrop.

There is now a coal power station that has further developed the central part of the impact crater. The stratigraphy in this section was adapted and modified from Wilson and Stearns (1968).

The Ordovician Hermitage Formation is made up of both calcareous shale and limestone. The shale is sandy and is various shades of gray, brown, and black in color. The limestone is fine to medium grained and gray in color. The formation is thinly bedded and easily weathered. The total thickness is 200 to 330 feet.

The Silurian Brassfield Limestone is a thin formation and is marked with a basal glauconite bed. It is generally olive gray to brown in color and thinly bedded. Partings of shale and chert nodules are present.

The Silurian Wayne Group is made up of limestone and shale. The limestone is argillaceous and has some undulated bedding. It is generally fine grained and thinly to moderately bedded. It ranges from reddish from to light gray and green in color. Fossil fragments and calcite crystals are present. The is very thin, only about 2 to 3 feet of total thickness. It is calcareous and green to gray in color.

The Devonian through Mississippian Chattanooga Shale is a thinly laminated carbonaceous shale. It ranges in thickness from 15 to 58 feet and in color from dark dray to grayish black and pale yellow to brown when weathered. The Chattanooga Shale is widespread and therefore is an excellent regional datum.

The Mississippian Fort Payne Limestone is located on the southern rim of the Wells Creek Structure. It is a light to dark gray limestone and is thinly to medium bedded. It contains chert and dolomite, and is interbedded with green shale throughout.

The Mississippian Warsaw Limestone ranges in color from light to dark gray and texture from fine to coarse grained. It contains highly fossilized sections. The bedding varies from 6 inches to 6 feet. There are several thin zones of brown dolomite and is characterized by large blocks of chert. These blocks range in size from 1 to 2 feet thick.

The Mississippian St. Louis Limestone has two distinct units. The lower unit is brownish gray and fine to medium grained. It is poorly sorted and fossiliferous. It contains bryozoans, crinoids, and brachiopods. The upper unit is light gray to light brown and is very fine to medium grained. It is thin to medium bedded and fossiliferous. Both units contain thin brown to gray dolomite beds.

The Cretaceous Tuscaloosa gravel is undeformed and overlies the structure. It is made up of light gray gravel with silt and clay lenses. This unit acts as the upper age constraint for the impact structure.

2.5 REGIONAL STRUCTURAL HISTORY

The Late Paleozoic Alleghenian Orogeny was the result of continental-continental collision of Laurentia and Gondwana, forming the Appalachian Mountain region. This orogenic event was the last of the Paleozoic and resulted in the melding of Laurentia and Gondwana to form Pangea. The collision caused uplift of the Trans-Pangean mountains and subsequent sedimentation in the region. The uplift in this area was driven by thrust faulting of Cambrian-Ordovician rocks overlain by Middle Ordovician to Lower Mississippian rock (Gwinn, 1964; Wilson & Shumaker, 1992). The structures are both situated near the Nashville Dome, to the east and west respectively, in central Tennessee. The Nashville Dome resulted from sediment loading in the

Appalachian Basin and uplifting along the Cambrian Nashville Rift (Abolins et al., 2017). The structures are both located outside of this uplift and are surrounded by flat lying strata. The Wells Creek is located to the west of the Nashville Dome on the Western highland Rim and the Flynn Creek is located to the east in the Appalachian Basin (Fig. 1).

Deposition and burial of this region occurred throughout the Paleozoic, with about 14,000 ft of strata covering basement rock by the end of the Paleozoic (Stearns and Reesman, 1986). The Chattanooga shale was deposited in the middle of the Wells Creek Structure stratigraphically and covered the Flynn Creek impact site as a result of the Chattanooga sea filling the Appalachian Basin. Much of this was quickly eroded by way of further uplift of the Alleghenian Orogeny and, subsequently, the Nashville Dome (Borella and Osbourne, 1978). The Flynn Creek impact event occurred in 10-50 m of water and deposition of the Chattanooga Shale was minimal (Schieber and Over, 2005; Bray et al., 2019). The location of the Wells Creek, both higher elevation as well as further distance from the basin had less burial at this time. This further uplift and erosion exposed the Flynn Creek impact structure and lead to deposition of the Cretaceous Tuscaloosa Gravel at the Wells Creek impact structure.

A chemical remanent magnetization (CRM), found in Lower Ordovician Knox Group limestones in eastern Tennessee, determined by Bachtadse et al. (1987) can be linked to the Alleghenian orogeny. This magnetization was interpreted as a syn-tilting magnetization that is held in magnetite. The magnetization is interpreted to be caused by a widespread fluid remagnetization event based on inferred paleotemperatures.

Although the abundance of heated brines associated with orogenic events seems to be a likely cause for remagnetization, studies conducted in this region suggest other possible mechanisms for the remagnetization event associated with the Alleghenian Orogeny (Evans et al., 2000). Elmore et al., (2001), conducted a study on two formations, the Helderberg Group and the Oriskany Formation, located in the central Appalachian Valley and Ridge Province. This study examines possible drivers for the remagnetization and determined that not only orogenic type fluids played a role, but also, that the possibility of burial diagenetic processes, such as smectite-to-illite transformation or maturation and migration of organic matter, could have played a role (Elmore et al., 2001).

3. PALEOMAGNETIC STUDIES IN CARBONATE IMPACT STRUCTURES

Target rocks of impacting bolides will behave differently depending on composition. Differences in mechanical and plastic deformation, magnetic properties, and post-impact fluid flow are all related to the type of target rock. Magnetic and gravity anomalies are strong and more likely to be present in igneous and metamorphic rocks, and the only definitive indictor of an impact event in sedimentary rocks is the presence of shatter cones (Pilkington and Grieve, 1992) and planar deformation features like indexed quartz

Numerous studies, discussed below, have attempted to isolate remanent magnetizations related to impacts in carbonate rocks. A small percentage of samples taken from the Kaibab limestone at Meteor Crater, Arizona, were determined to have both a primary remanent magnetization as well as a secondary remanent magnetization that was acquired post-deformationally. The secondary remanent magnetization can be attributed to the resetting of the low coercivity fraction of remanence during the passing of a low-pressure shockwave and therefore interpreted as a shock remanent magnetization (SRM). The Coconino sandstone at Meteor Crater is interpreted to carry a thermal remanent magnetization (TRM) which is interpreted as being set by high temperatures associated with shock deformation. This was determined by analyzing the high natural remanent magnetization (NRM) values in conjunction with the a high NRM/IRM ratio which can indicate that fine-grained magnetite was present and possibly precipitated from melt glass (Cisowski and Fuller, 1978).

Dietz (1947) identified a 4km diameter radial structure in Kentland, Indiana as an impact structure due to the presence of shatter cones. Jackson and Van der Voo (1986) isolated a post-depositional magnetization in this structure within the host Middle Ordovician carbonate rocks. This magnetization has a normal polarity, low unblocking temperatures (about 300°C), and is interpreted as late Cretaceous in age. This magnetization is interpreted to have been acquired during the extended cooling after the impact event as a thermoviscous remanent magnetization (TVRM). Hamilton et al., (2018) re-examined the structure, sampling both country rock and impact breccias, and determined there to be a CRM associated with the Kentland impact, caused by hydrothermal fluid alteration. This was interpreted as a result of both paleomagnetic and diagenetic analysis conducted on the structure. Evidence for hydrothermal fluid alteration can be attributed to vuggy porosity, completely dissolved dolomite clasts, and dissolved cement in sandstone clasts (Hamilton et al., 2018).

The Devonian Alamo Breccia, located in Nevada, is interpreted as a marine carbonate target impact event. A contact test was performed to determine if a magnetization existed exclusively within impact-effected rocks (the Alamo Breccia) or within the host limestones and dolomites. The contact test was a negative; the entire area was remagnetized and there is evidence for diagenetic fluid alteration throughout the rock. The magnetization is interpreted at a CRM imparted by externally derived fluids. This interpretation is supported by Strontium isotope ratios and is not localized within the breccia—indicating a widespread remagnetization event (Evans et al., 2012).

The impact event associated with the Miocene Reis crater in Germany targeted mainly carbonate sedimentary rocks that overlaid crystalline basement rock (Pohl et al., 1977). The result is a suevitic polymict breccia consisting of crystalline clasts with a few incorporated sedimentary clasts. Paleomagnetic studies of this breccia indicate the presence of a TRM that was acquired during the heating and melting of the breccia (Pohl et al., 1977).

Analysis of inclination information derived from unoriented core samples taken from three impact-related breccias in the Manson impact rocks in Iowa was conducted by Steiner et al. (1996). A characteristic remanent magnetization (ChRM), dominantly found in magnetite, was contained in the matrix and breccia clasts. A post-depositional remanence was found held in sedimentary breccia and the inclinations correlated to Cretaceous-aged magnetizations. A steeper inclination, representing secular variation of the Cretaceous geomagnetic dipole, was found in association with a melt breccia. A reversed polarity magnetization residing in hematite and interpreted as subsequent hydrothermal activity was found; although it was poorly defined, this was important in helping develop magnetostratigraphy for this part of geologic history, as most of the Cretaceous was in a normal superchron.

Various paleomagnetic studies have been conducted on breccia samples collected from cores of the Chicxulub impact structure. Inclinations representing the Cretaceous-Paleogene boundary were found in conjunction with a reverse polarity ChRM in melt rocks by Urrutia-Fuugauchi et al. (1994). These inclinations are also consistent in breccias that contain shock features. Melt breccia matrices holding

dual polarity magnetizations were discovered by Steiner et al. (1996), these samples also corresponded to late Cretaceous in age. The heterogeneity and likelihood of hydrothermal activity after an impact event possibly led to a reversed ChRM and opposite polarity remanence in suevitic breccias (Urrutia-Fuugauchi et al., 2004). Target carbonates that held alternating normal and reverse polarity
detrital remanent magnetizations (DRM) were studied and interpreted by Robolledo-Vieyra and Urrutia-Fucugauchi (2004).

Originally described by Offield and Pohn (1979), the Decaturville impact structure in Missouri contains breccia with various carbonate lithologies that range from Cambrian-Ordovician in age. Dulin and Elmore (2008) isolated a CRM that was early to middle Permian in age in both host rock and breccias and is interpreted as a post-deformational magnetization. Although this study further constrained the age of the impact event compared with the stratigraphic constraints, the origin of the magnetization is still unclear; it is interpreted as a CRM caused by fluid alteration immediately following the impact because it is a post-depositional magnetization.

Carporzen et al. (2005) conducted a study on the Vredefort impact in South Africa as an analogue for impact craters located on Mars. Large impact structures tend to exhibit decreased magnetization when compared to surrounding regions—generally attributed to shock demagnetization caused by shock waves induced during an impact event. This study found that the Vredefort impact exhibits high intensity magnetization when compared to equivalent lithologies in other regions that have not been impacted. The magnetizations are highly randomized and essentially cancel each other out when viewed as a whole—creating a false interpretation of shock demagnetization. This study concluded that the magnetic grains that carried this magnetization were in fact created during the impact and that these grains exhibited high paleointensities leading to the interpretation that impacts are magnetizing events as opposed to demagnetizing events.

Kavkova and Kletetscha (2019) conducted a study on the Santa Fe impact crater near Santa Fe, NM. This study analyzed samples within the impact to test whether or not impacts are generally magnetizing or demagnetizing events. This study using incremental alternating field (AF) demagnetization and found that as the samples were demagnetized, the paleointensities significantly decreased and paleodirections become more scattered. This study concluded that large impact events have the potential to be demagnetizing events.

4. METHODS

4.1 FLYNN CREEK METHODS

4.1.1 PALEOMAGNETISM

Nine sites (6-9 samples per site) were sampled along Flynn Creek Road in the center of the Flynn Creek structure in tilted beds of the Flynn Creek Breccia (Fig. 3). The samples were collected by both using a gasoline-powered portable drill and by collection of oriented slabs that were drilled in the lab with a drill press. The samples were oriented using a clinometer and Brunton Compass.

The samples were then cut into 2.2 cm length specimens. The natural remanent magnetizations (NRMs) were measured with a three-axis 2G Enterprises cryogenic magnetometer with DC SQUIDS in the magnetically shielded paleomagnetic laboratory in Sarkeys Energy Center, University of Oklahoma. Specimens from the Flynn Creek Breccia and the Fort Knox Limestone were subjected to alternating field (AF) demagnetization (0-120mT), in steps of 10 mT, in a 2G Enterprises AF demagnetizer. Twenty samples were thermally demagnetized in a stepwise fashion (100-600°C, steps of 100°C through 300°C and then 20°C steps until 600°C) using an ASC Scientific Thermal Demagnetizer. The demagnetization data was analyzed for magnetic directions using the Super-IAPD program (http://www.ngu.no/geophysics/soft32.htm). The data was plotted on Zijderveld diagrams—orthogonal projections representing the horizontal and vertical components of the magnetization in the sample (Zijderveld, 1967). Magnetic directions were determined using principle component analysis (Kirschvink, 1980) with mean angular deviations (MAD) less than 15°, although most MAD's were 10° or less. Fisher (1953) statistics were used to compute the mean directions. Both a regional and local tilt-test was attempted (Watson and Enkin, 1993) and bedding corrections were made to analyze site groupings both geographically and stratigraphically.

Unoriented core from the Flynn Creek structure collected by Roddy (1967-1979), housed at USGS Astrogeology Science Center in Flagstaff, AZ, was sampled and prepared using a rock saw and drill press. Core sections were chosen based on lithology (Flynn Creek Breccia) and size of breccia clasts, in order to perform a conglomerate test if large enough clasts were able to be sampled. A modified conglomerate test would be performed on the breccia if multiple clasts were included in each drilled specimen. There were 35 specimens collected from core that covered a transect of the Flynn Creek structure (Fig. 3). These specimens had their NRMs measured and underwent AF demagnetization (0-120 mT, 10mT steps) in a 2G Enterprises magnetometer and 2G Enterprises AF demagnetizer. They were then analyzed using the Super-IAPD program (http://www.ngu.no/geophysics/soft32.htm). The data was plotted on orthogonal projection diagrams (Zijderveld, 1967). Magnetic directions were determined using principle component analysis (Kirschvink, 1980) with mean angular deviations (MAD) less than 15°, although most MAD's were 10°. The core was unoriented, therefore, we corrected the core direction using the viscous remanent magnetization (VRM) component. This correction is made by rotating the VRM component to 0, correlating it to modern magnetization, ponding ChRM the same distance (Fig. 5). Fisher (1953) statistics were used to compute the mean directions.

Inclination-only plots were also constructed in order verify magnetic components and age in the absence of a successful orientation of the core using the VRM method.

4.1.2 ROCK MAGNETICS

The AF demagnetization results as well as isothermal remanent magnetization (IRM) acquisition were used to determine the magnetic minerology. An IRM was imparted by an impulse magnetizer to representative samples in a stepwise fashion from 0 to 2500 mT. The samples were then subjected to a second AF demagnetization analysis. Analysis of IRM acquisition was performed using Microsoft Excel.

4.1.3 PETROGRAPHY

Petrographic analysis was performed on polished thin sections using both reflected and transmitted light to help determine magnetic minerology as well as impact related deformation. Analysis of thin sections were performed using a Zeiss microscope and imaging was performed using an Axio microimaging camera. Investigation and analysis of magnetic mineralogy was conducted using a FEI Quanta 250 scanning electron microscope (SEM).

4.2 WELLS CREEK METHODS

4.2.1 PALEOMAGNETISM

Eight sites were sampled along the southern rim of the Wells Creek structure from the Fort Payne Limestone (7 sites) and the Warsaw Limestone (1 site) (Fig. 2). Six to nine samples were drilled per site for a total of 61 specimens. The samples were collected by both using a gasoline-powered portable drill and by collection of oriented slabs that were drilled in the lab with a drill press. The samples were oriented using a clinometer and Brunton Compass.

The samples were then cut into 2.2 cm length specimens. The NRMs were measured with a three-axis 2G Enterprises cryogenic magnetometer with DC squids in a magnetically shielded room. Sampling of the Flynn Creek Breccia and the Fort Knox Limestone were subjected to alternating field (AF) demagnetization (0-120mT) in a 2G Enterprises AF demagnetizer. Samples were also thermally demagnetized in a stepwise fashion (100-600°C, steps of 100°C through 300°C and then 20°C steps until 600°C) using an ASC Thermal demagnetizer. The demagnetization data was analyzed for magnetic directions using the Super-IAPD program (http://www.ngu.no/geophysics/soft32.htm). The data was plotted on orthogonal projection diagrams (Zijderveld, 1967). Magnetic directions were determined using principle component analysis (Kirschvink's less than 15°, although most MAD's were 10° or less. Fisher (1953) statistics were used to compute the mean directions. Both a regional and local tilt-test was attempted (Watson and Enkin, 1993) and bedding corrections were made to analyze site groupings both geographically and stratigraphically.

4.2.2 ROCK MAGNETICS

The AF demagnetization results as well as IRM acquisition were used to determine the magnetic minerology. An IRM was imparted by an impulse magnetizer to representative samples in a stepwise fashion from 0 to 2500 mT. the samples were then subjected to a second AF demagnetization analysis. Triaxial decay analysis was then performed in temperature steps up to 700°C. Analysis of IRM was performed using Microsoft Excel.

4.2.3 PETROGRAPHY

Petrographic analysis was performed on polished thin sections using both reflected and transmitted light to help determine magnetic minerology as well as impact related deformation. Analysis of thin sections were performed using a Zeiss microscope and imaging was performed using an Axio microimaging camera. Investigation and analysis of magnetic mineralogy was conducted using a backscatter Scanning Electron Microscope.

5. RESULTS

5.1 FLYNN CREEK PALEOMAGNETISM

Magnetic components were defined from data collected during stepwise thermal demagnetization and alternating field demagnetization. Of the samples subjected to thermal demagnetization, only 18 specimens produced usable data-the other data were too noisy to analyze. Alternating field (AF) demagnetization better isolated the remanent magnetizations-49 specimens produced usable data (Fig. 6). AF demagnetization removed a component interpreted as a viscous remanent magnetization (VRM) at low intensities (0-20mT). The VRM is a magnetization that is held in multi-domain magnetic grains that acquire Earth's magnetization as it changes over time (Tauxe et al., 2002). Generally, the VRM is considered "noise" and rendered useless, but in this study it was used to help orient the unoriented cores that were sampled. The VRM can be used as an analogue to the Modern magnetic direction as it preserves average magnetization over the last tens to hundreds of thousands of years (Fig. 5).

The characteristic remanent magnetization (ChRM) isolated from within the Flynn Creek structure has southeasterly declinations and moderate to steep down inclinations (declination = 152.3°, inclination = 12.2°, n/n_o = 46/71, k = 25.2, $\alpha95$ = 11.3) (Table 1). The magnetization decays to origin by 120 mT or around 500°C, dependent on whether alternating field or thermal demagnetization was conducted on the specimens. From the nine sites collected in the field and the nine different cores, 67 specimens carried the ChRM. The NRMs of the samples were weak, averaging 0.04-0.1 mA/m. Low initial intensities are common in limestones, and have been observed in other carbonate impacts (Dulin and Elmore 2008, Hamilton et al. 2018, Evens et al, 2012). .

Both a regional and local tilt-test was attempted (Watson and Enkin, 1993), but was statistically insignificant due to the small variation in regional tilts. Therefore, a bedding correction was made and the grouping parameters for both the geographic and stratigraphic site means were compared (Table 1). The geographic site means had a better grouping (k=25.2) than stratigraphic site means (k=7.1), which is indicative of a port-deformational ChRM. The modified conglomerate test also indicated a post-deformational ChRM as evidence by consistent consistent magnetic components throughout the sampled breccias. The geographic mean of the ChRM has a declination = 152.3°, inclination = 12.2°, k = 25.15, and $\alpha95$ = 11.3 (Table 1)(Fig. 7).

The age of the ChRM from both the field sites as well as the core sites was determined by plotting the pole position of the post-tilting magnetization on the apparent polar wander path (APWP) for North America (Torsvik et al., 2012). The pole position lies at 39.9°N, 131.3°E (d_p = 5.8°, d_m = 11.5°)(Fig. 8). This lies on the late Carboniferous-early Permian portion of the APWP. An inclination-only plot was constructed for North America to plot the unoriented core inclinations to confirm the plotted pole position. The VRM method successfully worked to orient the Flynn Creek samples as evidence by the modern inclination at the Flynn Creek impact structure being in line with the mean value of the corrected VRM components for each specimen (modern inclination = 65°, corrected VRM = 67.2°).

5.2 FLYNN CREEK ROCK MAGNETISM

An IRM was imparted on two samples of Flynn Creek Breccia collected from the field. The samples were nearly completely saturated by 300 mT (Fig. 10), which is indicative of a low coercivity magnetic carrier such as magnetite. One of the samples showed a slight rise above 300 mT, indicating the presence of a higher coercivity phase, such as hematite, although this is not interpreted as the carrier of the NRM based on AF and thermal decay of the ChRM by 120mT or 500°C, respectively.

5.3 FLYNN CREEK PETROGRAPHIC RESULTS

The Flynn Creek Breccia samples are classified as fossiliferous wackestone or packstone with some sparry calcite present (Fig. 11). Brachiopods and crinoids are present. Some of the allochems, collected from deformed formations, seem to be sheared and broken (Fig. 11). Dolomite is present throughout and pyrite is abundant. Iron oxides can be found as well. SEM analysis indicates the presence of iron oxides and pyrite alteration. SEM analysis also indicated the presence of iron oxides and clays associated with porosity—indicative of fluid alteration (Fig. 11).

5.4 WELLS CREEK PALEOMAGNETISM

Magnetic components were defined from data collected during stepwise thermal demagnetization and alternating field demagnetization. Of the samples subjected to thermal demagnetization, 27 specimens produced usable data (Fig. 12) the other data were too noisy to analyze.

The ChRM has southeasterly declinations and moderate to shallow down inclinations (declination = 152°, inclination = 18.5°, n/n_o = 43/61, k = 105.7, $\alpha 95$ = 6.5)(Table 1). The magnetization decays to origin by 120 mT or before 500°C, dependent on whether alternating field or thermal demagnetization was conducted on the specimens. The fact that magnetization decayed to nearly zero by 120mT in AF demagnetization and is unblocked by 580°C suggests that the magnetization resides in magnetite. From the nine sites collected in the field, 57 specimens carried the ChRM. As in the Flynn Creek samples, the Wells Creek NRMs are also weak, ranging from 0.06 to 0.08 mA/m.

Both a regional and local tilt-test was attempted (Watson and Enkin, 1993), but was statistically insignificant due to the small variation in regional tilts. Therefore, a bedding correction was made and the grouping parameters for both the geographic and stratigraphic site means were compared (Table 1). The geographic site means had a better grouping (k=105.7) than the stratigraphic means (k=14.5), which is indicative of a port-deformational ChRM. The geographic mean of the ChRM has a declination = 152°, inclination = 18.5°, k = 105.7, and $\alpha95$ = 6.5 (Table 1)(Fig. 13).

The age of the ChRM from both the field sites as well as the core sites was determined by plotting the pole position of the post-tilting magnetization on the apparent polar wander path (APWP) for North America. The pole position lies at 37.1°N, 127.9°E (dp = 3.5°, dm = 6.8°) (Table 1). This lies on the late Carboniferous-early Permian portion of the APWP.

5.5 WELLS CREEK ROCK MAGNETISM

An IRM was imparted on two samples of Fort Payne limestone collected from the field. The samples were nearly completely saturated by 500 mT (Fig. 14), which is indicative of a low coercivity magnetic carrier such as magnetite. There is slight increase in saturation around 2000 mT, this indicates that hematite is present but based on paleomagnetic and petrographic evidence the magnetic carrier is interpreted as magnetite.

5.6 WELLS CREEK PETROGRAPHIC RESULTS

The Fort Payne limestone samples, located on the southern rim of the Wells Creek impact structure, are classified as a fossiliferous grainstone (Fig. 15). Crinoids are the most abundant and brachiopods are present as well. Some of these allochems found in the deformed rocks are sheared and broken. Dolomite is present as well as pyrite. Iron oxides and evidence for alteration were found in SEM analysis

6. DISCUSSION

The magnetization found in both these impact craters plot on the late Carboniferous to early Permian portion of the APWP (Fig. 8). The Flynn Creek at latitude = 39.9°, longitude = 131.3° with d_p = 5.8° and d_m = 11.5°. The Wells Creek at latitude = 37.1°, longitude = 127.9° with d_p = 3.5° and d_m = 6.8°. It is clear that these magnetizations are not unique to each impact but rather the result of a younger regional remagnetization, similar to that found in the Alamo Breccia in Nevada that exhibited a post deformational CRM imparted by externally derived fluids (Evans et al., 2012). Based on AF decay by 120 mT, low unblocking temperatures, and IRM acquisition (Fig. 10, Fig. 14) the interpreted carrier of this magnetization is magnetite. Petrographic and SEM analysis (Fig. 11, Fig. 15) indicate alteration of pyrite and secondary iron oxides; this, along with the regional setting near the Alleghenian Orogeny and Appalachian Basin can lead to the interpreted mechanism of remagnetization to be fluid alteration. Fluid alteration is the likely mechanism as evidence by thermal decay up to 500°C (Fig. 6, Fig. 12), clays and dolomite associated with porosity, and alteration of pyrite (Fig. 11, Fig. 15). The heated brines associated with the Alleghenian Orogeny would have infiltrated the impact sites, and likely the surrounding region, imparting a CRM.

The deformed carbonates in the Flynn Creek and Wells Creek impact structures both contain a late Carboniferous to early Permian magnetization that is interpreted to reside in magnetite. Magnetization can be imparted by impacts, but because the ChRM carried at the individual structures is so widespread (the structures are about 140 miles apart) it is unlikely that the impact was directly the cause of the magnetization. This magnetization also correlates to a ChRM reported by Bachtadse et al. (1987) and another by Elmore et al. (2001) in both eastern Tennessee and the Appalachian Valley and Ridge Province. The origin of the ChRM is a remagnetization event associated with the Alleghenian Orogeny, although the mechanisms for that remagnetization could vary.

Bachtadse et al. (1987) interpreted the magnetization to be a syn-tilting magnetization, held in magnetite, that was imparted by heated orogenic brines. Elmore et al. (2001) found this same magnetization in two Formations, the Helderberg Group and the Oriskany Formation, and proposed that there could be the possibility of other mechanisms driving the remagnetization—potentially, a combination of orogenic fluids and burial diagenetic processes. Tilt tests conducted on samples in and between the Flynn Creek and Wells Creek impact structures were inconclusive—likely due to little variation in orientations. The bedding correction indicated that the site means were better grouped in geographic coordinates—indicating a post-deformational magnetization. The modified conglomerate test conducted on the Flynn Creek core also indicated that the magnetization was imparted post-deformationally.

Elmore et al. (2012) discusses remagnetization mechanisms in sedimentary rocks and places them in two groups, either externally derived fluid remagnetization or burial remagnetization mechanisms. External fluid remagnetizations are caused by a number of different fluid interactions, most notably orogenic fluids; although, mineralizing fluids, weathering fluids, and hydrocarbons can impart magnetizations as well although no evidence of hydrocarbons was found through petrographic or SEM analysis.

Mineralizing fluid remagnetization can be associated with Mississippi Valley Type (MVT) deposits (Symons et al., 2005) and although these are found in Tennessee, they are confined to regions outside of our study area (Bachtadse et al., 1987). Bachtadse et al. (1987) determined that the magnetite carrier found was secondary and was younger than the MVT deposits—this was based on a tilt test indicating that the magnetization created by the MVT fluid migration occurred pre-deformation and the magnetization found in the Knox group was imparted post deformation. Petrographic analysis of the two Tennessee impacts suggest that pyrite was altered, potentially leading to iron oxides being formed, but no evidence of galena or sphalerite was present. The modified tilt test that was performed on the Flynn Creek impact crater also suggests a post deformational magnetization. As a result, the magnetization found by Bachtadse et al. (1987) was not related to the MVT mineralization event, but it cannot be ruled out that the magnetic carriers were formed due to this process. The ChRM found in the Flynn Creek and Wells Creek structures is interpreted as secondary remagnetization; the mineralization is post deformational and not wide-spread—it is likely not related to MVT mineralization.

Weathering fluid induced magnetizations are generally carried in hematite. With low unblocking temperatures (<580°C) and decay by 120m, the ChRM in the impact craters are carried in magnetite, and is likely not related to meteoric fluids. IRM acquisition data from both the Flynn Creek and Wells Creek structures also indicates that magnetization is held in magnetite, due to nearly complete saturation by 500 mT. The Flynn Creek and Wells Creek impact structures are a considerable distance away from each other and from the locations of sampling in both Bachtadse et al. (1987) and Elmore et al. (2001). Although the impacts were not buried to significant depths and may be subject to weathering processes due to that fact and their relatively higher elevation near the Nashville Dome, it is unlikely that this magnetization was imparted by weathering fluid alteration.

Burial-driven remagnetization is unlikely because the lack of burial history of the impact craters. The minimal burial at these sites and the geographic high that the Wells Creek impact structure is located at contradicts the notion that burial diagenetic processes could have played a role in imparting the ChRM found in these sites. The majority of burial is also associated with the Chattanooga Shale, which occurred before the Wells Creek impact event even happened (Fig. 4) further supporting that burial processes are not the mechanism for which this magnetization was imparted. The smectite-illite transition has been invoked as a mechanism for remagnetization (Elmore et al., 2012). There are some clays present in these rocks, as identified by SEM and petrographic microscopy; additional work is needed to determine the percentages and types of clay before this can be ruled out as a remagnetization mechanism.

This leads to an interpretation that the remagnetization was caused by orogenic fluids resulting from the Alleghenian orogeny and the magnetization can be interpreted as a CRM—by evidence of fluid alteration found in petrographic analysis and unblocking temperature up to 500°C. These fluids could have migrated along aquifers (Bethke & Marshak, 1990) driven by compression similar to the “Squeegee Model” of Oliver (1992) or by gravitational flow of fluids (Bethke & Marshak, 1990; Garven, 1995). The Flynn

Creek and Wells Creek impact structures are a considerable distance from the orogenic thrust belt, being on the opposite side of the Appalachian Basin, it is unlikely that gravitation flow of meteoric fluids would have been able to infiltrate these structures, as is evidence by lack of weathering mineralization. The Wells Creek impact structure also resides on a geographic high, on the Western Highland Rim of the Nashville Dome, leading to a likely interpretation that some type of compression would have driven fluids to these structures to cause the remagnetization.

Regardless of the origin of the magnetization found in both the Flynn Creek and Wells Creek Structures, the paleomagnetic results help to confine the age of the Wells Creek Structure—moving the upper limit from Cretaceous to late Carboniferous or early Permian. The Flynn Creek Impact age was not further confined, but because it carries the same magnetization it can be used to help verify the age and extent of the CRM found in this region.

7. CONCLUSION

The Flynn Creek and Wells Creek impact structures both contain a magnetization residing in magnetite. The age of this magnetization is late Carboniferous to early Permian, constraining the age of the Wells Creek Impact structure significantly better than the stratigraphic age constraints (300-325 Ma). The origin of the magnetization is a regional remagnetization event associated with the Alleghenian Orogeny, likely a CRM related to orogenic brines that were driven to the far western side of the Appalachian Basin orogenic compressional forces. The results of this study show that paleomagnetic methods can be used to help constrain the timing of deformation of the Wells Creek impact structure. The results also indicate that the remagnetization event associated with the late Paleozoic Alleghenian Orogeny effected an even larger region than that immediately surround the uplifted region and that this magnetization was likely imparted as a result of fluid alteration driven by compressional forces.

8. DATA TABLE

Site	N/No	Dec	Inc	Dec	Inc	k	Alpha 95
Flynn Creek		**Stratigraphic**		**Geographic**			
FC1	2/6	129.4	-2.1	129.6	12.7	12.05	79.8
FC3	2/9	163.5	18.6	161.6	7.3	116.77	23.3
FC4	7/8	162.7	30.3	159.3	9.2	116.07	5.6
FC5	8/8	157.9	1.8	157.9	1.8	36.11	9.3
FC6	5/9	164.4	42.9	150.1	14.9	5.48	36
FC7	6/9	215.8	56.3	157.3	29.3	7.93	25.4
FC9	4/6	146.8	6.5	144.3	0.4	48.29	13.4
Flynn Creek Core							
FC67-3	1/1			177.7	2.3	N/A	0
FC67-4	2/2			110.8	6.9	36.39	42.7
FC67-5	4/4			160.2	10.5	17.78	22.4
FC79-12	3/5			151.5	10.9	12.99	35.7
FC67-18	2/2			165.5	18.6	17.9	63
Flynn Creek Mean							
FC MEAN	46/69	Geographic		152.3	12.2	25.15	11.3
		Stratigraphic		158.4	23.3	7.34	23.9
Wells Creek		**Stratigraphic**		**Geographic**			
WC4	10 OF 13	151.4	-8.7	151.1	15.3	87.34	5.2
WC5	7 OF 9	154.7	10	143.2	16.1	19.07	14.2
WC6	8 OF 12	152.4	16.5	157.3	17.7	10.75	17.7
WC7	8 OF 10	141.4	18	147.1	22.1	6.58	23.3
WC8	6 OF 8	159.1	28.4	160.2	12.7	40.23	10.7
WC9	4 OF 9	166.5	52.3	152.8	26.2	69.42	11.1
Wells Creek Mean							
WC MEAN	43/61	Geographic		152	18.5	105.7	6.5
		Stratigraphic		153.3	19.5	14.48	18.2
Pole Position		**Latitude**	**Longitude**	**Dp**	**Dm**		
Flynn Creek		39.9	131.3	5.8	11.5		
Wells Creek		37.1	127.9	3.5	6.8		

Table 1: DATA TABLE OF GEOGRAPHIC SITE MEANS

9. FIGURES

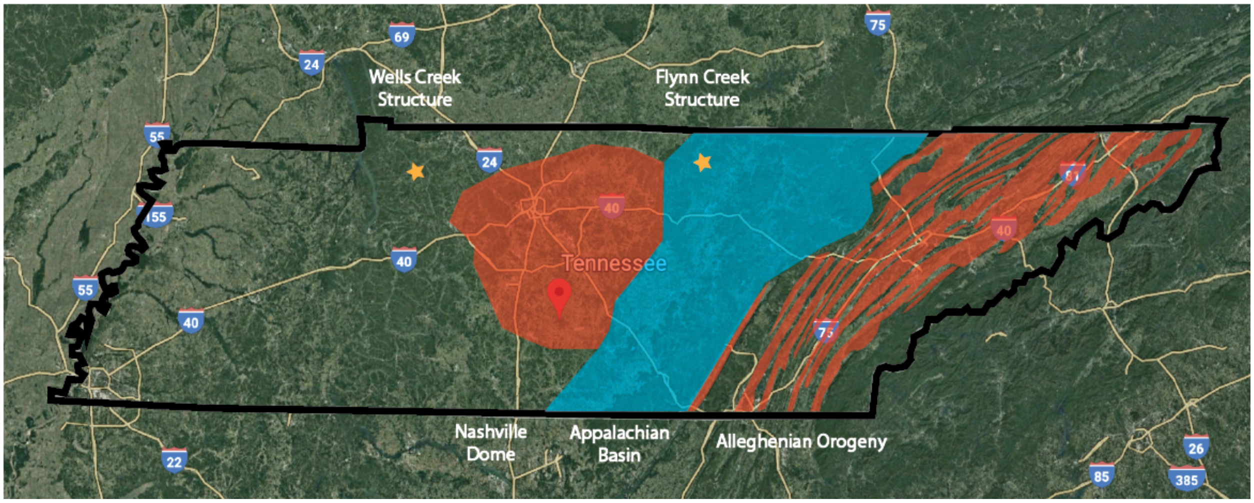


Figure 1: MAP OF TENNESSEE

Satellite map of Tennessee that shows both the Flynn Creek and Wells Creek impact structures (yellow stars). The radii of the structures are smaller than the stars. The areas highlighted in red are areas of uplift, the Alleghenian Orogeny and the Nashville Dome. The area highlighted in blue is the Appalachian Basin. The Flynn Creek structure lies to the east of the Nashville Dome within the Appalachian Basin and the Wells Creek Structure lies to the west of the Nashville Dome on the Western Highland Rim. (modified from Google Earth)

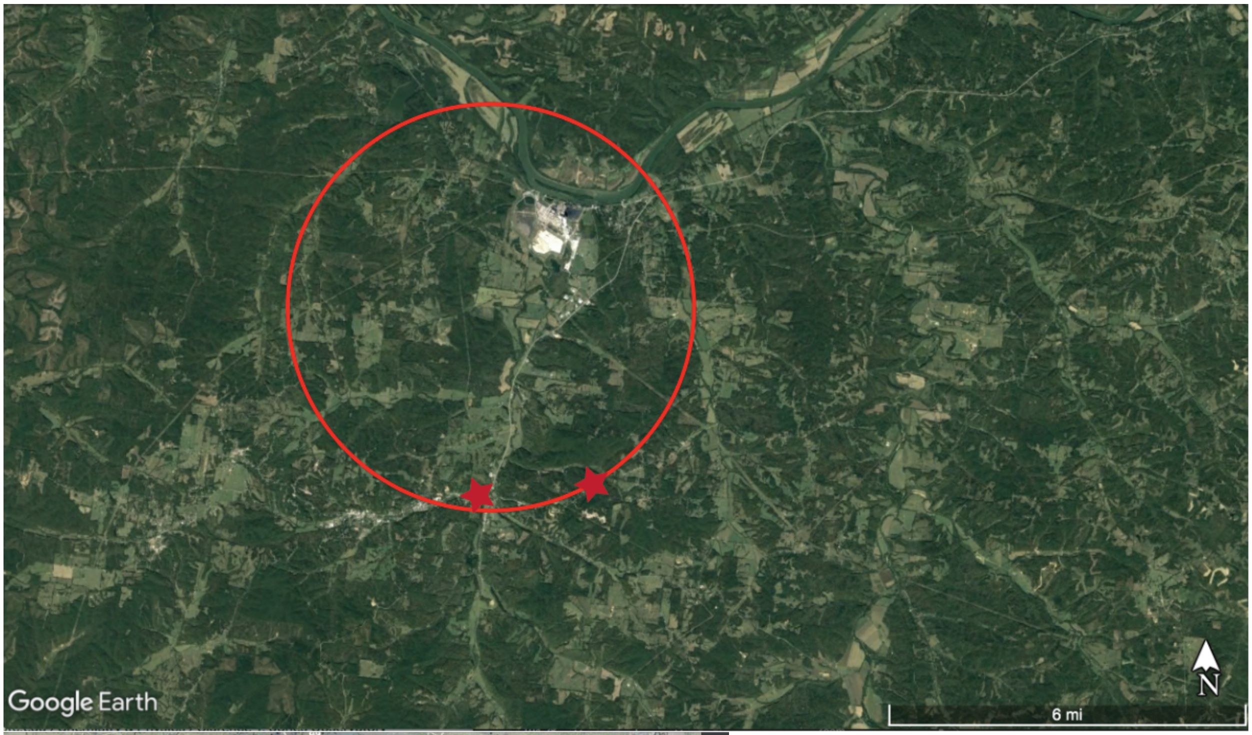


Figure 2: WELLS CREEK MAP

The upper image is a satellite map showing the radial structure of the Wells Creek impact structure with sample locations marked with red stars. The western site is the Fort Payne Limestone and the eastern site is the Warsaw Limestone. The map to the left is the corresponding geologic map—radial faulting can be seen. (Google Earth, USGS MapViewer)

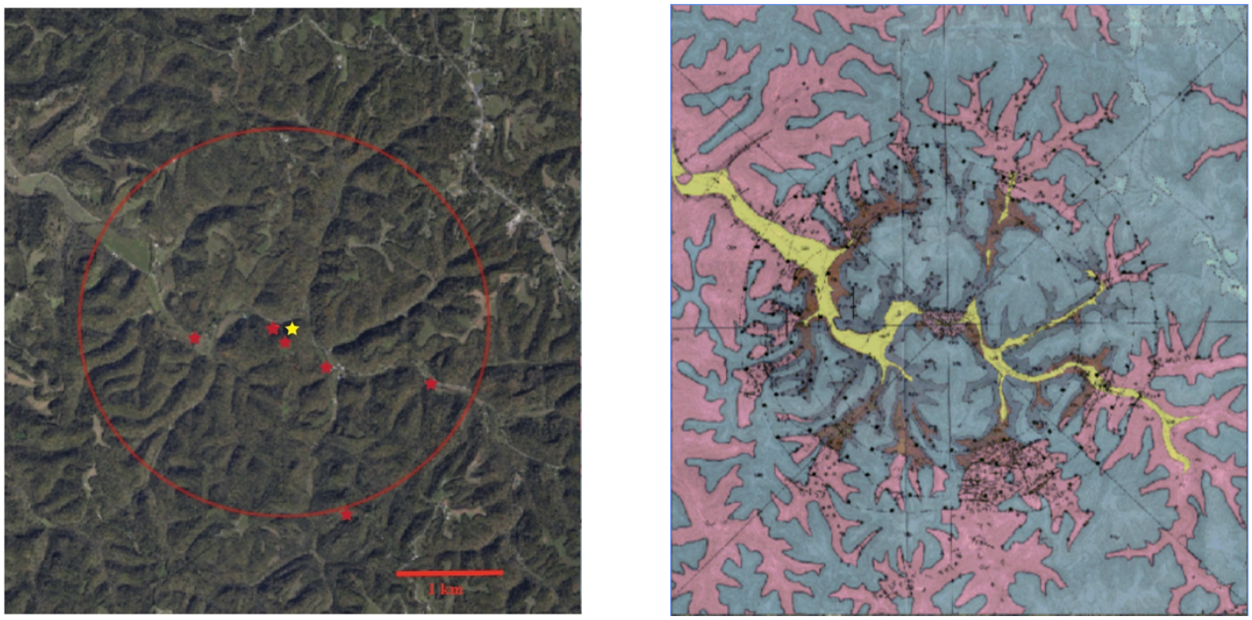


Figure 3: FLYNN CREEK MAP

The image on the left is a satellite map of the Flynn Creek Structure showing its radial structure with sample locations marked. The red stars indicate sample locations taken from core and the yellow star indicates field sampling locations. The image on the right is the corresponding geologic—radial drainage patterns can be seen. (Google Earth, Evenick and Hatcher, 2007)

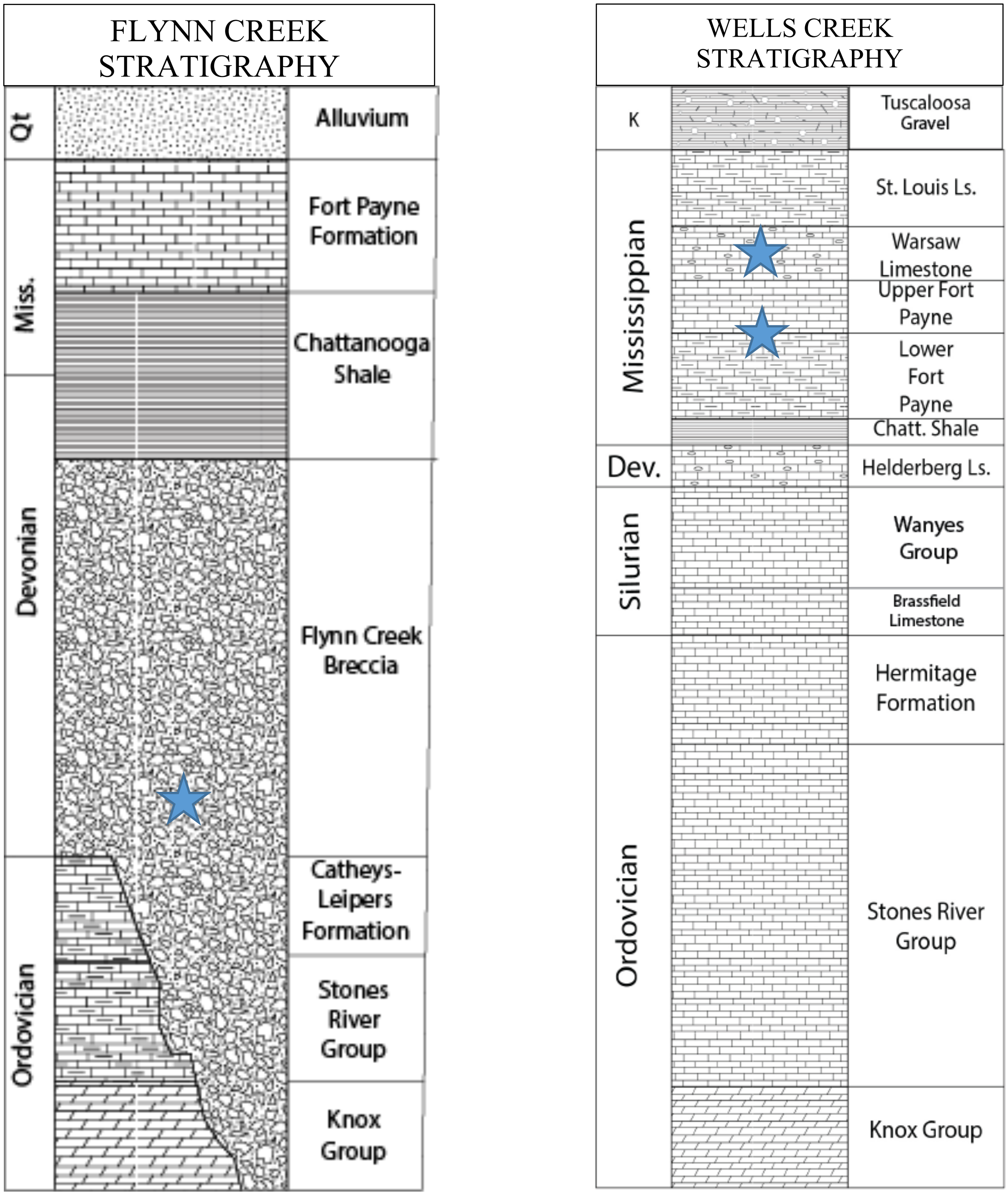
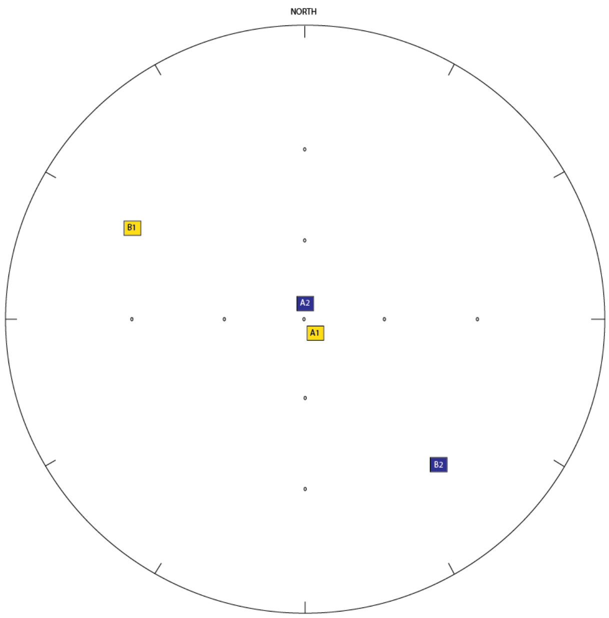


Figure 4: STRATIGRAPHIC COLUMN

Stratigraphy columns of the Flynn Creek (left) (modified from Conant and Swanson, 1961; Evenick and Hatcher, 2007) and Wells Creek (right) (modified from Wilson and Stearns, 1968) impact structures with blue stars indicating the units that were sampled.



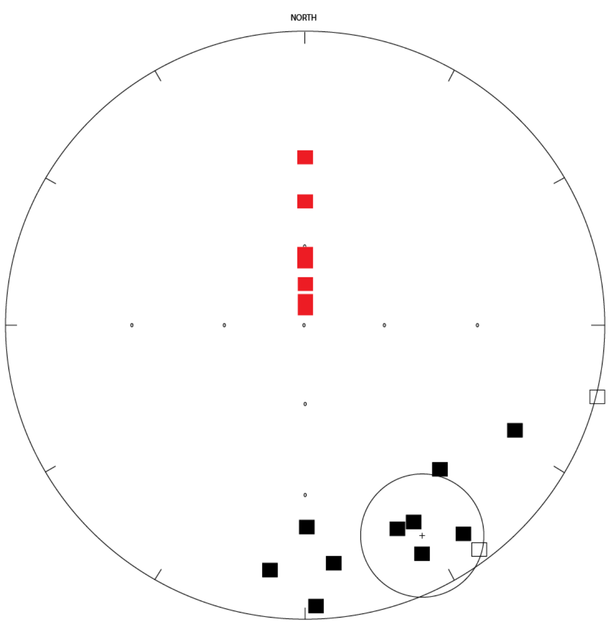


Figure 5: VRM CORRETION FOR UNORIENTED CORE

The upper image shows the VRM correction performed for the unoriented core collected from the Flynn Creek impact structure. The yellow box labeled “A1” is the VRM component picked for the specimen and the blue box labelled “A2” is the corrected VRM. The declination was reduced to 0 rotating the point to zero. The boxes labelled “B1” and “B2” are the corresponding components. The declination was rotated the same number of degrees as the VRM component in order to adjust for the lack of core orientation in these samples.

The lower image is an equal area plot of all the specimens from the Flynn Creek core, closed symbols are positive inclinations and open symbols are negative inclinations. The red boxes are the corresponding VRM components that have all been corrected.

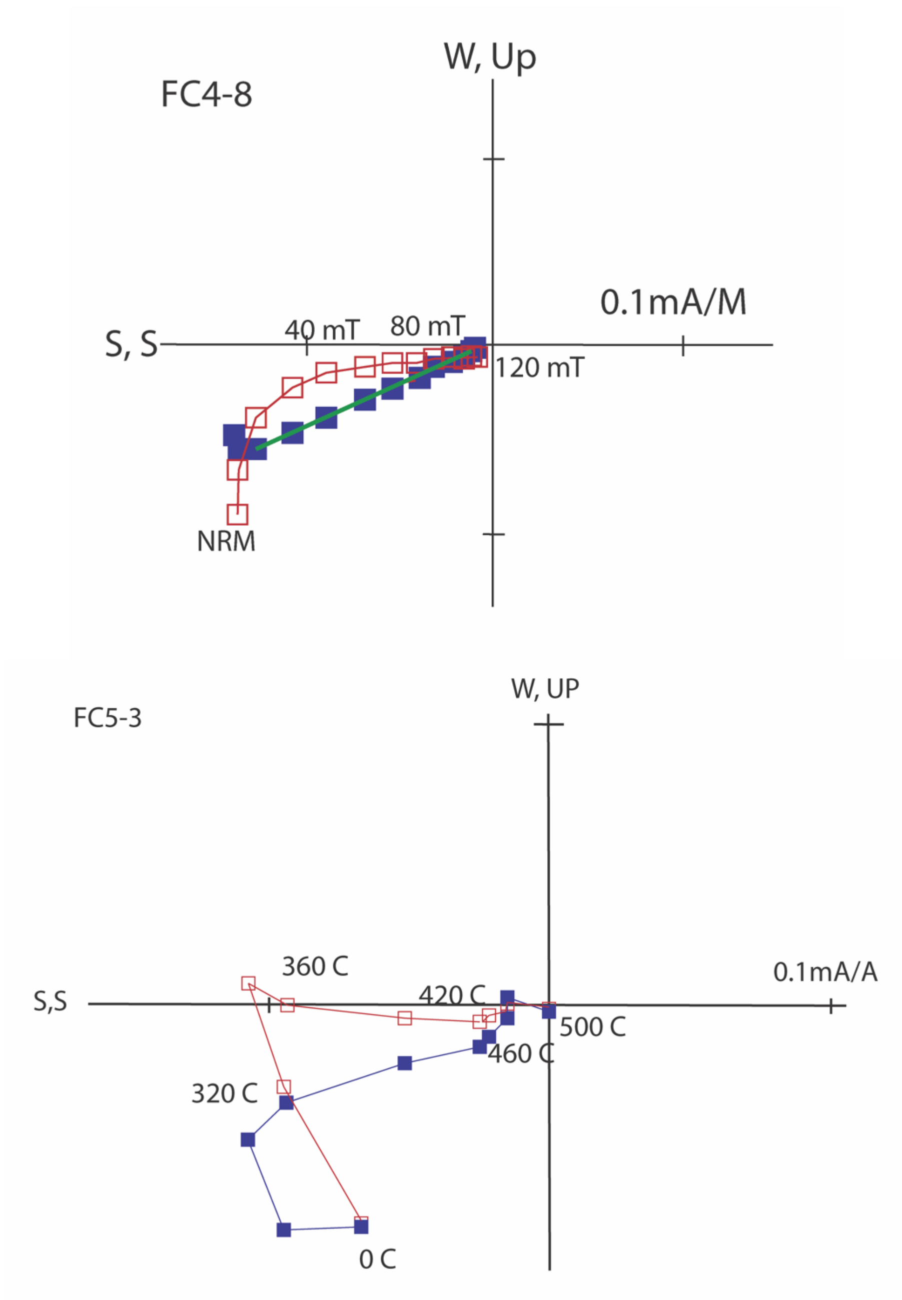


Figure 6: FLYNN CREEK ZIJDERVELD DIAGRAMS

Zijderveld diagrams showing the decay of magnetization within the limestones. Closed symbols represent the horizontal component; open symbols the vertical. The upper image shows representative AF demagnetization and the lower shows representative thermal demagnetization. Both show southeasterly components and down inclinations.

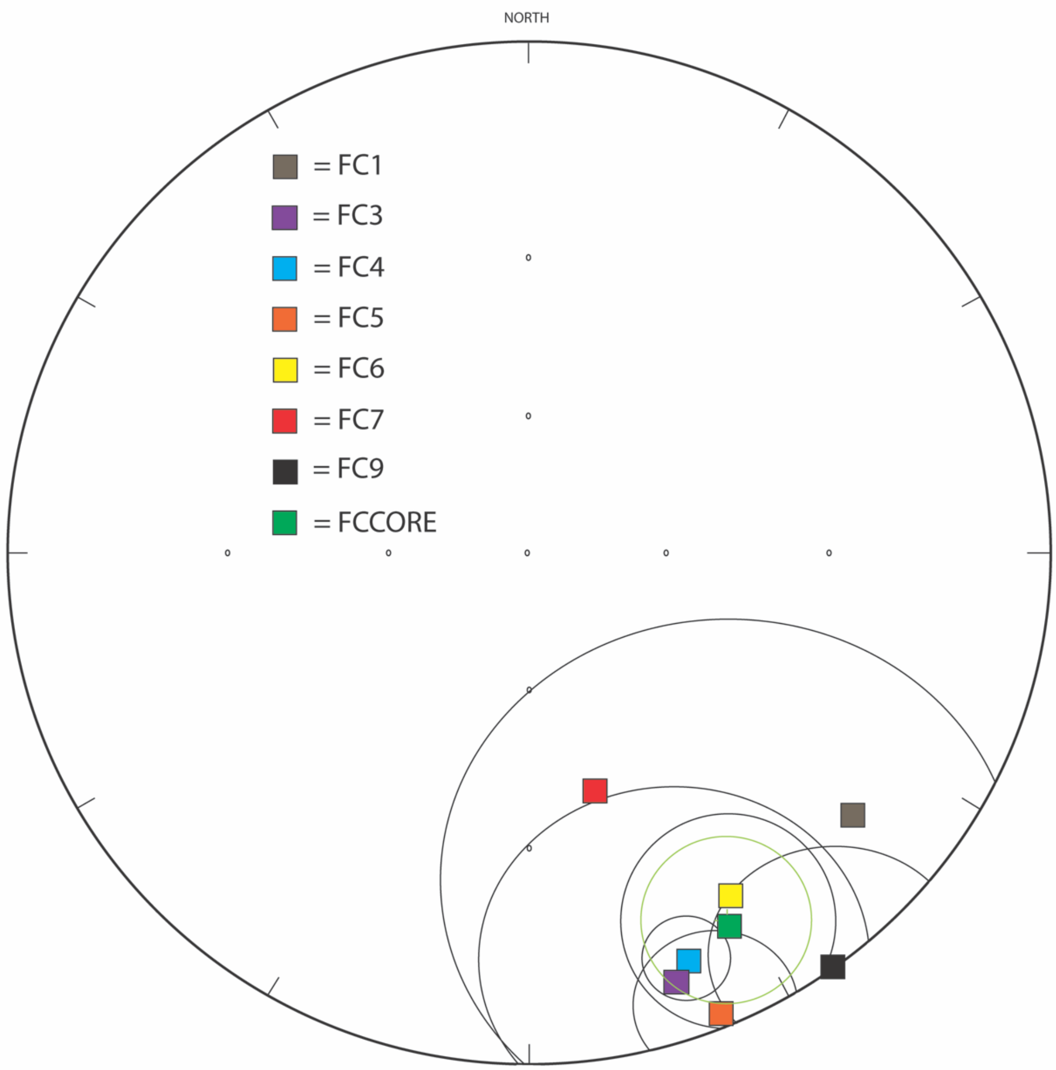


Figure 7: FLYNN CREEK SITE MEAN EQUAL AREA DIAGRAM

Equal area diagram showing the site means for the Flynn Creek Breccia collected from the core as well as from the field. The core was analyzed as one site. The different colored boxes represent different sites and the circle represents the mean of the site means. The black circles represent individual site means and the light green circle and crosshair represents the site mean.

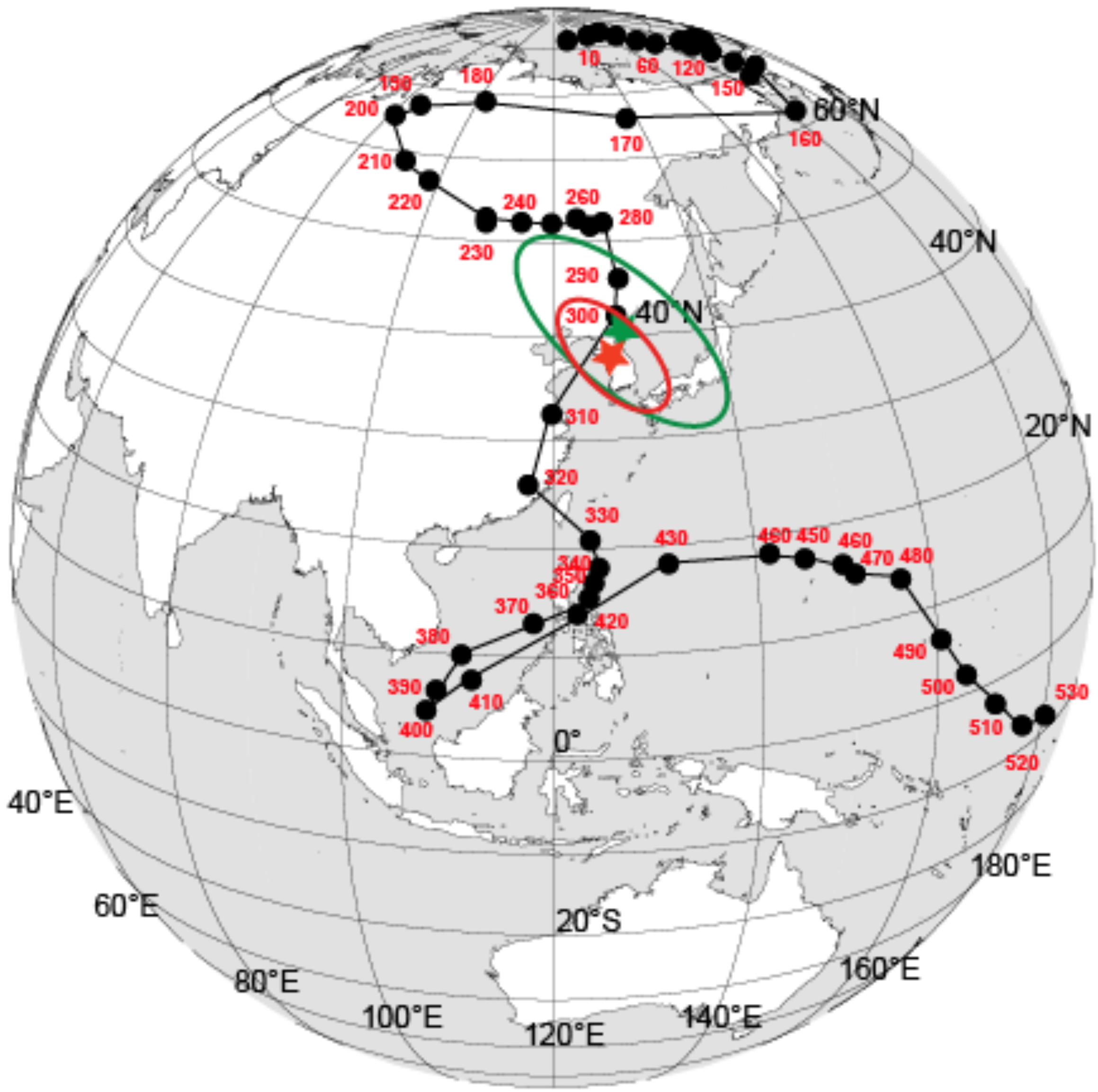


Figure 8: APPARENT POLAR WANDER PATH

The APWP for North America showing both the Flynn Creek (green star and ellipse) and Wells Creek (red star and ellipse) impact structures. The star indicates the pole position and the ellipse indicates the error.

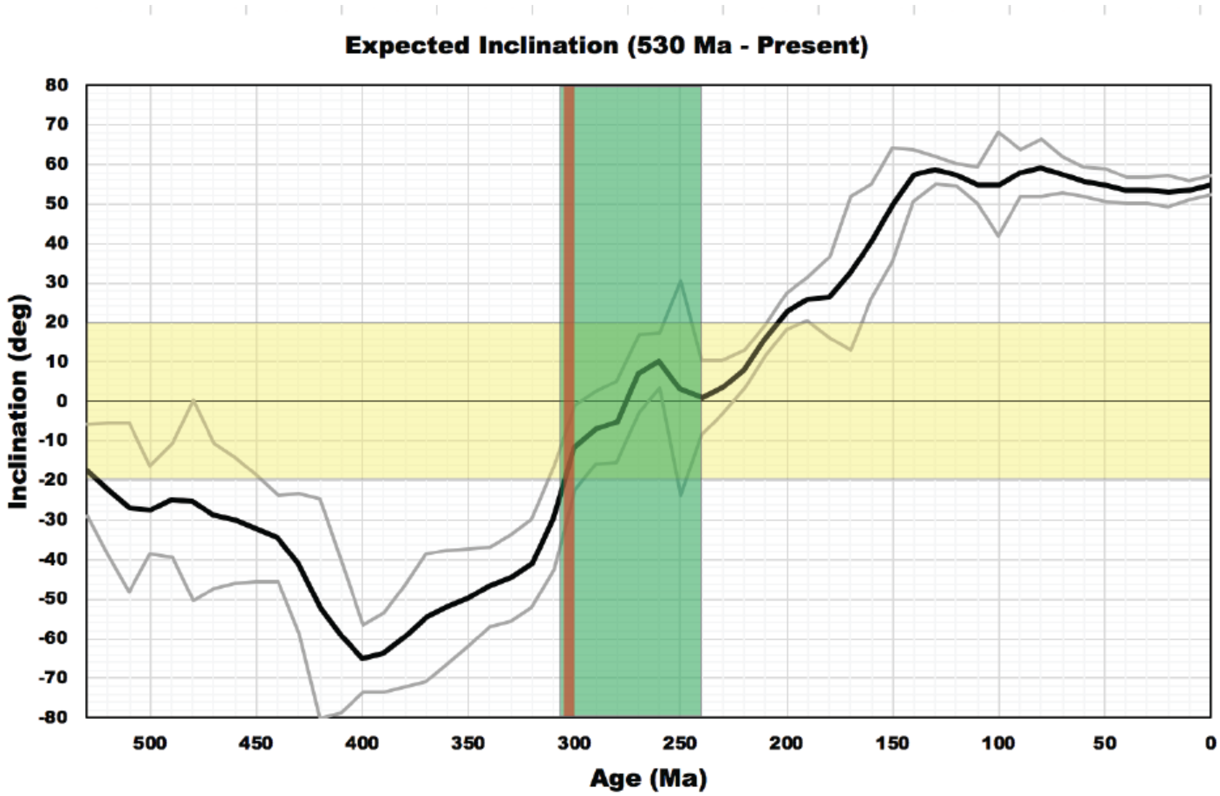


Figure 9: INCLINATION ONLY PLOT

Inclination only plot for the Flynn Creek impact structure. Horizontal yellow box indicates the inclination values found within the core specimens. Vertical green box shows the pole position with error of the Flynn Creek impact structure without including the core specimens on the APWP. Vertical red box shows the pole position with error of the Wells Creek impact structure on the APWP.

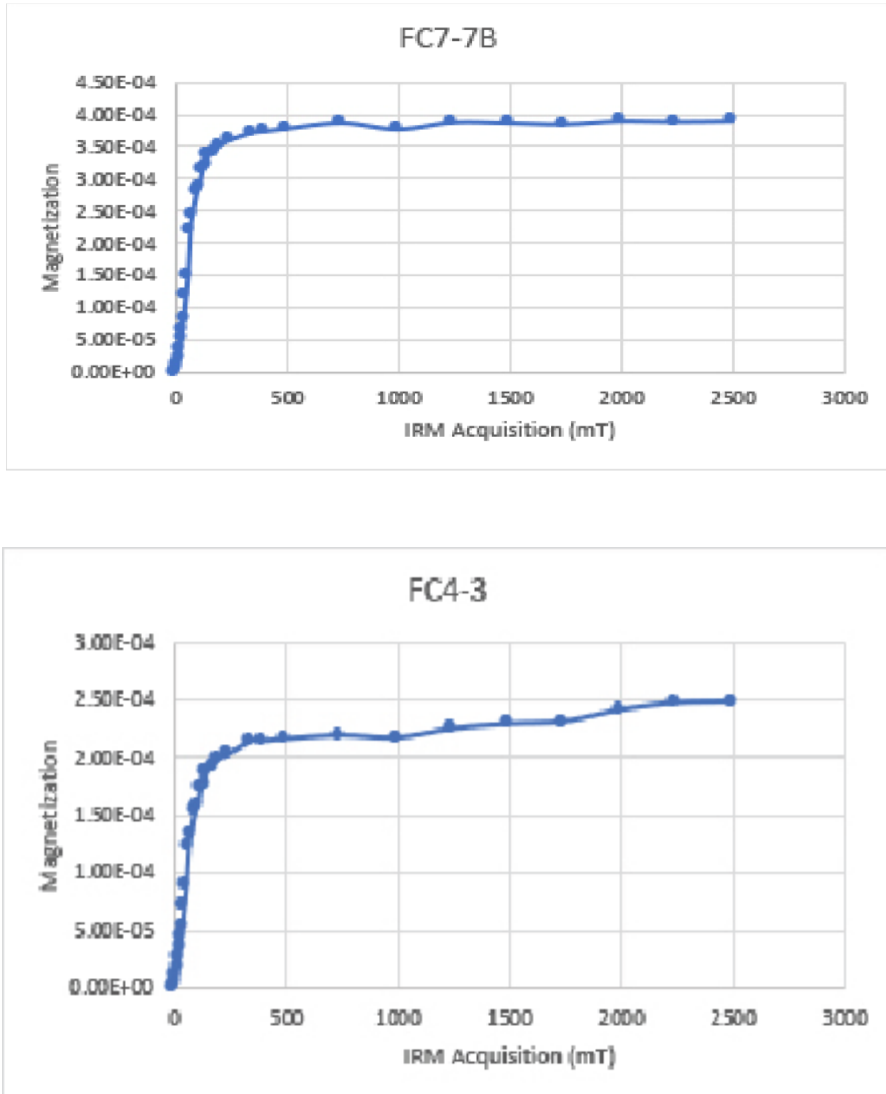


Figure 10: FLYNN CREEK IRM ACQUISITION

IRM acquisition for two specimens within the Flynn Creek Breccia that exhibit nearly complete saturation by 300 mT.

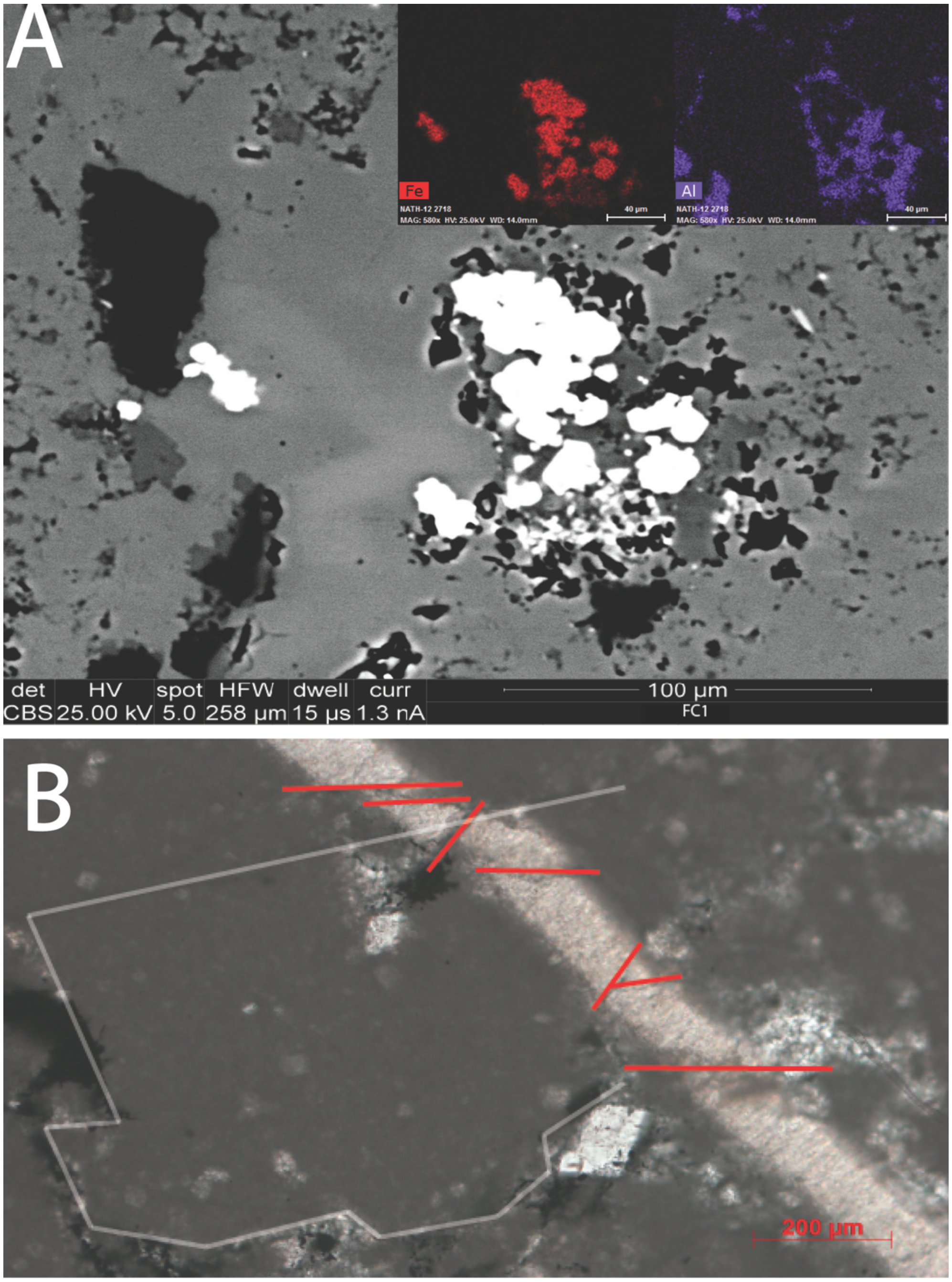


Figure 11: PETROGRAPHIC AND SEM—FLYNN CREEK

A) Backscattered electron SEM image of an iron oxide (white mineral), interpreted as secondary magnetite, surrounded by authigenic clays (dark gray mineral)—both found in association with pore space. Iron mapping (red) and aluminum mapping (purple) can be seen in the upper right hand corner.

B) Shows a reflected light image of the Flynn Creek Breccia with a breccia clast outlined in white and a broken allochem with fractures outlined in red. Dolomite associated with pore space.

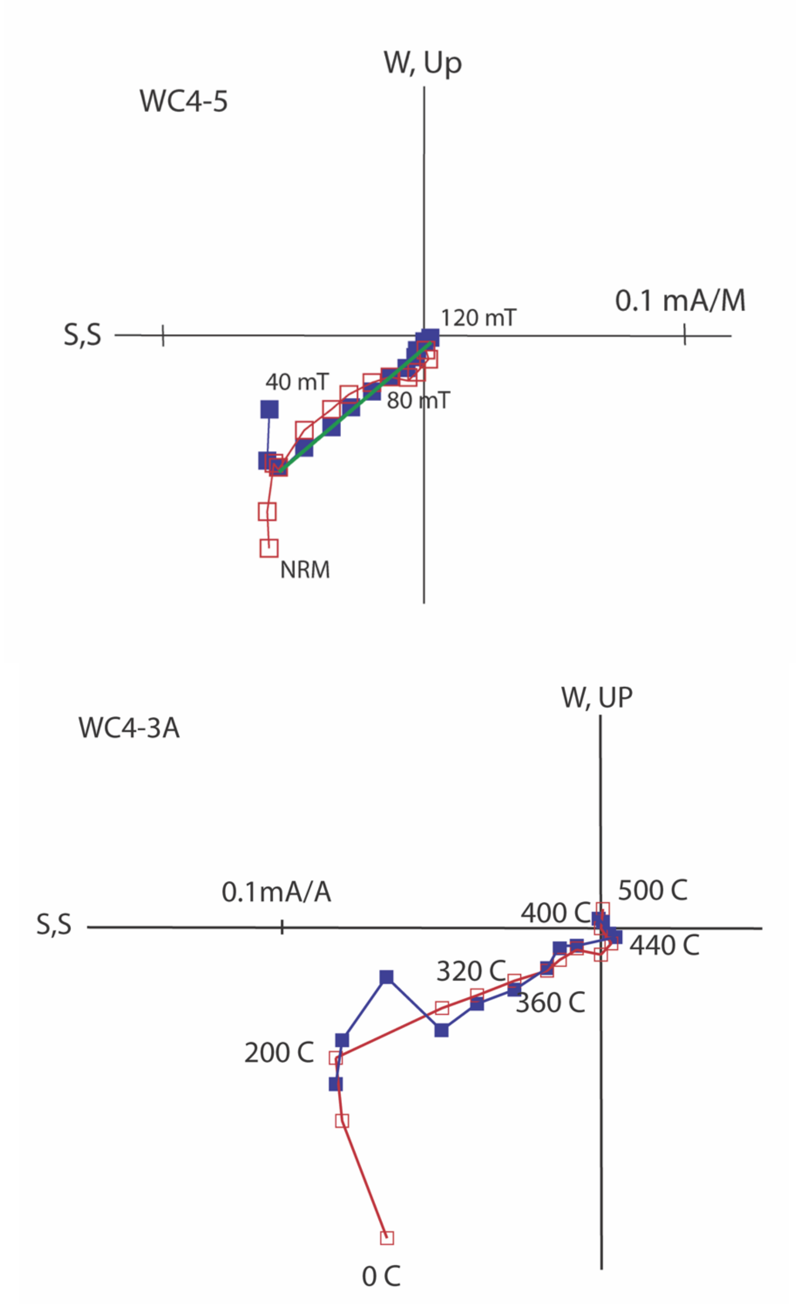


Figure 12: WELLS CREEK ZIJDERVELD DIAGRAMS

Zijderveld diagrams showing the decay of magnetization within the limestones. Closed symbols represent the horizontal component; open symbols the vertical. The upper image shows representative AF demagnetization and the lower shows representative thermal demagnetization. Both show southeasterly components and down inclinations.

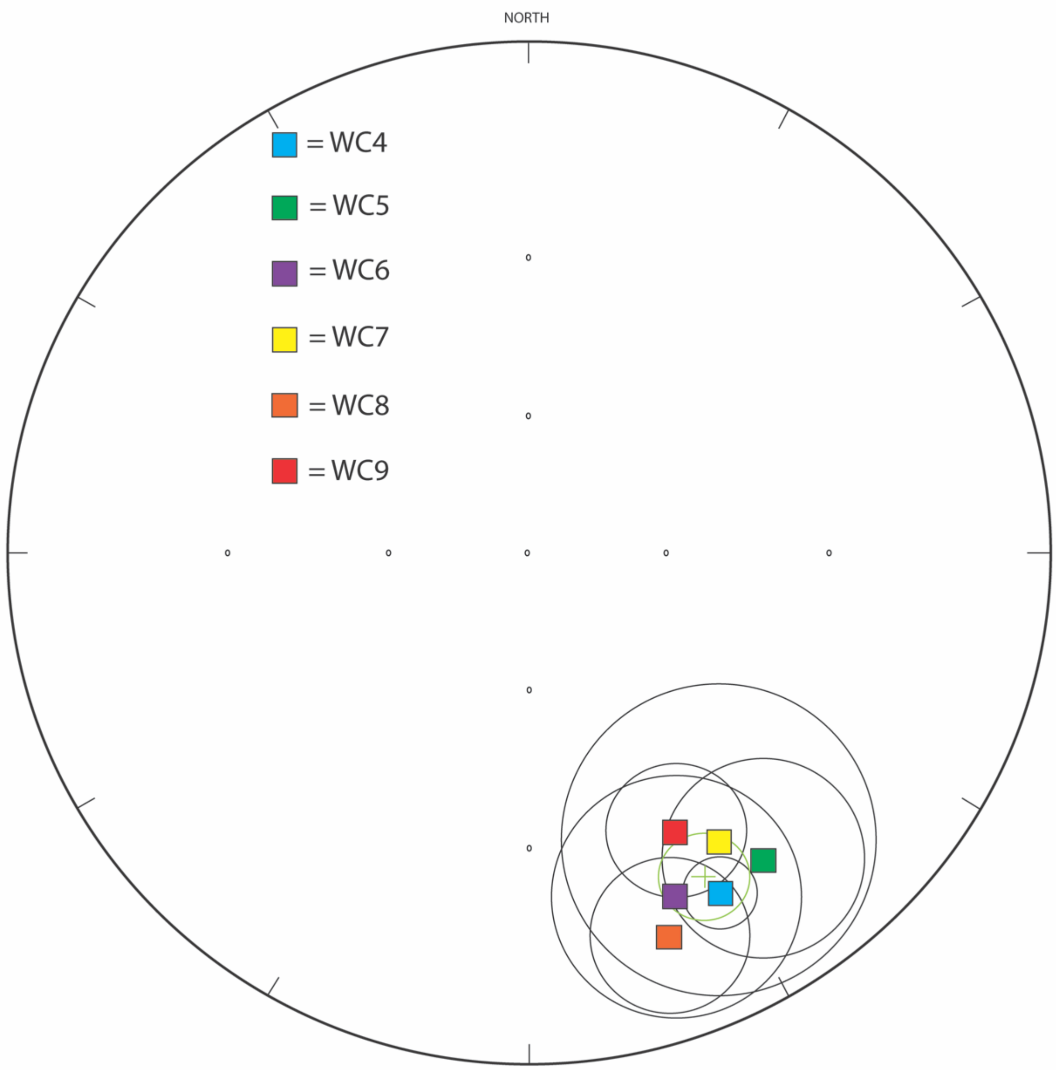


Figure 13: WELLS CREEK SITE MEAN EQUAL AREA DIAGRAM

Equal area diagram showing the site means for the Fort Payne Limestone collected from the southern rim of the Wells Creek impact structure. The different colored boxes represent different sites and the circle represents the mean of the site means. The black circles represent individual site means and the light green circle and crosshair represents the site mean.

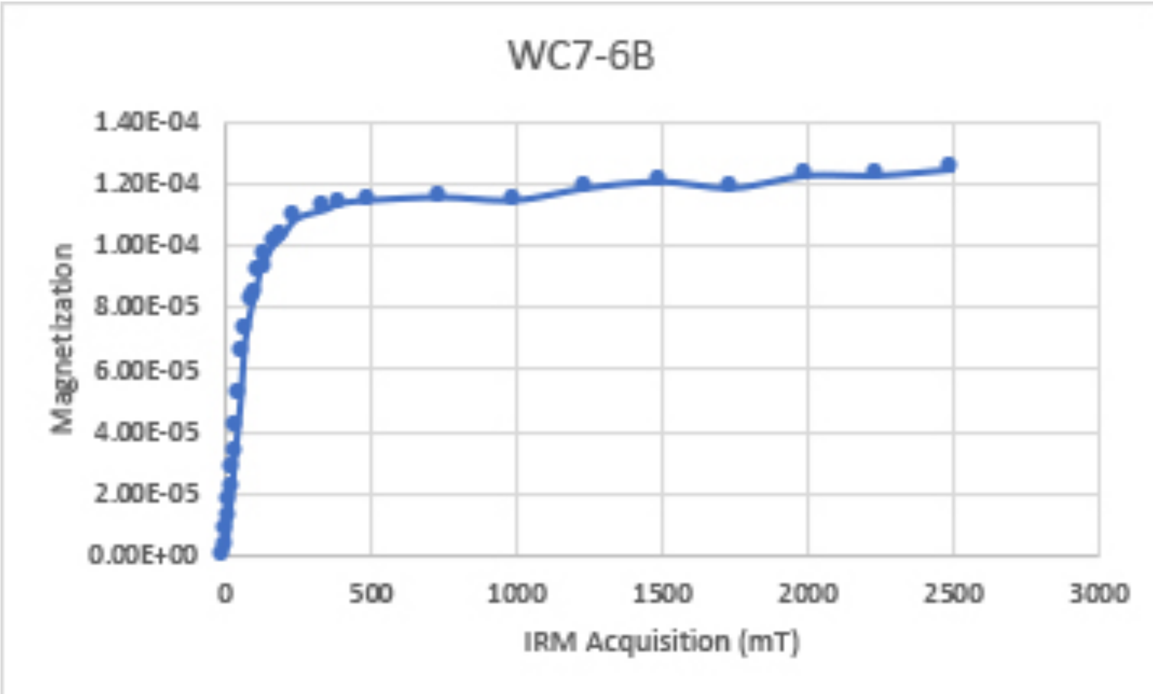


Figure 14: WELLS CREEK IRM ACQUISITION

IRM acquisition for two specimens within the Wells Creek impact structure that exhibit nearly complete saturation by 300 mT.

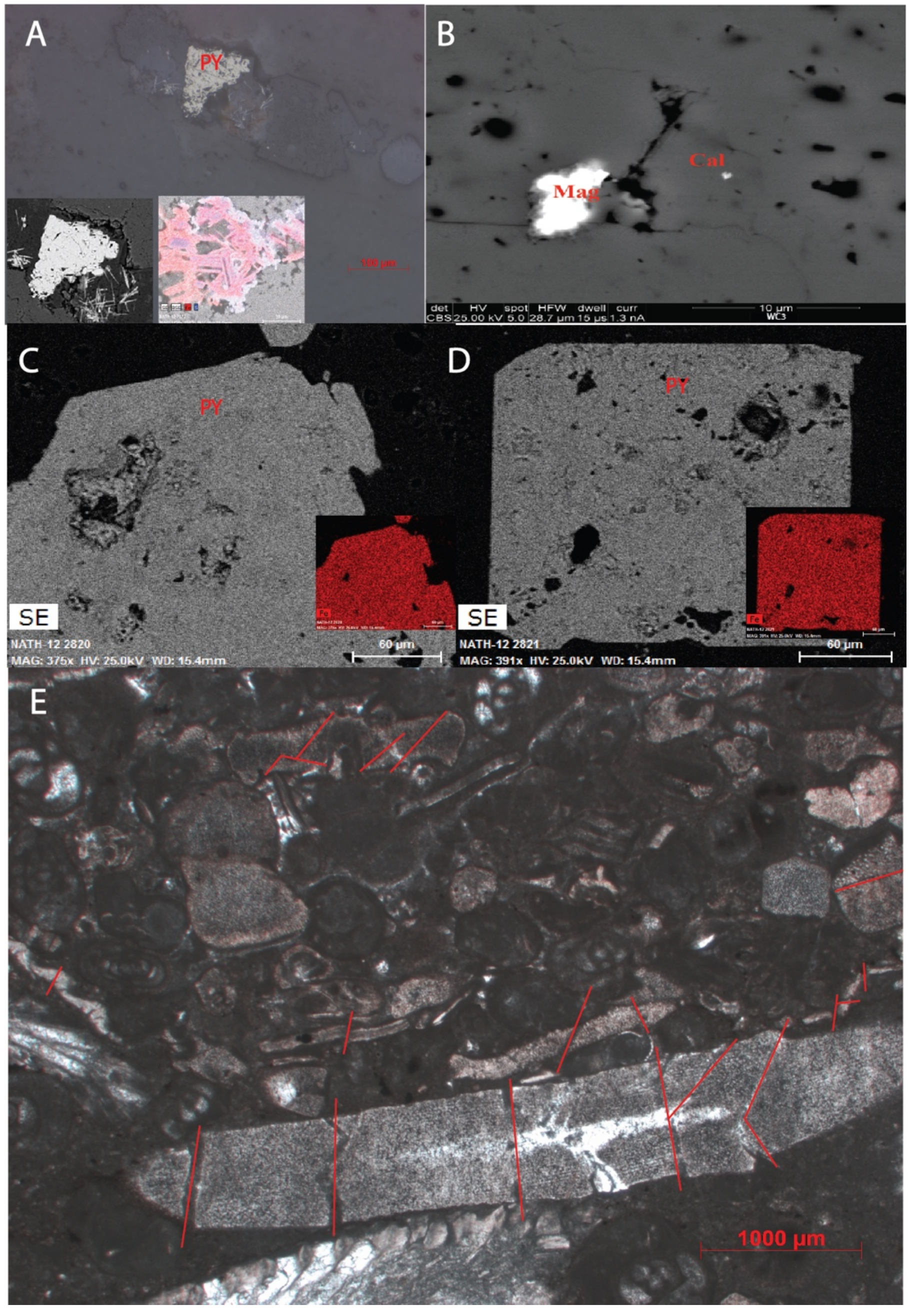


Figure 15: PETROGRAPHIC AND SEM—WELLS CREEK

A) shows a reflected light image of pyrite with a backscattered electron SEM inset image and an elemental inset map (box shown on SEM image) showing iron and sulfur. B) Backscattered electron SEM image of a magnetic grain, interpreted as magnetite. C) and D) show SEM images of two altered pyrite grains with accompanying iron mapping images. E) is a transmitted light image of the Fort Payne limestone, outlining the fractures within the allochems in red.

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