IMPACT AT INGALLS? EVIDENCE FOR A SUBSURFACE ORDOVICIAN METEORITE IMPACT NEAR INGALLS, OKLAHOMA

by

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Introduction

Purpose of Study

Meteorite impacts have been important processes in the history of our Solar System. The planets in our Solar System formed due to collision and subsequent accretion of planetesimals. Currently, impacts are the only weathering process active on many bodies throughout the Solar System; for example, the surfaces of the Moon and Mars are heavily influenced by impact craters (French, 1998). Impacts have had an important role in the history of Earth as well. The current hypothesis for the formation of the Moon is that it formed early in Earth's history as the result of a giant impact. An impactor the size of Mars struck the Earth and knocked off molten material, which eventually formed a separate body that began orbiting the Earth (Boss, 1986). The Chicxulub impact at the Yucatan Peninsula of Mexico has long been thought of as the cause of the mass extinction at the end of the Cretaceous (Koeberl, 1997; Schulte et al., 2010), although this theory is still subject to much debate (Keller et al., 2004).

The preservation potential of impacts on Earth is relatively low because of its highly active surface. Due to the various geologic processes taking place, impact craters are eroded and buried over time (Grieve, 1997). As a result, large impacts are rarely visible on the surface of Earth (Lowman, 1997). However, a structural anomaly has been discovered in the subsurface of north central Oklahoma near the town of Ingalls in Payne County, and initial mapping of the structure has led to the hypothesis that it may be a meteorite impact. The purpose of this study is to investigate the claim that the subsurface structure at Ingalls is indeed the result of a meteorite impact. Using the stratigraphic and petrographic data available from the site, the study will attempt to seek evidence for an impact at Ingalls and add the structure to the list of fewer than 180 known impact craters on Earth (Pati and Reimold, 2007).

Previous Work

To date, there is no published material on the structure at Ingalls. The subsurface feature was discovered by a group of petroleum geologists who encountered it while looking over well logs in an attempt to find hydrocarbons in the area. After mapping the area with the available logs, the researchers noticed patterns in the subsurface units that were uncharacteristic of the regional stratigraphy. Based on the results of their mapping and the lack of any regional context for the site, an interpretation was made that the structure is the result of an ancient meteorite impact. A comparison of the Ingalls structure was made to the nearby impact structure at Ames, OK in Major County, located less than 75 miles (120 km) west of Ingalls. The Ames structure has been accepted as an impact by the scientific community, and it was the subject of a 1995 symposium by the Oklahoma Geological Survey (Johnson and Campbell, 1997). The well-documented structural and stratigraphic aspects of the Ames impact structure served as an analogy for the Ingalls structure, and the interpretation of the structure was made in that context. The researchers who discovered the Ingalls feature provided this study with their unpublished data from the area, which became the starting point for further research. These preliminary interpretations as well as physical evidence from the site serve as the basis for this study.

Background

Impact Processes

Meteorite impacts can be extremely violent events. According to French (1998), impacts involve a cosmic projectile passing through Earth's atmosphere and smashing into the surface with a velocity of at least 11 km/s, or nearly 25,000 mph. This great velocity is transmitted into energy when the impactor comes in contact with Earth, and the energy forms shock waves that penetrate through the rocks below the surface. This incredible amount of energy associated with the impact is enough to cause drastic changes to the landscape at the collision site, including breaking, melting, and even vaporizing the rocks into which the energy is released. The displaced material leaves a void on the surface that takes the form of a crater, and this resulting structure is subject to the environmental processes taking place at the site. Younger craters, like the Barringer Crater in Arizona, have not undergone enough weathering to significantly alter the crater, and they still retain their crater morphology (Koeberl, 1997). Impacts that occur under water are subject to more complex processes than those on land, because the water displaced by the impact immediately rushes back into the crater (French, 1998). The resurge of water results in instant modification of the material in the area, bringing outside material into the crater and potentially destroying the crater rim (Dypvik and Jansa, 2003). Deposition resumes once the water and impact debris has settled, and there will be preferential sediment accumulation in the depositional center that is the impact crater. After settling, the crater will be subjected to the same geologic history as the rest of the area (French, 1998). Some of the impact remnants may be preserved, but future depositional or erosional processes that take place in the area may eventually bury or remove any evidence for the impact (Koeberl, 1997). There are two main types of impact craters: simple and complex (Lowman, 1997). Both types have general crater characteristics such as a rim and infill, but complex craters have sharp, fault boundaries and a central peak of rock unearthed during impact called a central uplift (Koeberl, 1997; Figure 1). Although they are generally larger than 2.5 miles (4 km) in diameter, complex craters can result from smaller impacts if the impactor strikes sedimentary rock instead of crystalline basement. The central uplifts occur as a result of rebound from the massive energy released into the target rocks (French, 1998).

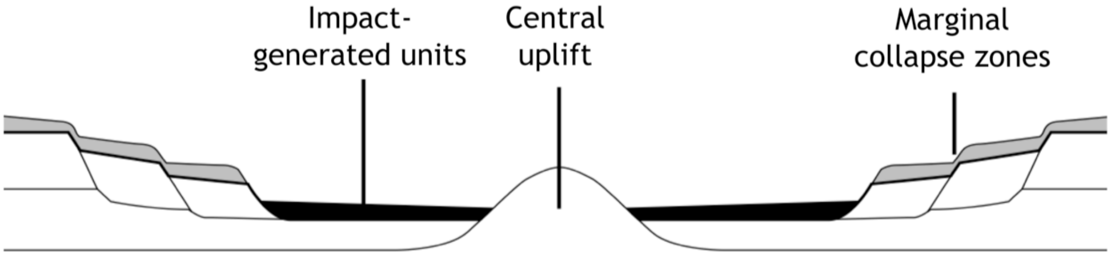


Figure 1. Schematic cross section of complex impact crater. Shows removed material, concentric faults, and central uplift, all of which are present in the Ingalls structure. Modified from French (1998).

The strongest evidence for an impact is the presence of features caused by shock metamorphism, a process which takes place when rocks are subjected to pressures ranging from 2-70 GPa, (Koeberl, 1997). It has been demonstrated that the massive release of energy during an impact is the only way to produce pressures of this magnitude, which are greater than those experienced by rocks as far as 45 miles (75 km) below the surface of Earth (French, 1998). The amount of energy generated by a small impact (10^{18} J) is an order of magnitude greater than the amount released during major terrestrial events, such as the eruption of Mount St. Helens in 1980 or the San Francisco earthquake of 1906 (Koeberl, 1997). The amount generated by a large impact (10^{23} J) is comparable to the total amount of energy released by the Earth in an entire year. The intense and instantaneous energy needed to induce shock metamorphic pressures has not been attained by any other terrestrial process, which is why the presence of highly-shocked minerals or shock features is nearly unambiguous evidence for the impact origin of a feature (Koeberl, 1997). The only other plausible explanation for the presence of shocked grains in a rock unit is that the grains were ejected from a different impact site, since ejecta material can travel hundreds of miles (French, 1998). Because of this possibility, the best way to definitively identify an impact structure is to find many grains with shock features. Examples of shock features that can be found on individual mineral grains include planar fractures (PFs) or planar deformation features (PDFs). Other potential petrographic shock evidence includes presence of the minerals coesite, stishovite, or lechatelierite, which are high-pressure polymorphs of quartz (Fischer, 1997). Recent literature suggests that other shock evidence can be found in the form of feather features (FFs), which are often found in shocked grains in conjunction with PFs (Poelchau and Kenkmann, 2011).

Ames Impact Structure

A significant amount of literature regarding the Ames impact site (Figure 2) was published as part of the Oklahoma Geological Survey symposium on the structure, and several of these papers are referenced in this study (Bridges, 1997; Buthman, 1997;

Carpenter and Carlson, 1997; Coughlon and Denney, 1997, Donofrio, 1997; Grieve, 1997; Koeberl, 1997; Koeberl et al., 1997; Kuykendall et al., 1997; Lowman, 1997). The Ames impact site is described by Carpenter and Carlson (1997) as the remnant structure of a meteorite explosion over Major County, Oklahoma late in the Early Ordovician. The structure is roughly circular in map view, with a diameter of around 9 miles (15 km). It was noticed after wells drilled in the area found an unusually thick and structurally low section of strata, the Hunton Limestone, and it was interpreted as an impact structure after the rim of the crater was discovered and drilling data in the area was modeled with a computer. The structure contains significant accumulations of oil and natural gas, and it is likely that it will end up being the most productive known impact structure (Carpenter and Carlson, 1997). Because of its vast oil and gas reserves, at least 100 wells have penetrated the structure, making large amounts of data available in the form of well logs and rock samples. Despite other theories about the cause of the structure, study of the material from the site has led to the conclusion that the site is indeed an impact, with numerous sets of planar deformation features (PDFs) and other shock metamorphic features providing unambiguous evidence for an impact origin of the structure (Koeberl et al., 1997).

The Ames impact structure serves as an excellent analog for the study of the Ingalls structure. The Ames structure is larger by nearly an order of magnitude, but its presence as a confirmed complex impact structure provides a point for comparison when examining the data from Ingalls. Figure 2 shows the locations of the two structures along with the major geologic provinces of Oklahoma. Like the Ames site, the structure at Ingalls is dated in the Ordovician, and this age similarity coupled with its

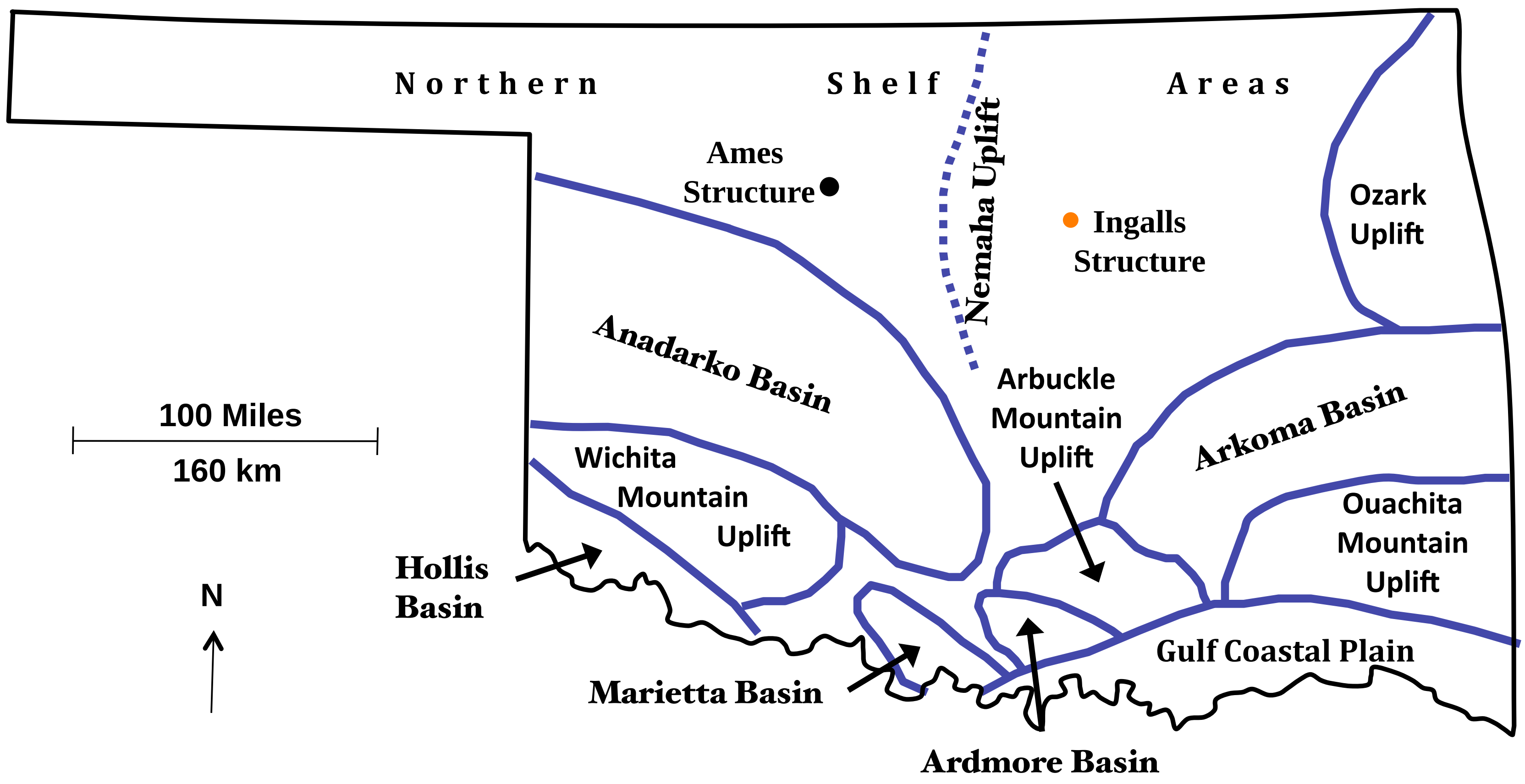


Figure 2. Map showing the major geologic provinces of Oklahoma as well as the Ames impact structure in Major County. The Ingalls structure is located in Payne County, less than 75 miles (120 km) from the Ames structure. Dots representing structures not to scale. Modified from Carpenter and Carlson (1997).

proximity to the Ames structure brings about the question of whether the two are related in origin. It has been suggested that there was a significant increase in the influx of meteorites coming to earth during the Ordovician, based on fossilized meteorites found in Ordovician limestone as well as an increased number of confirmed impacts dated to the same period (Korochantseva et al., 2007). If an impact origin were confirmed for the structure at Ingalls, it would provide further evidence for this hypothesized influx of material, and it could prompt further study regarding the potential relationships between known impact sites.

Ingalls Geologic Setting

The site for this study is located in sections 21, 22, 27, and 28 of T19N R4E, immediately east of the town of Ingalls in Payne County, OK (Figure 3). Payne County is in north central Oklahoma, just east of the Nemaha Uplift and approximately 100 miles north of the basinal axes of both the Anadarko and Arkoma Basins (Figure 2). A stratigraphic column for the Ingalls area is shown in Figure 4. Being on the shallow shelves of these major basins, the stratigraphic units at Ingalls are much shallower than most of their counterparts across Oklahoma. One example of this regional depth difference is the Woodford Shale, a major petroleum source rock and a recently growing exploration target. In the subsurface of Oklahoma, the Woodford Shale stands out as a prominent stratigraphic marker, marking the Upper Devonian and Lower Mississippian across most of the state (Amsden, 1980). The Woodford is less than 4000 feet (1220 m) below the surface at Ingalls, compared to depths of over 10,000 feet (3050 m) in the sedimentary basins (Amsden, 1975; 1980).

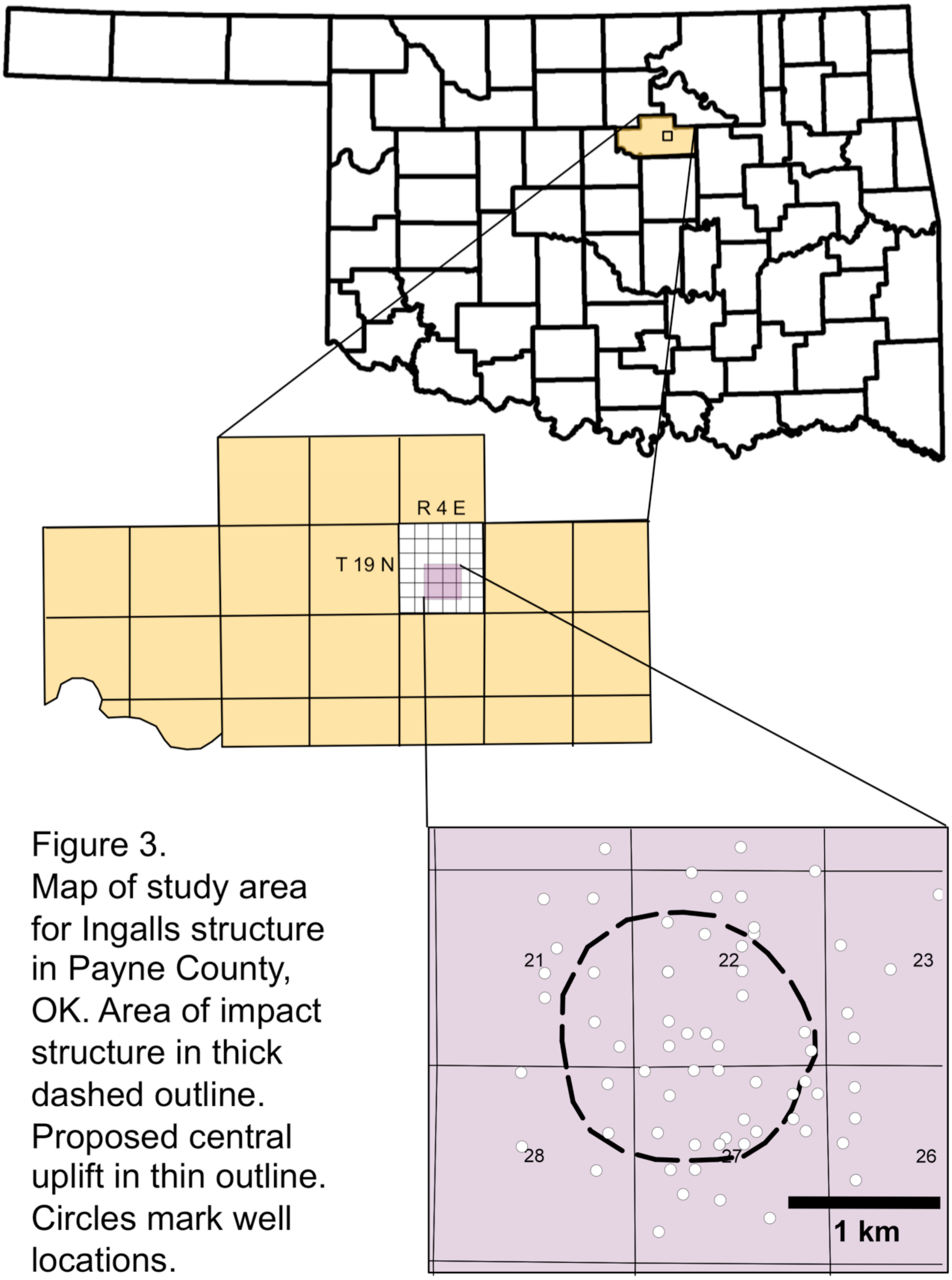


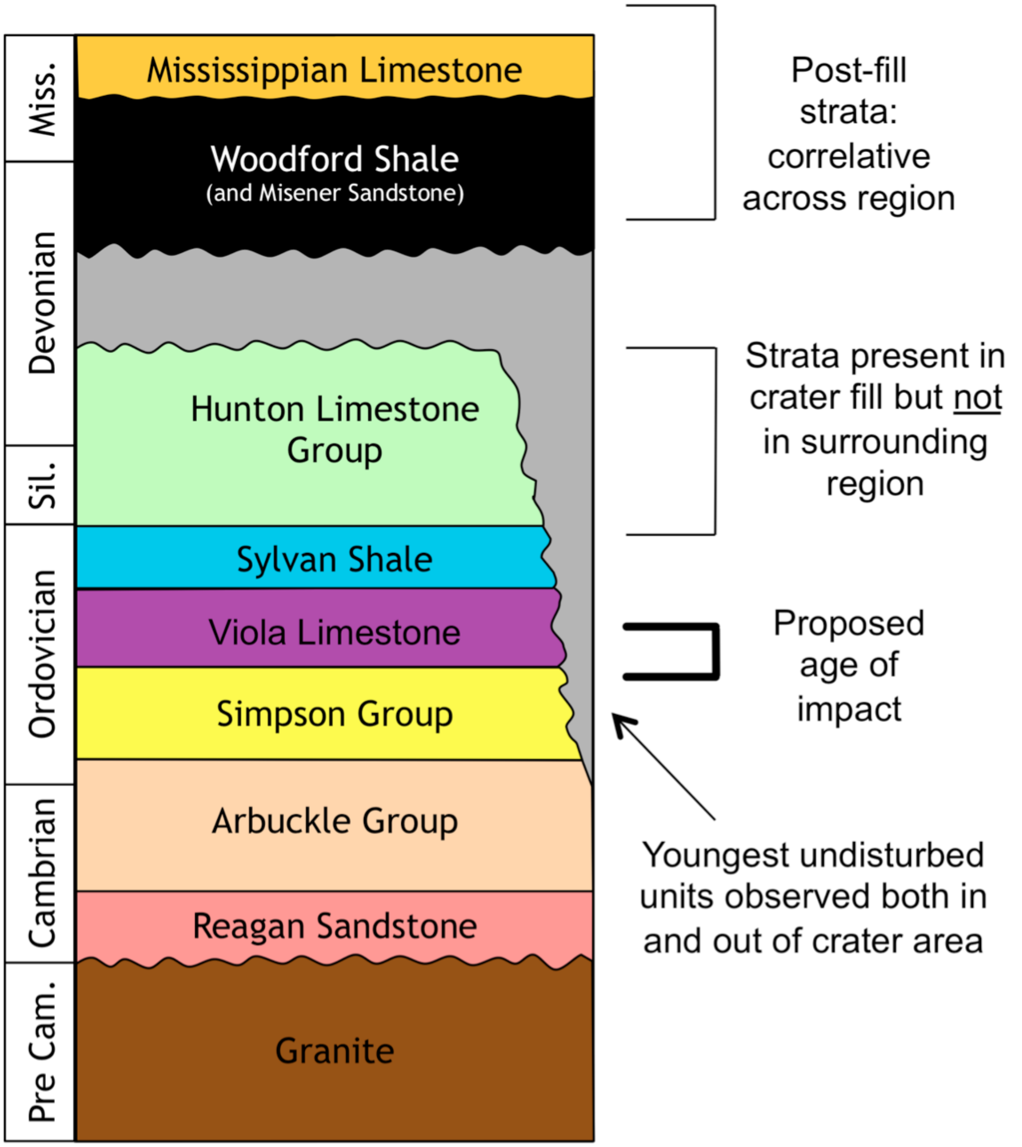
Figure 3.
Map of study area for Ingalls structure in Payne County, OK. Area of impact structure in thick dashed outline. Proposed central uplift in thin outline. Circles mark well locations.

The topic of the study is a nearly circular subsurface structure approximately 1.2 miles (2 km) in diameter. The Woodford Shale is the youngest undisturbed unit present in all wells within and surrounding the structure. The presence of the Woodford as the cap rock of the structure provides information about the age of the events taking place there. The hypothesized impact, as well as the subsequent structural deformation and deposition into the crater, must have occurred before the onset of Woodford deposition, setting the minimum age of the event at late Devonian. A precise date for the impact event is difficult to determine with the data available, but a maximum age of early Ordovician has been determined from units found both within and outside the structure.

Ingalls Structure

The rock units comprising the structure at Ingalls range in age from the early Ordovician Arbuckle Group to the Siluro-Devonian Hunton Limestone (Figure 4). Tectonic processes and a major period of erosion across Oklahoma during the Devonian caused formations lying below the Woodford Shale to dip to the southwest and pinch out to the north and east (Amsden, 1980). Because of this erosion, wells drilled farther northward and eastward will experience thinner sub-Woodford stratigraphic sections, with some of the units missing entirely (Tarr et al., 1983; Figure 5). These regional trends are well documented across Oklahoma, and numerous studies and maps of the sub-Woodford stratigraphy have been published (Amsden, 1975; 1980; Tarr et al., 1983). The Hunton Limestone is the youngest unit affected by the Devonian erosion, and a regional truncation line for the Hunton lies approximately 12 miles (20 km) to the

Figure 4. Stratigraphic Column of Ingalls area showing the units present regionally and within the proposed impact structure.



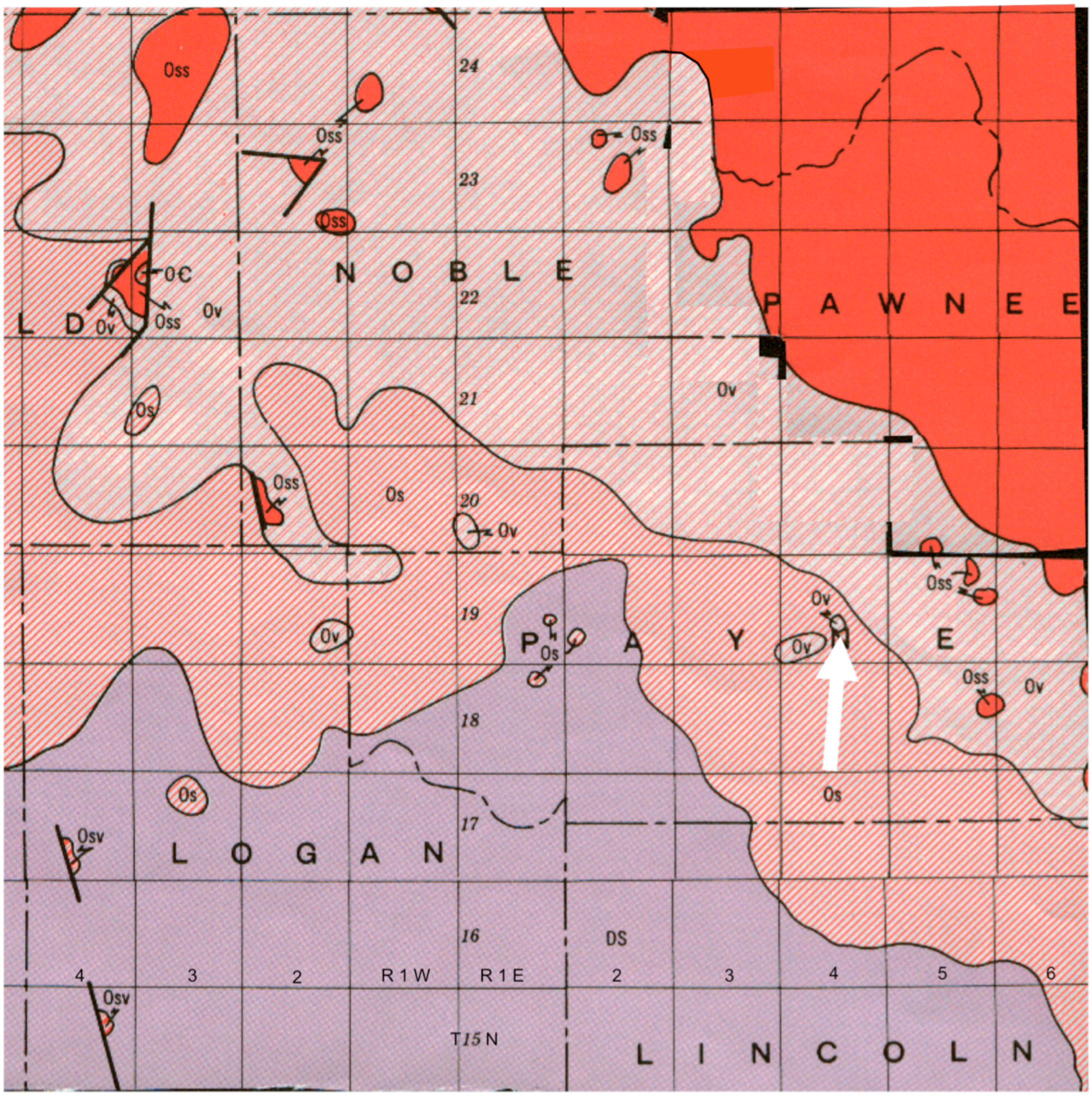


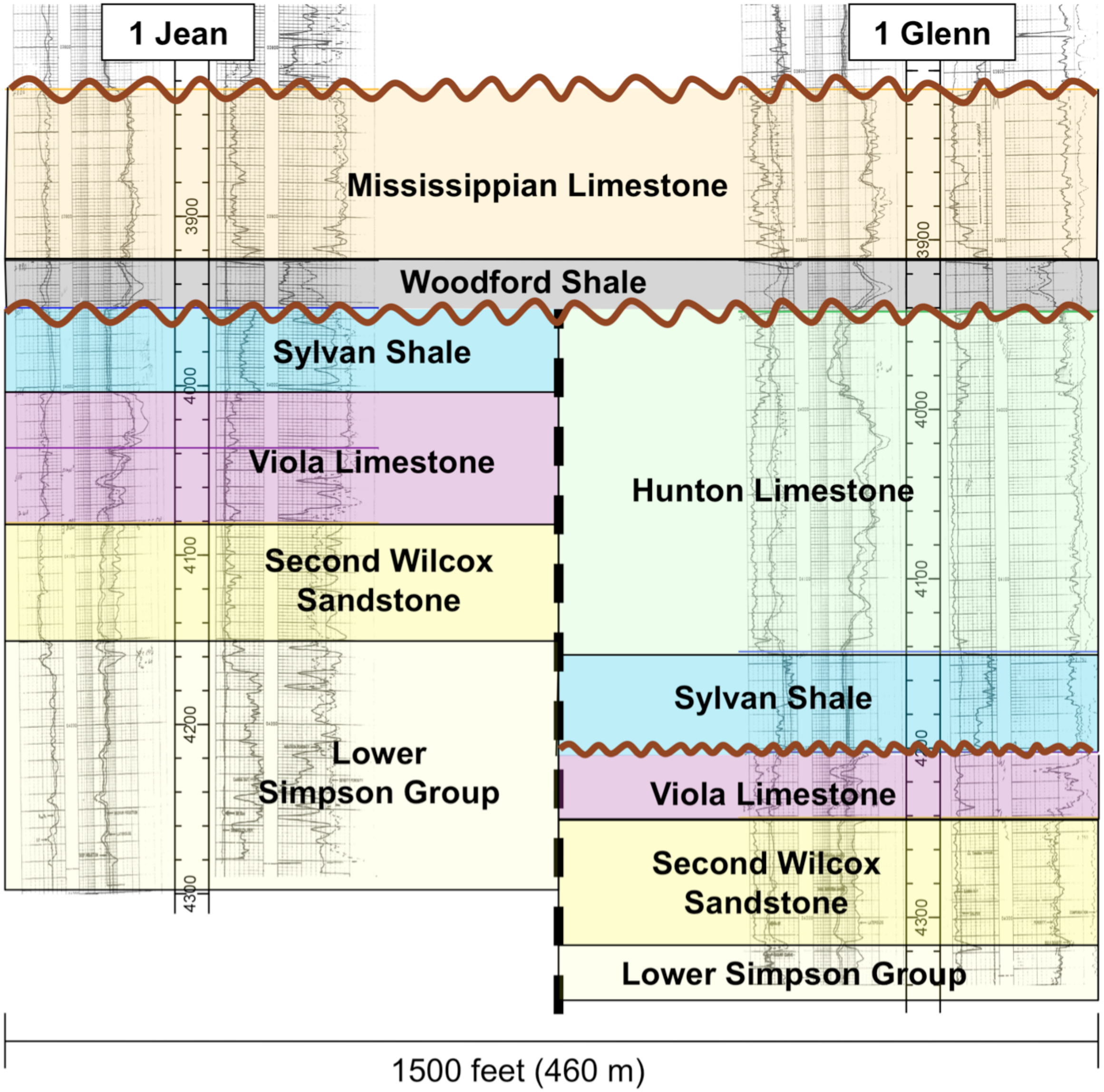
Figure 5. Woodford Shale subcrop map for north-central Oklahoma. The map displays regional truncation lines for stratigraphic units below the Woodford Shale. A small area of irregular sub-Woodford stratigraphy can be seen at the Ingalls structure in Payne County (white arrow), but it is incorrectly interpreted as Viola Limestone. The units in the structure are Hunton Limestone, a Siluro-Devonian formation which is absent for several miles to the south and west. Modified from Tarr et al. (1983).

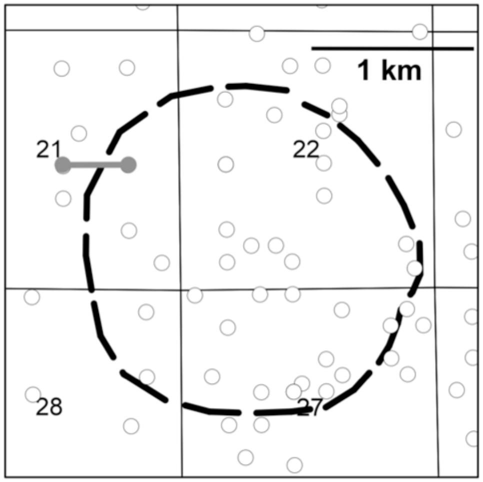
south and west of the structure at Ingalls (Tarr et al., 1983). None of the wells drilled into the area surrounding the Ingalls structure encounters any Hunton because it has been completely eroded away. Wells drilled into the structure see as much as 200 feet (60 m) of rock below the Woodford that is interpreted as Hunton Limestone. Figure 6 shows an example of this extra section. The additional rock at Ingalls represents a significant amount of extra deposition or non-erosion at the site, which is likely the result of a major geologic event.

The Hunton Limestone is immediately underlain by the Sylvan Shale and Viola Limestone (Figure 4). These units are present in wells both within and surrounding the Ingalls feature, but they have increased and varying bed thicknesses throughout the structure along with irregular well log characteristics. These irregularities can likely be attributed to the same cause as the additional Hunton deposition.

The shape of the Ingalls structure is approximately that of a steep-sided, circular bowl. The boundaries of the structure are very abrupt, and the presence of younger lithology within the structure suggests that the boundaries between the structure and the surrounding rock take the form of nearly vertical normal faults. The irregular thicknesses of the stratigraphic units at Ingalls are likely indicative of more normal faults interspersed throughout the structure. In the center of the structure lies a suite of rock, elliptical in map view, whose strata are units of the mid-Ordovician Simpson Group. Not only is this central suite older than the surrounding structure, it is even older than the rocks outside the structure. The positioning of these rock groups produces an irregular pattern: regionally undisturbed rocks surrounding a circular suite of younger strata which themselves surround a spire of older and seemingly

Figure 6. Well log cross section showing abnormal stratigraphy of wells drilled in the Ingalls structure. These two wells are only about 1500 feet (460 m) apart, yet their sections show marked differences. The well in the structure (right) sees significant amounts of offset and extra deposition relative to the well outside of the structure (left). These differences are interpreted as resulting from a meteorite impact.





uplifted rocks. Any potential structural explanation for these age relationships would require both extension and contraction.

Preliminary information suggests that an impact origin is a reasonable explanation for the structural and stratigraphic patterns present at Ingalls. Buthman (1997) claims that numerous impact structures of Ordovician age are present across central Oklahoma. The study examines the shape and distribution of several hydrocarbon producing fields surrounding the Anadarko basin and comes to the conclusion that many of these fields are likely to have been formed from meteorite impacts. Although no specific sites are identified by Buthman (1997), an increase in the amount of meteorite material coming to earth during the Ordovician is also noted by other studies (Schmitz et al., 2001; 2003). Korochantseva et al. (2007) suggest that an increase of cosmic material impacting earth during this period is the result of the breakup of the asteroid that is the parent body of the L-chondrite meteorite family. The above studies indicate that impact events were prevalent during the Ordovician, and the Ingalls structure fits many of the characteristics of likely impact sites noted by French (1998) and Koeberl (1997). A meteorite impact at Ingalls would have caused massive faulting, a significant removal of material, and the creation of a crater-shaped area with a central peak. This crater would have been a topographic low point in the region and therefore would have experienced additional deposition during the post-impact evolution of the site. An impact at Ingalls along with subsequent deformation and deposition at the site would explain the structure's sharp vertical boundaries, its irregular bed thicknesses and additional stratigraphic units, its strange age relationships, and the peak of older rocks in its center. The possibility of an impact origin for the Ingalls structure must be considered, and this study will pursue evidence in support of that hypothesis.

Methodology

Well Log Correlations

Over 150 wells were drilled in the Ingalls project area, but most of the wells did not provide any data to the study. Many of the wells in the area were drilled before well logging tools were invented. Other wells in the area were logged with outdated technology, leaving behind logs that were old and difficult to interpret. Another portion of the wells were targeting shallower zones, so the boreholes are not deep enough to encounter the structure. Only about 20 of the wells were drilled deep enough to encounter the structure while also having logs that are modern enough to be used for correlations. Figure 7 shows the wells deep enough to penetrate the structure and highlights which of these had logs available. The logs for these wells, along with those for many of the wells in the surrounding area, were provided to the study by Orca Resources.

For the well log study, three type logs were selected to represent the stratigraphy in and around the proposed impact site. Two of these type logs provide regional stratigraphic sections against which wells penetrating the structure can be compared. One of the logs allows for contrast between the units within the structure and those surrounding it; the other serves as a regional comparison for the rocks composing the hypothesized post-impact crater fill. Additional type logs represent the structure itself as well as the suite of older rocks at the center of the structure. Once the

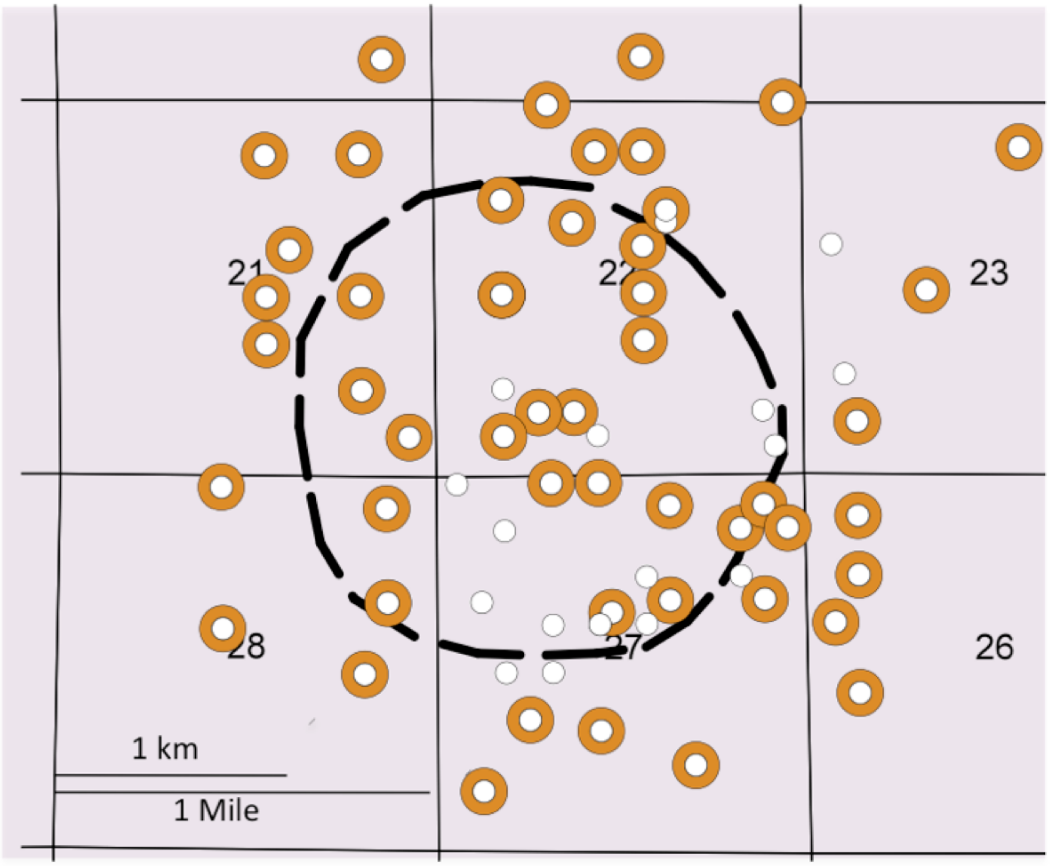


Figure 7.
Map of study area for Ingalls structure in Payne County, OK. The limits of the Ingalls structure are represented by the thick outline. The circles mark the 68 wells that are deep enough to encounter the strata of the structure. Wells with orange circles have log data.

type logs were chosen, boundaries of stratigraphic units were selected on all logs in the project. Most of the rock units that are present at the Ingalls structure and the surrounding area have very characteristic log signatures that make them easy to pick out on well logs. Correlations of the units were made between wells in order to establish limits of the structure and show trends throughout the study area. The correlations allowed for mapping of the area and provided background for interpretations of the structure's origin and development history.

Petrographic Analysis

Rock samples from the Ingalls structure were examined for petrographic evidence of shock metamorphism. Shock metamorphic effects are sufficient criteria for identification of the impact origin of a structure (French, 1998). In fact, shock effects provide the only unambiguous form of evidence for impact besides pieces of the actual meteorite itself (Koeberl, 1997). Samples from the Ingalls structure came from drill cuttings retained from wells drilled into the structure. Orca Resources donated drill cuttings from their 1-22 Rebound SWD well to the study, and these cuttings provided the most comprehensive record of a stratigraphic section in the area, having samples collected every 20 feet (6 m). Other cuttings for the project came from the Oklahoma Petroleum Information Center (OPIC) in Norman, OK. Cuttings and cores from many wells drilled in Oklahoma are donated to the Oklahoma Geological Survey (OGS), and these are stored in the OPIC facility and are made available for investigation. The OPIC database was accessed in search of sample material from the Ingalls area. No cores from wells drilled into the Ingalls structure were present in the database. Cuttings from 10 wells penetrating the structure were available for access, with sample intervals ranging from every 5 feet to every 50 feet. Most of the cuttings from OPIC were collected from formations that would have been deposited significantly after the event causing the structure. These samples would be devoid of shock features since they were not in place at the time of the impact. The samples were cross-referenced with well logs to determine their position within the stratigraphic section, and cuttings from formations deep enough to have been affected by the impact became part of the search for evidence of shock.

Planar deformation features (PDFs), planar fractures (PFs), and other shock metamorphic features are best found in quartz (French, 1998; Koeberl, 1997), so grains of quartz from the well cuttings became the target for the petrographic study. The well cuttings were separated by depth and quartz grains were manually extracted from the cuttings. These grains were inspected for evidence of shock metamorphism using refractive index oils. Each mineral has a specific refractive index, and when grains of a mineral are placed in oil of the same refractive index, the grains will not visibly stand out from the oil (Nesse, 2004). The index of refraction for quartz is 1.544 (Nesse, 2004), so the extracted quartz grains from the wells at Ingalls were placed on clear glass slides and set in refractive index oil with a refractive index of 1.54. This caused the grains themselves to almost completely disappear and allowed for identification of the potential shock evidence present on the grains. Investigation of the grains was conducted under a research microscope using a magnification of 200x. Grains showing potential shock features in the refractive index oil were isolated from the remaining grains and leeched in a heated solution of hydrochloric acid for 24 hours. The leeched grains were then made into grain mounts for investigation under a universal stage.

Results

Well Log Study

Figure 8 shows the resistivity and neutron logs for the 1 Jean well, which serves as the type log for the area surrounding the Ingalls structure. The 1 Jean logs show the Woodford Shale lying directly on top of the Sylvan Shale, and an abrupt contact that represents the Devonian erosional period separates the two formations. Below the Sylvan lies an uninterrupted section of Viola Limestone on top of the Simpson Group. This log sequence of the 1 Jean well is representative of the area's stratigraphy, and wells surrounding the Ingalls structure have logs similar to this. Wells drilled into the structure, however, have sequences that differ from the regional stratigraphy. One of the wells penetrating the Ingalls structure is the 1 Glenn, located approximately 1600 ft (500 m) east of the 1 Jean. The logs for 1 Glenn are shown in Figure 9. While the 1 Jean well has the Woodford Shale lying directly on Sylvan Shale, logs for 1 Glenn show 202 feet (62 m) of limestone separating the two formations. The only formation deposited after the Sylvan but before the Woodford was the Hunton Limestone, and the limestone encountered in the 1 Glenn well is interpreted by the study as Hunton. This interpretation can be evaluated by comparing the logs of the 1 Glenn well to those of a well that has a significant accumulation of Hunton Limestone. None of the wells in the immediate surrounding area has any Hunton present because of the erosion that took place in the area during the Devonian. To investigate the stratigraphy of the extra

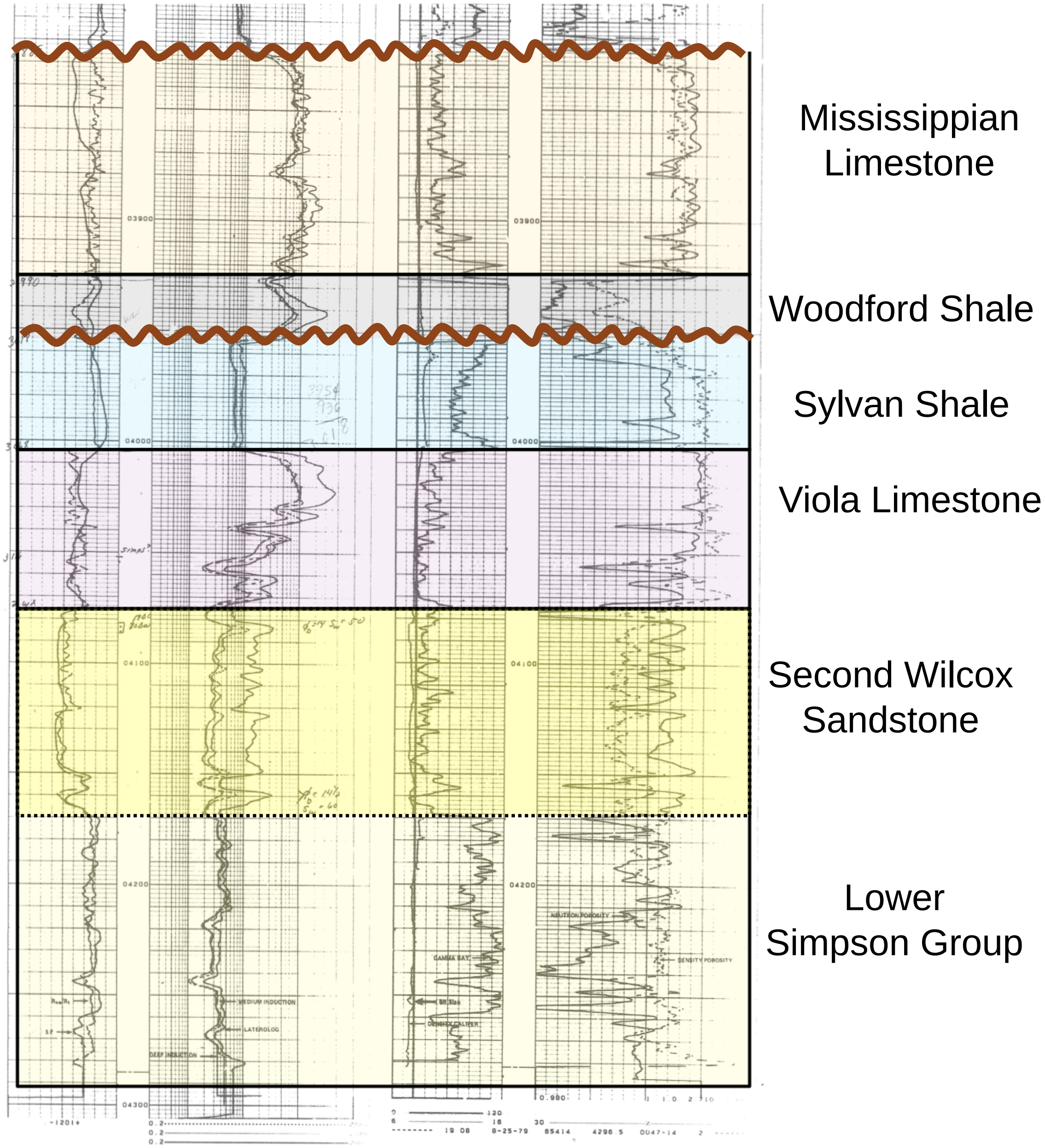


Figure 8. Interpreted well logs for the 1 Jean well. This log serves as the type log for undisturbed rocks in the area immediately surrounding the Ingalls structure. Below the Woodford Shale lies the Sylvan Shale, since the Hunton Limestone is regionally absent due to erosion. Below the Sylvan, the Viola Limestone sits atop the Second Wilcox Sandstone, a prominent member of the Simpson Group.

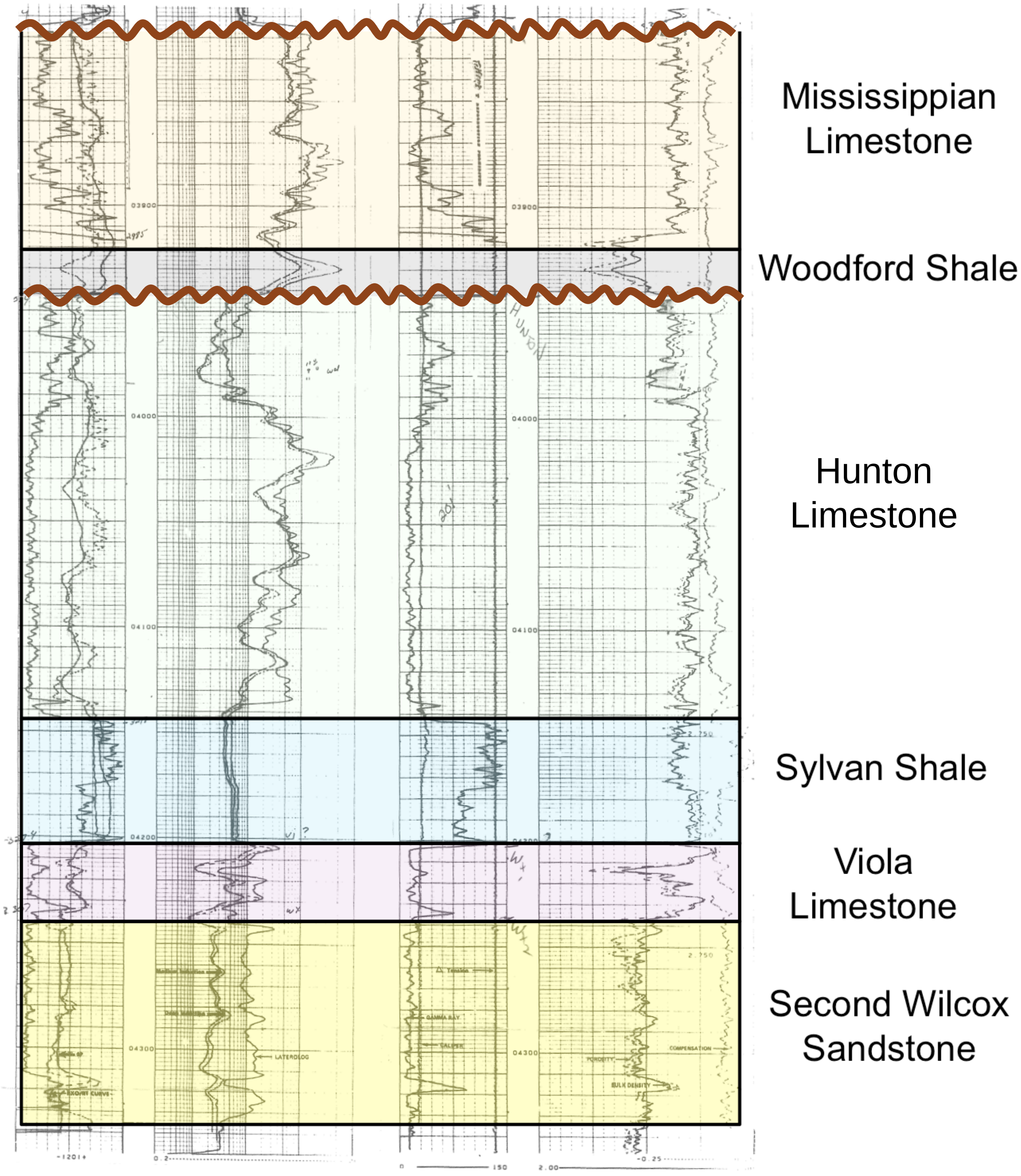


Figure 9. Interpreted well logs for the 1 Glenn well. This log serves as the type log for the Ingalls structure. Below the Woodford Shale lies the Hunton Limestone, despite the fact that the Hunton truncation line lies more than 10 miles (16 km) to the south and west of Ingalls. Almost 45 ft (14 m) of Viola Limestone is missing from the section.

section at Ingalls, logs from wells drilled at the Ingalls structure must be compared to those from wells southwest of the regional truncation line of the Hunton Limestone. Logs from the 1-3 Lynch well, located approximately 26 miles (42 km) to the south of the Ingalls structure, show a thick sub-Woodford section that allows for comparison with wells in the structure (Figure 10). Correlations between 1-3 Lynch and 1 Glenn, along with an understanding of the regional pre-Devonian stratigraphy, make it clear that the rock unit below the Woodford Shale in the Ingalls structure is the Hunton Limestone. Figure 11 shows a map of wells in the study area with Hunton Limestone present, and Table 1 lists the thickness of Hunton rock in each well. An isopach map (Figure 12) showing the combined thickness of the Hunton Limestone and Sylvan Shale illustrates the drastic changes seen within the Ingalls structure.

Further differences between the neighboring 1 Jean and 1 Glenn wells arise as their deeper strata are correlated (Figure 6). Each well has a section of Sylvan Shale 50-60 feet (15-18m) thick, but the basal Sylvan bed boundary for each well is drastically different. As stated above, the 1 Jean well logs show the Sylvan Shale lying conformably on the Viola Limestone in a manner consistent with wells in the region. The Sylvan Shale in the 1 Glenn well, however, sits atop a member of the Simpson Group, and the Viola Limestone is completely missing from the section. In fact, the 1 Jean well has 44 feet (13 m) of rock below the base of the Sylvan that is absent from the corresponding section of the 1 Glenn well. It is unlikely that this deposition failed to occur at Ingalls, because there is no evidence for a break in deposition between the Viola and the Sylvan anywhere in Oklahoma. It is more likely that an event caused the relationship after deposition of the Viola, either removing the material from the structure or faulting the

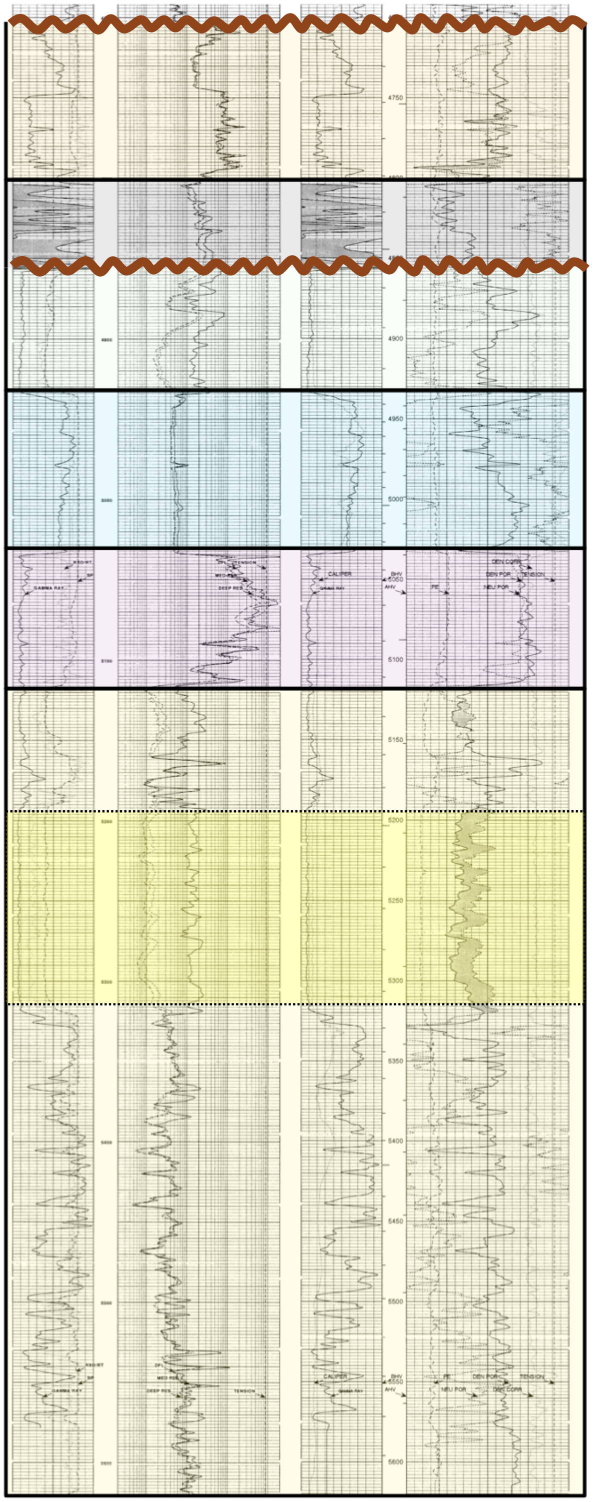


Figure 10. Interpreted well logs for the 1-3 Lynch well. The well is located 26 miles (42 km) south of Ingalls in a deeper part of the Arkoma basin, giving it a thick sub-Woodford section that allows for comparisons of strata above and below the proposed time of impact.

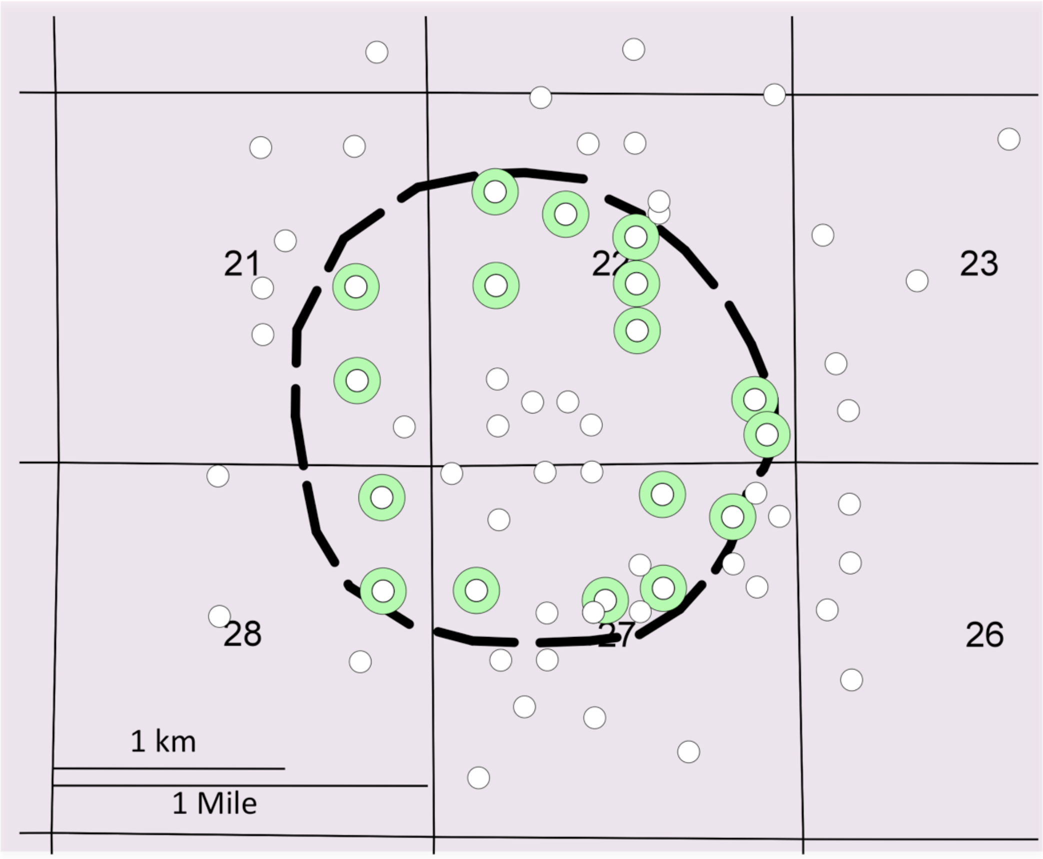
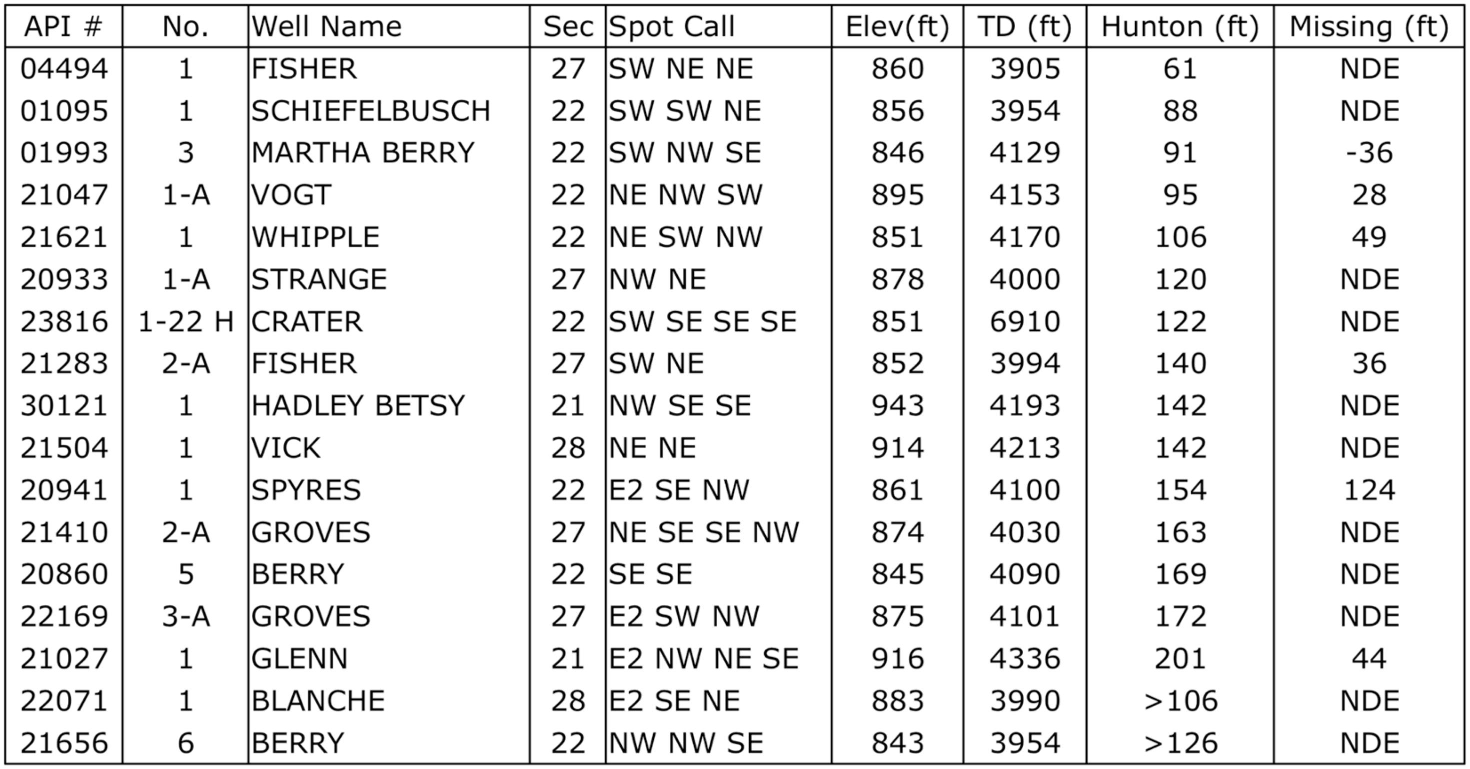


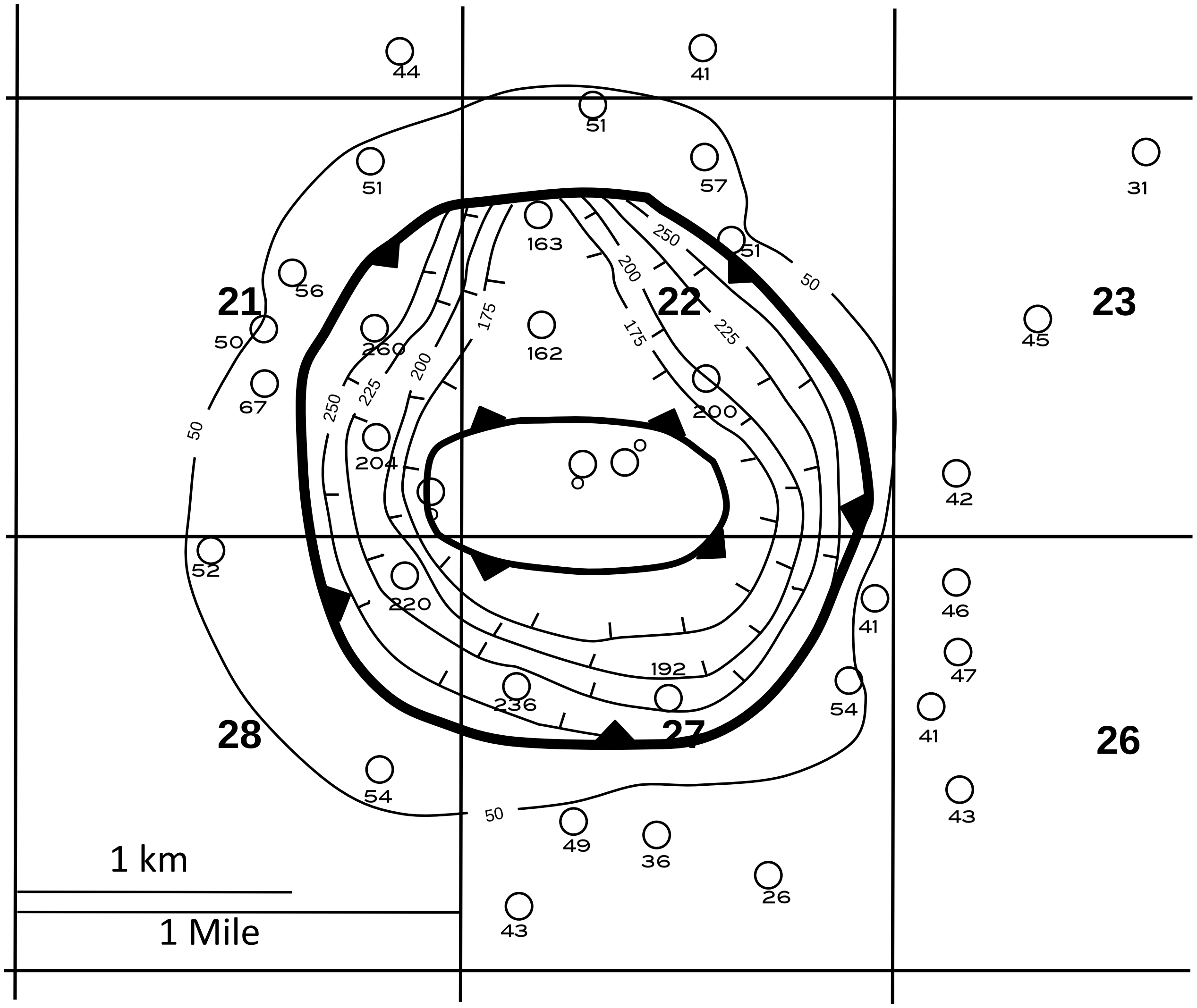
Figure 11.
Map of the Ingalls study area showing wells whose logs show the presence of Hunton Limestone below the Woodford Shale. The Hunton is younger than the sub-Woodford rocks in the wells surrounding the structure. Note the nearly circular shape of the structure and its sharp boundaries. Also note the absence of Hunton wells in the center of the structure.



API #	No.	Well Name	Sec	Spot Call	Elev(ft)	TD (ft)	Hunton (ft)	Missing (ft)
04494	1	FISHER	27	SW NE NE	860	3905	61	NDE
01095	1	SCHIEFELBUSCH	22	SW SW NE	856	3954	88	NDE
01993	3	MARTHA BERRY	22	SW NW SE	846	4129	91	-36
21047	1-A	VOGT	22	NE NW SW	895	4153	95	28
21621	1	WHIPPLE	22	NE SW NW	851	4170	106	49
20933	1-A	STRANGE	27	NW NE	878	4000	120	NDE
23816	1-22 H	CRATER	22	SW SE SE SE	851	6910	122	NDE
21283	2-A	FISHER	27	SW NE	852	3994	140	36
30121	1	HADLEY BETSY	21	NW SE SE	943	4193	142	NDE
21504	1	VICK	28	NE NE	914	4213	142	NDE
20941	1	SPYRES	22	E2 SE NW	861	4100	154	124
21410	2-A	GROVES	27	NE SE SE NW	874	4030	163	NDE
20860	5	BERRY	22	SE SE	845	4090	169	NDE
22169	3-A	GROVES	27	E2 SW NW	875	4101	172	NDE
21027	1	GLENN	21	E2 NW NE SE	916	4336	201	44
22071	1	BLANCHE	28	E2 SE NE	883	3990	>106	NDE
21656	6	BERRY	22	NW NW SE	843	3954	>126	NDE

Table 1.
List of wells in Ingalls study area with the presence of Hunton Limestone. Also includes interpreted thickness of missing Viola section compared to 1 Jean well. “NDE” indicates well did not go deep enough to determine thickness of missing section. Negative values indicate additional Viola section, likely due to faulting.

Figure 12.
Isopach map of the combined Hunton Limestone and Sylvan Shale units in the Ingalls structure area. The map shows an accumulation of Hunton and Sylvan in a concentric pattern. The interval is thickest along the outside of the structure, and the thickness decreases towards the center of the structure before truncating abruptly.



Sylvan against the Simpson. The missing section seen in the 1 Glenn well is evident in several wells throughout the Ingalls structure, and Table 1 shows the amount of sub-Sylvan section missing for each well in the structure.

While some of the wells at Ingalls have the presence of Hunton Limestone above the Sylvan Shale or the absence of Viola Limestone below it, a cluster of wells in the center of the structure have sub-Woodford sections that differ from both these wells and wells outside of the structure. Wells in this central cluster have missing units like other wells in the structure, but they are missing significantly more material while also lacking the Hunton Limestone that was observed in the other wells. The units missing from the center wells include the Hunton, Sylvan, and Viola; and the Woodford Shale lies directly on older rock that is interpreted to be part of the Simpson Group. This is a considerable amount of section for these wells to be missing, and it creates some interesting relationships between wells in the center of the structure and other wells in the structure. The 5 Orvis well is one of the wells in the central cluster, and Figure 13 shows its interpreted logs. While most wells penetrating the Ingalls structure encounter rocks younger than those of the surrounding area, wells penetrating the center of the structure encounter rocks older than those of the surrounding area. This means that the sub-Woodford rocks in the central cluster of wells have been somehow uplifted relative to those in the surrounding area. Indeed, correlations between the 1 Jean well and the 5 Orvis well indicate that the Simpson Group is 273 feet (83 m) structurally higher in the center well cluster than in wells outside the structure.

The uplifted center cluster of wells at Ingalls, combined with the presence of the Hunton Limestone and the missing Viola Limestone, provide evidence in support of the

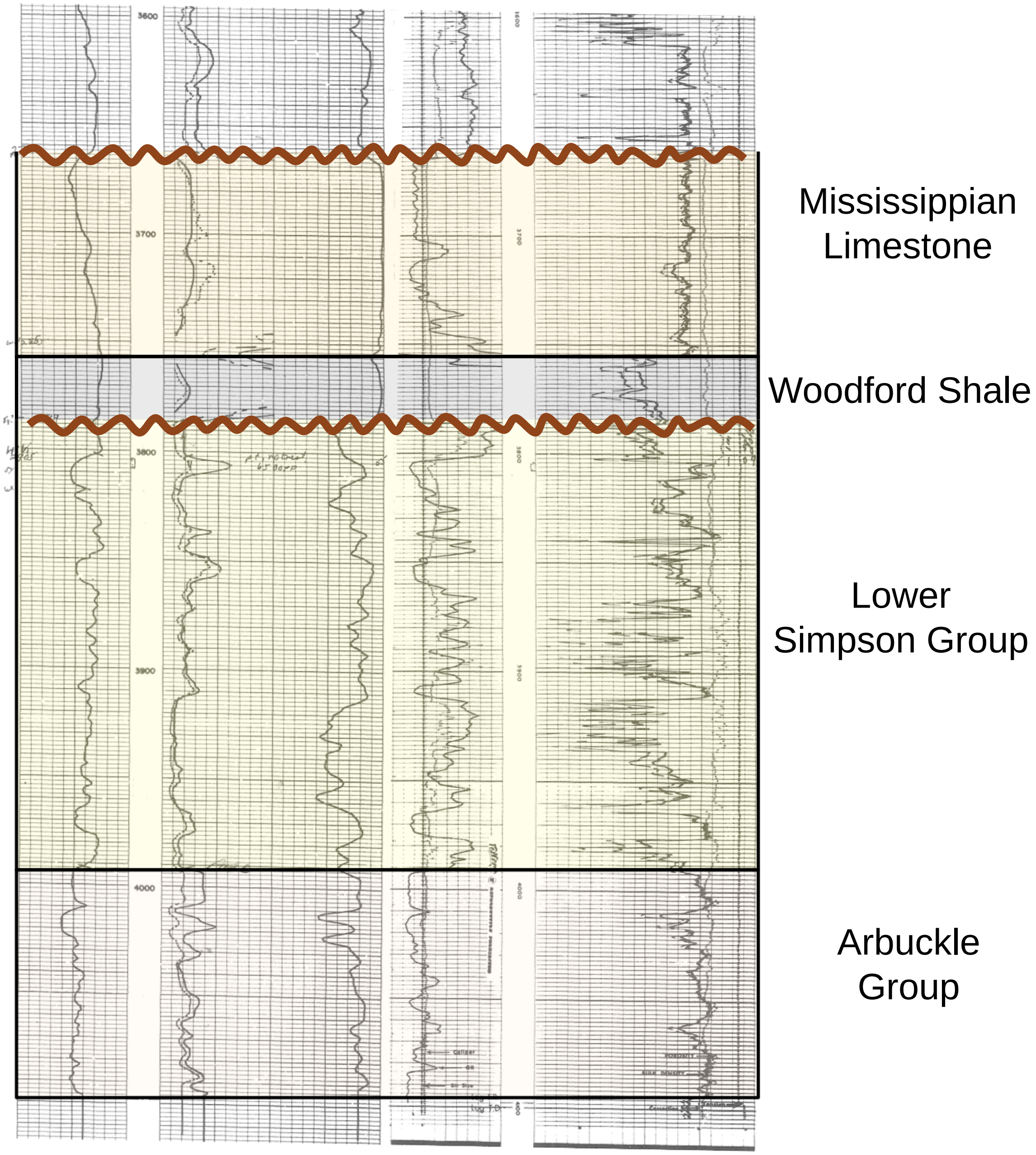


Figure 13. Interpreted well logs for the 5 Orvis well. This log serves as the type log for the central suite of rocks in the Ingalls structure. Multiple formations are missing below the Woodford Shale, and the formations present are at a significantly higher elevation than their regional counterparts.

hypothesis that the structure is the result of a meteorite impact. The interpretation of the site is that it is a complex impact structure resulting from an Ordovician meteorite impact that was partially eroded after impact and eventually buried by sediment. A generalized diagram of a complex impact structure can be seen in Figure 1. The sharp boundaries of the Ingalls impact structure are interpreted as normal faults that represent the collapsing edges of the crater walls; additional faulting is likely to be present and prevalent throughout the structure. The elevated spire of rock in the middle of the structure is interpreted as the central uplift feature that was produced immediately after the impact event. According to French (1998), central uplifts occur at larger impact sites as a result of isostatic rebound of the massive amount of energy released into the target rocks. The minimum diameter of a complex crater is approximately 1.2 miles (2 km) in sedimentary rocks, and the diameter of the Ingalls impact structure is very close to this value. Interpreting the middle part of the structure as a central uplift feature explains its abnormal lithology, including its missing units as well as its increased elevation relative to both the adjacent structure and the region surrounding it. As for the rest of the structure, it is interpreted that the impact event removed a significant amount of material from the area and resulted in the formation of a crater-shaped feature. The crater became a topographic low point in which sediment could preferentially accumulate. Throughout the period of deposition that followed the impact, the crater remained topographically lower than the land surrounding it. Deposition into the crater continued until the mid-Devonian, when a long period of erosion left the crater at roughly the same elevation as the surrounding area. This progression of events explains why the Hunton Limestone, which is absent for miles around the crater because of the mid-Devonian erosion, is present in significant thicknesses within the impact structure. An analogous pattern is seen at the Ames impact structure, where the same Hunton Limestone formation thickens by as much as 250 feet (76 m) within the impact structure (Carpenter and Carlson, 1997). The regional erosion of material during the mid-Devonian also explains why the Woodford Shale and subsequent stratigraphic units above the structure are conformable and correlative across the region. A map of the Ingalls area indicating the sub-Woodford stratigraphy encountered by each well in the study and the approximate boundaries of the structure is shown in Figure 14. A cross section showing the stratigraphic trends across the region is shown in Figure 15.

Petrographic Study

Using the boundaries of the Ingalls structure established by the well log study, cuttings from wells that penetrated the structure were gathered for petrographic study. Cuttings for the study must come from units that were affected by the impact, so they need to be as deep as the Viola Limestone or deeper. It is also possible to find shock evidence in cuttings from units in the central uplift, but it is not as likely to find shock features in these units (French, 1998). Most of the wells with cuttings in the Ingalls area were too shallow to encounter shocked units. After considering depths and locations of the wells within the structure, only 4 of the 10 wells had cuttings from units that would contain potential shock evidence. The wells with deep enough cuttings in the main part of the structure are the 1 Hadley Betsy and the 3 Martha Berry, while the wells with

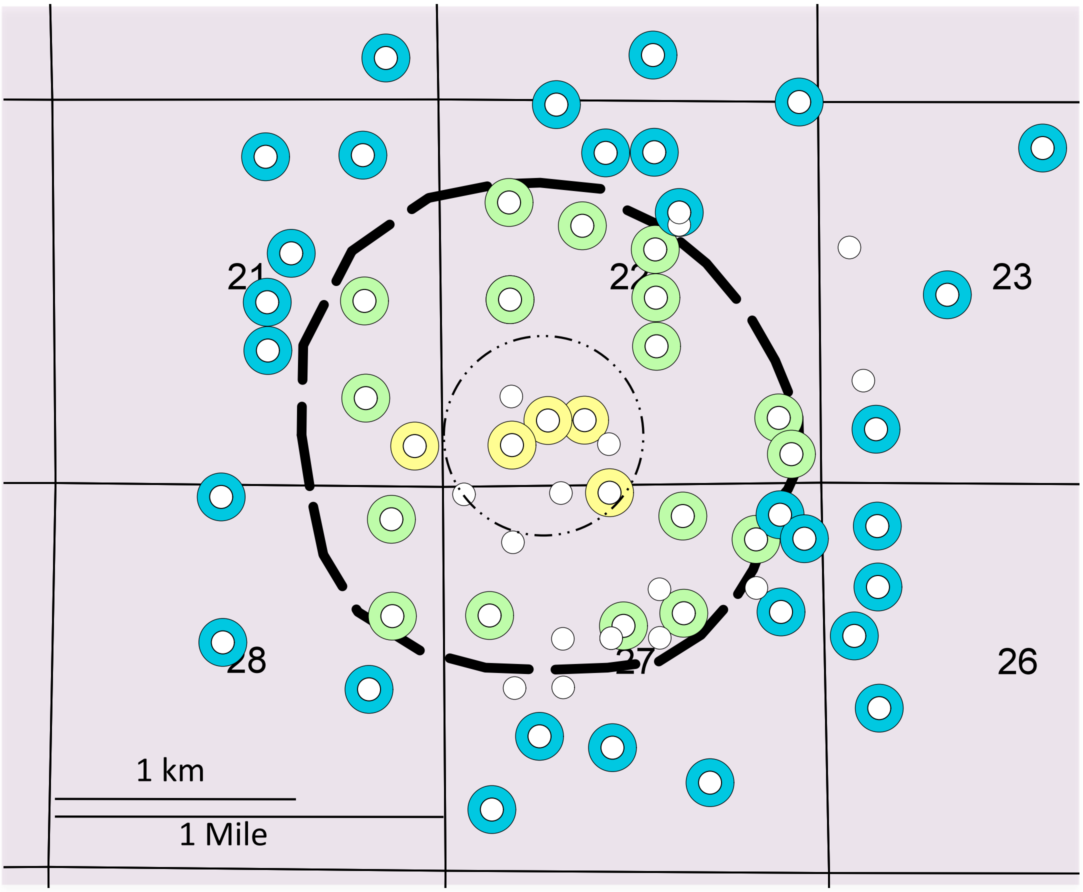


Figure 14.
Map of the Ingalls study area showing the type of lithology encountered by each well studied. Green circles represent wells that drilled into crater fill. Yellow circles represent wells that drilled into the central uplift. Blue circles represent wells outside of the structure. These data allow approximate boundaries to be drawn for the impact structure (thick dashed line) and the central uplift (thin dashed line) within it.

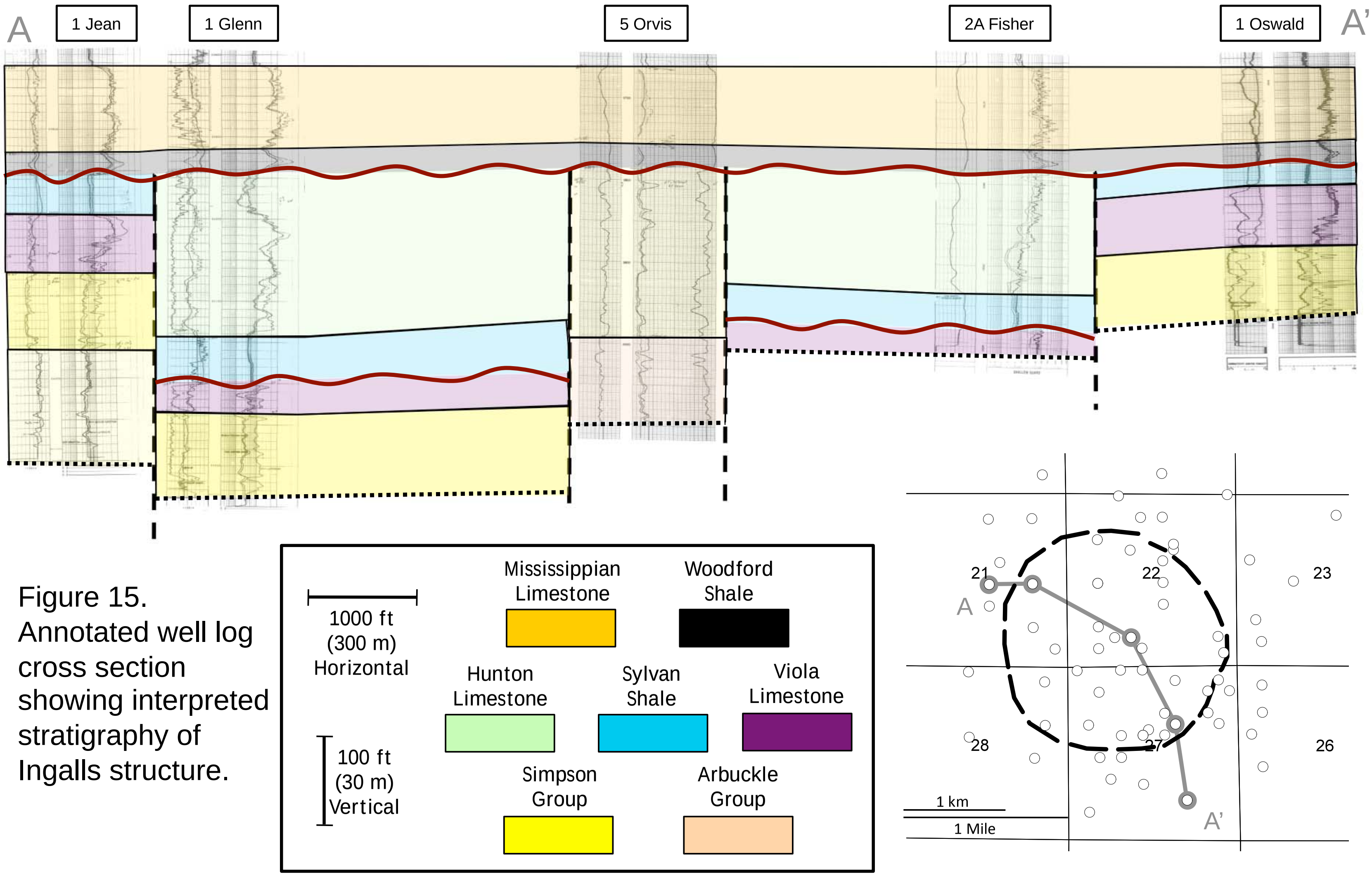


Figure 15. Annotated well log cross section showing interpreted stratigraphy of Ingalls structure.

cuttings from the central uplift are the 2 Chevalier and the 1-22 Rebound. Figure 16 shows a list of wells with cuttings and a map of their locations within the structure.

The first well examined was the 1-22 Rebound, which had comprehensive sample coverage and a suite of modern logs over a broad range of depths. The interpreted well logs for the 1-22 Rebound show the Woodford Shale lying above an abnormally thick section of the Simpson Group, whose additional thickness is the result of faulting within the central uplift. Quartz grains were extracted from zones throughout the Simpson section of the 1-22 Rebound well and placed in oil with refractive index of 1.54, then viewed under a microscope in search of shock evidence as described in the Methods section above. A picture of the grains can be seen in Figure 17. The grains showed signs of weathering with significant fracturing, making finding and recognizing shock features difficult. Potential shock evidence was found on one grain, in the form of feather features (FFs) extending at angles of approximately 45^0 from a series of planar fractures (PFs) on a grain from the section of Simpson above the fault. FFs are described by Poelchau and Kenkmann (2011) as thinly spaced lamellae that emanate from one side of a PF, and they were originally interpreted as incipient PDFs by French et al. (2004). Figure 18 shows a photomicrograph of the shocked grain showing the observed FFs and PFs. No other grains from the 1-22 Rebound well were found to contain evidence of shock.

The 2 Chevalier well was also determined to be a good target for shock evidence based on the depth of its cuttings. There are no logs for the well, but the depths of the cuttings were known. The well reached units several hundred feet below the Woodford shale, which means that some of its cuttings were likely from strata old

API #	No.	Well Name	Sec	Quarter	Elev (ft)	TD (ft)	Hunton (ft)	Missing (ft)	SAMP
23793	1-22 D	REBOUND	22	W2 SE SW	931	5300	0	REB	XX
01993	3	MARTHA BERRY	22	SW NW SE	846	4129	91	-36	XX
30121	1	HADLEY BETSY	21	NW SE SE	943	4193	142	NDE	XX
02663	2-DD	CHEVALIER AB	27	SE NW NW	903	4315	No Logs		XX
02698	4	FISHER	27	SW SW NE	843	3821	No Logs		X
03117	2	VOGT	22	NE SW SW	928	3872	No Logs		X
04718	12	GROVES	27	NW NE NW	892	3851	No Logs		X
01095	1	SCHIEFELBUSCH	22	SW SW NE	856	3954	88	NDE	X
04494	1	FISHER	27	SW NE NE	860	3905	61	NDE	X
23816	1-22 H	CRATER	22	SE SE SE	851	6910	122	NDE	X

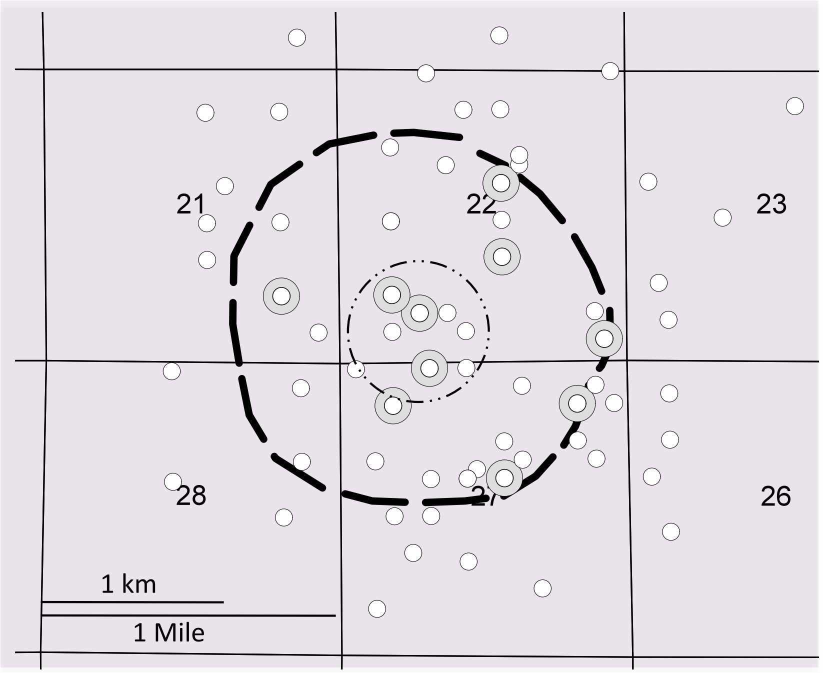


Figure 16.
Map and table of the Ingalls area showing wells within the structure that have cuttings available for study. The 1-22 Rebound, 3 Martha Berry, 1 Hadley Betsy, and 2 Chevalier wells had cuttings from units that may have been affected by the impact. The other wells were too shallow to reach these units.

Figure 17. Picture of cuttings from the 1-22 Rebound well.

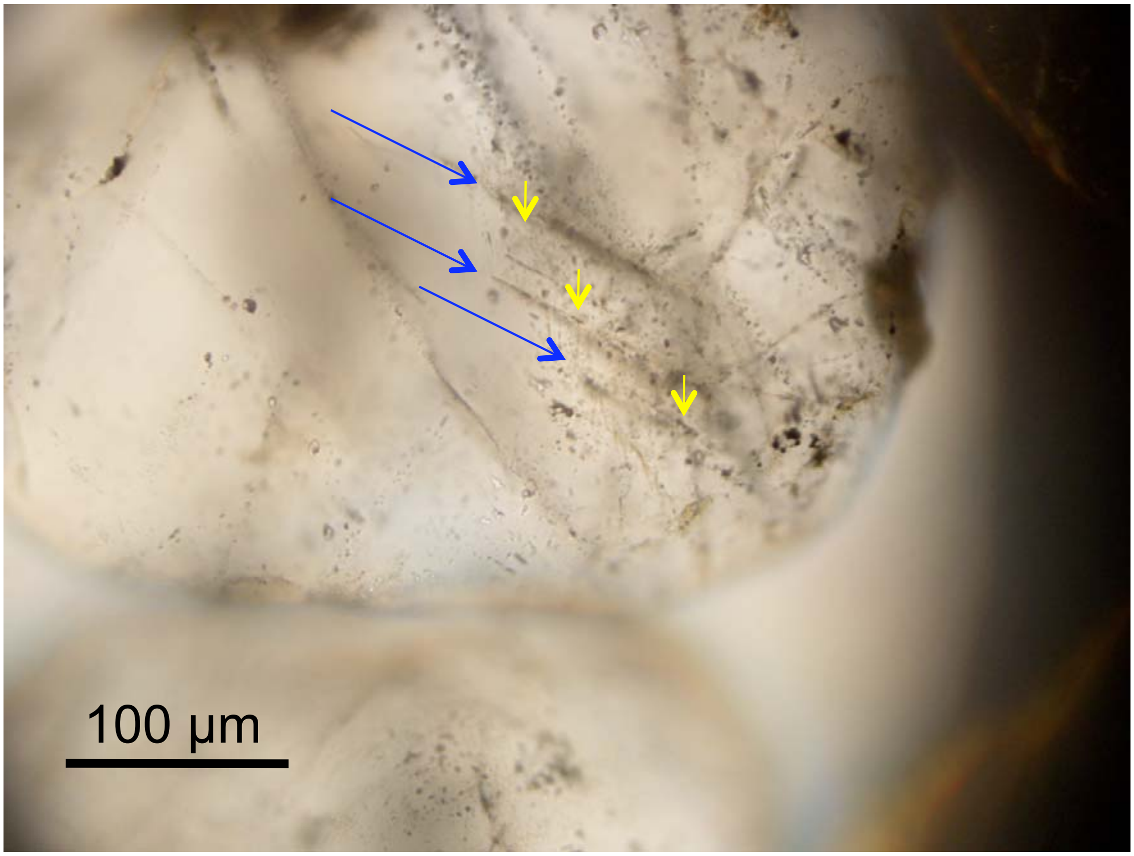


Figure 18.
Photomicrograph of grain from the 1-22 Rebound well showing groups of feather features (FFs) extending from a series of planar fractures (PFs). PFs and FFs are shock features formed in low pressure regimes (<10 GPa) at impact sites. Blue arrows point to the PFs, while yellow arrows point to the FFs emanating from them at angles near 45°.

enough to contain evidence of shock. Because no logs were run on the well, lithologic correlations could not be made to other wells, and the cuttings had to be examined despite coming from unknown stratigraphic units. Sample coverage was sparse, only covering two intervals of 3 feet (1 m) and 6 feet (2 m) respectively. The upper interval contained coarse sand and pebble-sized grains of quartz and limestone (Figure 19), and no shock evidence was found in these samples. But a few of the lower interval grains, which were sand-sized particles of quartz and plagioclase, appeared to contain shock features. Thin linear fractures resembling PFs and PDFs appeared on three grains within the lower sample interval. These grains were unable to be studied under a universal stage because they were not mounted, but the interval was marked for further investigation.

The other two wells with cuttings that could contain shock evidence were the 1 Hadley Betsy and the 3 Martha Berry. Each of the two wells was drilled into the crater fill, and each penetrated the Viola Limestone. The 1 Hadley Betsy stopped at the base of the Viola, while the 3 Martha Berry went about 75 feet (23 m) below the Viola into the Simpson Group. Samples covered intervals of less than 60 feet (20 m) at the bottom of each well. The amount of quartz present in the cuttings was limited because the encountered formations were mainly clean carbonate units. The few quartz grains extracted from the cuttings were inspected for shock evidence, but none was found.

After inspecting quartz grains from each of the four wells, the only petrographic evidence of impact-induced shock features was found on a grain from the 1-22 Rebound well and three grains from the 2 Chevalier. The 1-22 Rebound grain contained sets of FFs extending from three PFs, and the three grains from the 2 Chevalier showed signs of

Figure 19. Picture of cuttings from the 2 Chevalier well.

PFs and PDFs. All of the potential shock evidence was found in loose grains, which cannot be studied under a universal stage. Grain mounts are being made with material from both intervals where potential shock evidence was found, and these mounted grains will be investigated further to find and index more shock features.

Discussion

Summary of Evidence

Stratigraphic evidence from well logs supports the hypothesis that the Ingalls structure is a meteorite impact structure. The presence of Hunton Limestone, which is absent in the subsurface for miles (kilometers) around Ingalls, is indicative of extra deposition at the site that is interpreted as post-impact crater fill. Missing and irregular sections of Sylvan Shale and Viola Limestone indicate removal of material from the structure during the Ordovician, and it is interpreted that this erosion is the result of an impact at the site. The higher elevation of stratigraphically older units at the center of the structure represents the central uplift of material associated with the formation of a complex impact structure. Significant faulting, non-correlative units, and sharp boundaries present throughout the structure provide further support for the hypothesis, since these features are readily observed at other known impact sites.

Impact Interpretation

Although a precise timeline for the Ingalls structure is unable to be determined with the stratigraphic data available, the sequence of events leading to the present condition of the structure can be established. The impact event causing the Ingalls structure occurred in conjunction with deposition of the Viola Limestone. The Viola is present within the crater fill, but it has drastically varying thicknesses and irregular log signatures from well to well. The inconsistency of the Viola within the structure is the result of the impact event; however, it is unclear whether the impact event occurred before or after the onset of Viola deposition. The depositional consistencies of the Second Wilcox Sandstone (Simpson Group) and the Sylvan Shale within the structure indicate that the collision did not disrupt deposition of either of the two formations, and the impact may have occurred at any point in the interval between the two. It is likely that a significant amount of Viola Limestone was in place by the time of impact and was vaporized by the event, because carbonate material has a lower pressure threshold for vaporization (Shen et al, 2003). Once the area settled after the impact, deposition resumed on the irregular post-impact topography. After deposition of the Viola was complete, the Sylvan Shale was deposited during the late Ordovician, and the Hunton Limestone followed in the Silurian and early Devonian. A break in deposition and a period of significant erosion took place across Oklahoma during the mid Devonian, creating a relatively flat topographic surface across the area. This erosion exposed the Sylvan Shale in most of the region, but a roughly circular outcrop of Hunton Limestone was surrounding a suite of Simpson Group rocks at the surface above the impact. The presence of Hunton above the impact structure was the result of additional deposition after the impact, and the Simpson Group rocks represented the central uplift. When deposition resumed in the area during the late Devonian, the Woodford Shale was deposited onto the erosional surface, and all units that had been affected by the impact were buried. Additional deposition over the tens of millions of years since then has resulted in the current depth of the structure. Figure 20 shows a series of diagrams that illustrate the post-impact history of the Ingalls structure.

Further Investigation

Although the stratigraphic evidence in the Ingalls area supports the impact hypothesis, supporting petrographic evidence was scarce. Only the grain from the 1-22 Rebound with feather features and planar fractures along with the three grains with possible PDFs from the 2 Chevalier provided potential evidence for shock. Significant amounts of PDFs, impact melts, or other impact-produced materials were not found in the study samples. Several reasons for this absence of shock evidence from the Ingalls structure are plausible. The simplest is the lack of rock material available for study. Drilling cores, which would show relatively complete stratigraphic sections and which have been used to establish evidence for impact at subsurface structures such as Ames (Koeberl et al, 1997), were not available for any of the wells at Ingalls. The only available samples were well cuttings from four wells penetrating the structure. These cuttings were incomplete and represented only a tiny percentage of the stratigraphic material at each depth.

Further explanation for the lack of shock evidence at Ingalls comes from the physical dynamics of the material affected by the impact. According to French (1998), the formation of PDFs in quartz requires shock pressures above 7 GPa . But impact craters with diameters less than 3 miles (5 km) typically only encounter shock deformation pressures below 10 GPa (Poelchau and Kenkmann, 2011). This pressure threshold for PDF formation allows for the possibility that no PDFs were formed during

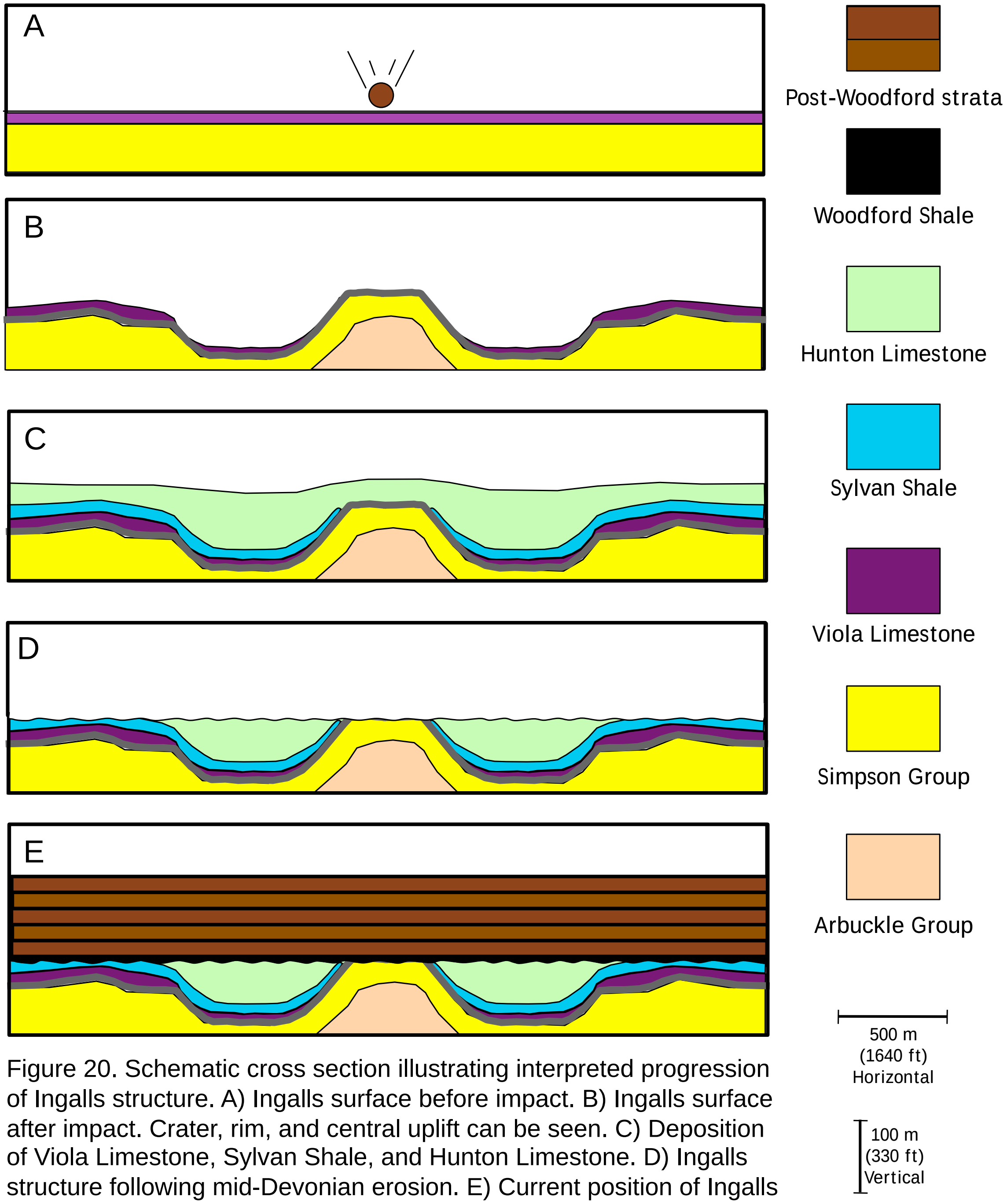


Figure 20. Schematic cross section illustrating interpreted progression of Ingalls structure. A) Ingalls surface before impact. B) Ingalls surface after impact. Crater, rim, and central uplift can be seen. C) Deposition of Viola Limestone, Sylvan Shale, and Hunton Limestone. D) Ingalls structure following mid-Devonian erosion. E) Current position of Ingalls structure, buried beneath post-Devonian sediment.

the Ingalls impact event. If higher shock pressures were achieved at Ingalls, they may have been great enough to melt the grains containing PDFs, since quartz grains in porous rocks such as sandstone can melt at pressures as low as 15 GPa (French, 1998). Any PDFs produced during the Ingalls impact and preserved in the rocks of the resulting structure would be very difficult to locate, especially considering the quantity and quality of sample material available to the project. Most cuttings from Ingalls came from the central uplift, but most of the shocked grains at impact sites come from impacted rock fragments that were preserved in the crater fill (French, 1998).

Other various rock types are found in association with impacts, and the general term 'impactite' has been adopted by French (1998) to describe rock units such as melts and breccias that were produced by impact events. Impactites vary greatly in terms of their composition, quantity, and distribution throughout a given impact site. Although these rocks are often present at impact structures and can even be the source of hydrocarbon production (Kuykendall et al, 1997), no distinctive impactite units were recognized in the stratigraphic study of the Ingalls structure. The lack of observed impactites at Ingalls is due in part to the scope of this study. The stratigraphic study of the Ingalls structure was conducted entirely through well logs. Well logs are useful for identifying subsurface stratigraphic units and for correlating these units across distances, but inferring detailed lithologic information from well logs requires a comprehensive set of modern log data. Data of this caliber was not available for most of the wells penetrating the structure because they were drilled before modern logging tools were available. Analysis of the available logs showed abnormal attributes within and immediately below the Viola Limestone, but these irregularities were not enough to characterize the zones as impactites. A physical inspection of rocks removed from the site would be required before an impactite label could be attached to the irregular log signatures.

Conclusion

When summarizing the information at Ingalls, it is difficult to derive a plausible alternative explanation for the origin of the structure. Alternative origin suggestions for verified impact structures such as Ames usually involve regional tectonism (Coughlon and Denney, 1997) or igneous activity (Bridges, 1997). There is no evidence of these activities near Ingalls during the hypothesized time of impact; the rocks composing the Ingalls structure are sedimentary units that are widespread and identifiable across the region. A structural explanation could be made for the elevated strata in the interpreted central uplift, but structural activity would fail to account for the younger Hunton Limestone in the crater fill that is absent regionally. The missing Viola Limestone and the additional deposition in the interpreted crater fill could possibly be explained by karst dissolution and collapse, but these processes would not explain the uplifted material in the center of the structure. Other alternatives may be possible, but any reasonable explanation for the origin of the Ingalls structure must account for its circular shape, sharp boundaries, additional deposition, missing units, and uplifted strata. A meteorite impact followed by the progression of events interpreted by this study seems to be the best explanation for the history of the structure at Ingalls.

Despite the results of this study and the lack of alternative explanations for the Ingalls structure, the evidence for an impact origin of the site is not definitive.

Considering that only a few grains containing shock features were found in the samples at Ingalls, one cannot conclude with certainty that the structure is indeed an impact; more shock evidence needs to be a found in rocks from the site before the impact hypothesis can be concluded. Still, an impact event is the most likely explanation for the origin of the structure, and the quest for gaining accepted recognition of the site as the Ingalls impact structure seems promising.

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Appendix

List of wells in study. Color behind rows indicates stratigraphic unit encountered below the Woodford Shale: green – Hunton; Blue – Sylvan; Yellow – central uplift; brown – no logs.

API #	Well No.	Well Name	Sec	TWP	RNG	Quarter	Elev	TD	Hunton	Missing	SAMPLES
21621	1	WHIPPLE	22	19N	04E	NE SW NW	860 KB	4170	106	49	
21047	1-A	VOGT	22	19N	04E	NE NW SW	905 KB	4153	95	28	
21283	2-A	FISHER	27	19N	04E	SW NE	863 KB	3994	140	36	
01993	3	BERRY MARTHA	22	19N	04E	SW NW SE	846 GR	4129	91	-36	XX
21504	1	VICK	28	19N	04E	NE NE	914 GR	4213	142	NDE	
21027	1	GLENN	21	19N	04E	E2 NW NE SE	916 GR	4336	201	44	
01095	1	SCHIEFELBUSCH	22	19N	04E	SW SW NE	856 GR	3954	88	NDE	X
22071	1	BLANCHE	28	19N	04E	E2 SE NE	889 KB	3990	106+	NDE	
21656	6	BERRY	22	19N	04E	NW NW SE	853 KB	3954	126+	NDE	
20941	1	SPYRES	22	19N	04E	E2 SE NW	870 KB	4100	154	124	
21410	2-A	GROVES	27	19N	04E	NE SE SE NW	884 KB	4030	163	NDE	
04494	1	FISHER	27	19N	04E	SW NE NE	868 KB	3905	61	NDE	X
23816	1-22 H	CRATER	22	19N	04E	SE SE SE	851 GR	6910	122	NDE	X
30121	1	HADLEY BETSY	21	19N	04E	NW SE SE	951 KB	4193	142	NDE	XX
20860	5	BERRY	22	19N	04E	SE SE	854 KB	4090	169	NDE	
20933	1-A	STRANGE	27	19N	04E	NW NE	887 KB	4000	120	NDE	
22169	3-A	GROVES	27	19N	04E	E2 SW NW	882 KB	4101	172	NDE	
20085	1	BETSY HADLEY	21	19N	04E	SW NW SE	940 KB	4107			
20335	1	MILLER	27	19N	04E	S2 SE NE SW	917 KB	3896			
20590	1	SCHIEFELBUSCH	22	19N	04E	NE NE NE	873 KB	3892			
20853	1	HARRIS	23	19N	04E	N2 S2 SW SW	832 GR	4053			
20865	1	D DAVIS	26	19N	04E	N2 S2 NW NW	934 GR	4049			
20869	1	FLOWERS	23	19N	04E	SW NW NE	902 KB	3855			
20871	2	FISHER	27	19N	04E	W2 E2 NE NE	871 KB	3932			
20874	1	DAVIS	28	19N	04E	NE NE NW	979 GR	4115			
20880	2	D DAVIS	26	19N	04E	N2 SW NW	934 GR	3950			
20916	1	MILLER	27	19N	04E	N2 SW	903 KB	4300			
20917	2	MILLER	27	19N	04E	W2 SW SW	893 KB	3985			
20939	1-A	FISHER	27	19N	04E	E2 W2 SE NE	835 GR	3945			
20947	3	D DAVIS	26	19N	04E	SW SW NW	934 GR	4000			
20974	1	BUCK DAVENPORT	21	19N	04E	SW NW SE	905 KB	4475			
21043	1	JEAN	21	19N	04E	NW NW SE	926 GR	4300			
21044	2-21	CULLERS	21	19N	04E	S2 SW NE	917 KB	4125			
21101	1	MCCOWN	21	19N	04E	W2 SW NE NE	880 KB	4116			
21107	3	SCHIEFELBUSCH	22	19N	04E	S2 N2 SW NE	885 KB	4065			
21191	1	OSWALT	27	19N	04E	NE SW SE	912 KB	4000			
21279	2	MENNEM	28	19N	04E	NW NE SE	929 KB	4090			
21300	3	FISHER L	27	19N	04E	SE NE NE	849 KB	3957			
21514	2	SPYRES	22	19N	04E	SE NE NW	895 KB	3985			
21568	28-18-1	SCOOT	28	19N	04E	SE SE NW	919 GR	4030			
21611	4	SCHIEFELBUSCH	22	19N	04E	SW NW NE	922 KB	4091			
21715	1	WILSON	15	19N	04E	SW SW SE	937 KB	4200			
21795	3	SPYRES	22	19N	04E	E2 NW NE NW	901 KB	3999			
22250	1	HARRIS	23	19N	04E	NW NE SW	903 KB	4077			
22962	3-16	STATE	16	19N	04E	S2 SE SE	910 DF	4100			
23809	1	JEANIE	26	19N	04E	NW SW	890 DF	4030			
23793	1-22 D	REBOUND	22	19N	04E	W2 SE SW	940 DF	5300	0	reb	XX
03118	4	VOGT	22	19N	04E	SE SW SW	942 KB	4071	0	reb	
04491	1	VOGT	22	19N	04E	NE NW SW	903 KB	3944	0	reb	
20608	5	ORVIS	22	19N	04E	E2 SE SW	897 KB	4101	0	reb	
20832	2	HADLEY	21	19N	04E	SE SE SE	930 GR	4640	0	reb	
20881	1-A	GROVES	27	19N	04E	W2 NE NE NW	899 KB	3940	0	reb	
02686	10	GROVES	27	19N	04E	NW NW NW	925 GR	3905			
02687	11	GROVES	27	19N	04E	SW SE NW	881 GR	3862			
02692	7	MILLER	27	19N	04E	NE NW SW	883 GR	3881			
02694	1	MILLER-GROVES	27	19N	04E	SE SE NW	859 GR	3889			
02702	2	MILLER	27	19N	04E	NW NE SW	862 GR	3900			
03112	2	ORVIS	22	19N	04E	SE SE SW	976 GR	4105			

02698	4	FISHER	27	19N	04E	SW SW NE	843	GR	3821	X
03117	2	VOGT	22	19N	04E	NE SW SW	936	KB	3872	X
04718	12	GROVES	27	19N	04E	NW NE NW	902	KB	3851	X
02663	2-DD	CHEVALIER AB	27	19N	04E	SE NW NW	903	GR	4315	XX
02678	2	GROVES	27	19N	04E	SE SE NW	859	GR	3820	
02696	2	FISHER	27	19N	04E	NW SW NE	858	GR	3840	
02697	3	FISHER J E	27	19N	04E	NW SE NE	853	GR	3944	
03125	1	Ashburn	23	19N	04E	NE NW SW SW	824	GR	3936	
20968	1-A	KERBY	23	19N	04E	SW SW NW	994	GR	4040	
21064	2	SCHIEFELBUSCH	22	19N	04E	SW NE	865	GR	4100	

Vita

Personal Background	Benjamin Charles Herrmann Sandy, Utah Son of Carl Jeffrey Herrmann and Janice Elizabeth Podpechan
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Experience	Teaching Assistant, August 2007 – May 2009 Oklahoma State University, Stillwater, OK Intern Geologist, May 2009 – August 2009 Devon Energy, Houston, TX Teaching Assistantship, August 2009 – May 2011 Texas Christian University, Fort Worth, TX Intern Geologist, May 2010 – August 2010 Devon Energy, Oklahoma City, OK
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Abstract

IMPACT AT INGALLS? EVIDENCE FOR A SUNBSURFACE ORDOVICIAN METEORITE IMPACT NEAR INGALLS, OKLAHOMA

by Benjamin Charles Herrmann, M.S., 2011
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Thesis Advisor: Rhiannon G. Mayne, Assistant Professor of Geology

A nearly circular subsurface structure 2 km in diameter has been identified in north-central Oklahoma near the town of Ingalls in Payne County. The structure lies beneath ~1100 m of sedimentary rock, and stratigraphic information from well logs suggests that the structure developed from the Ordovician through the Devonian. Sedimentary units within the structure have widely varying thicknesses and abnormal characteristics. Rocks in the center of the structure have been uplifted nearly 100 m. The best explanation for these stratigraphic relationships is a meteorite impact, and the purpose of this study is to seek evidence supporting an impact origin for the Ingalls structure. Cuttings from wells drilled into the structure were investigated for evidence of shock metamorphism, the rock deformation caused by intense pressures generated only by meteorite impacts. Results indicate that the hypothesis of an impact at Ingalls is likely, but definitive evidence has not yet been found.