U-Pb AND Hf DETRITAL ZIRCON GEOCHRONOLOGY AND PROVENANCE OF THE MISSOURIAN COTTAGE GROVE SANDSTONE, NORTHERN ANADARKO BASIN, OKLAHOMA

By

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Abstract: The Late Pennsylvanian Cottage Grove Sandstone in the northern Anadarko Basin of northwest Oklahoma is characterized as a series of shallow marine shoals that display reservoir heterogeneity largely driven by detrital composition and diagenetic alteration. Porosity within the formation is mostly secondary due to the dissolution of carbonate cements, detrital matrix, and labile grains such as abundant schistose metamorphic rock fragments and less abundant, occasional plutonic rock fragments that are observed by petrographic analysis and that are both of unknown origin. Depositional settings for the Cottage Grove Sandstone transition from shallow marine deposits in northwest Oklahoma to fluvial-deltaic deposits in central Oklahoma suggesting sediment dispersal from the east-southeast. Petrology of the Cottage Grove Sandstone suggests a complex assemblage of source terranes that host sedimentary, metamorphic, and minor contributions of plutonic, igneous rocks.

This study presents 288 new detrital zircon U-Pb ages and 26 new εHf(t) measurements for the Cottage Grove Sandstone with a goal of identifying sedimentary provenance. Overall, U-Pb ages are characterized by 44% Grenville (950-1,250 Ma), 16% Midcontinent Granite-Rhyolite (1,300-1,550 Ma), 10% Appalachian synorogenies (290-500 Ma), 9% peri-Gondwanan (500-800 Ma), 7% Yavapai-Mazatzal (1,600-1,800 Ma), 6% Superior (>2,500 Ma), 1% Penokean (1,800-2,000 Ma), and <1% Wichita (530-540 Ma) sourced zircons. U-Pb signatures compared between the Cottage Grove and previous studies suggest that sediment sourcing occurred from terranes to the north and east-northeast. Geochronologic data also suggest possible connections between source terranes, sedimentary basins, and associated dispersal systems, such as fluvial routing systems that are thought to have flowed from the northern Laurentian craton and the east-northeast Appalachian orogen to subsiding basins of the Midcontinent during the Late Mississippian to Late Pennsylvanian. εHf(t)-U-Pb signatures support that 290-500 Ma aged zircons were sourced from the Appalachian synorogenies. εHf(t)-U-Pb signatures and petrographic evidence support that 500-800 Ma aged zircons were sourced from the Ganderia and Avalonia peri-Gondwanan terranes of the northern Appalachians. Sediments sourced directly to the Anadarko Basin likely entered the Oklahoma region from the north, northeast, and/or east. Recycled sediments contributed from the Ouachita Mountains were likely restricted to the more mature, resistant grains such as quartz and associated zircons.

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CHAPTER I

INTRODUCTION

The Late Pennsylvanian Missourian series Cottage Grove Sandstone is an important oil- and gas-producing reservoir in the western Oklahoma part of the Anadarko Basin with cumulative production since 1954 reaching more than 52 MMBO (million barrels of oil), 382 BCFG (billion cubic feet of gas), and 115 MMboe (million barrels of oil equivalent). Production is from stratigraphic traps and reservoir heterogeneity exhibited by the Cottage Grove Sandstone and other Pennsylvanian, tight, sandstones of the Midcontinent can make drilling and producing these formations problematic unless there is a fundamental understanding of the paleogeography and its influence on sediment source, dispersal patterns, depositional processes, and detrital composition.

Within the study area of Dewey and portions of Ellis, Roger Mills, Woodward, Custer, and Major Counties, Oklahoma, the Cottage Grove Sandstone is described as a series of shoals that formed in a shallow marine, shelf environment. The sand bodies were thought to be heavily influenced by wave action during storm events which caused winnowing of crests and discontinuous geometries that trend in a northeast-southwest direction (Fruit and Elmore, 1988). Based on the wireline log signature that displays an overall fining upward pattern from a sharp basal contact, sand deposition is interpreted to have occurred in an overall transgressive environment within the study area. The Cottage Grove interval is generally denoted by marine, radioactive “hot” shales, which are easily detected on gamma-ray wireline logs and serve as regional marker beds that facilitate locating the upper and lower limits of the interval. The upper marker bed is the Avant “hot” shale marker (associated with the overlying Avant Limestone), whereas the lower marker bed is the Hogshooter “hot” shale marker (associated with the underlying Hogshooter Limestone). These marker beds aid in the correlation and identification of the Cottage Grove interval on wireline logs throughout the basin. In Canadian County, central Oklahoma (southeast of the study area), the Cottage Grove Sandstone is described as an elongate, single sand body, with a north-south trend (Waller, 1985). This deposit is interpretated to be a high-constructive, distal marine delta (Waller, 1985).

Based on petrographic analysis conducted herein and by previous researchers (Wade, 1987; Waller, 1985; Towns, 1978) it is observed that most of the porosity within the Cottage Grove is secondary due to the dissolution of cements, detrital matrix, and labile grains, such as feldspars and rock/lithic fragments. Understanding the compositional variability of the Cottage Grove and how it changes throughout the region is critical for identifying productive reservoir facies, especially now that the formation has in the past two decades, become a target for horizontal drilling techniques. It is observed that sediment sourcing and the direct influence it has on detrital and overall rock composition, as well as diagenetic alteration after deposition (such as cementation and generation of secondary porosity) are two primary characteristics that produce spatio-temporal heterogeneity, and directly influence the reservoir quality of the Cottage Grove Sandstone within the Anadarko Basin.

To gain a better understanding of potential source terranes and dispersal pathways/systems, that directly influence the detrital composition and therefore the reservoir quality of the Cottage Grove Sandstone, the primary objective of this study is to evaluate the sedimentary provenance of the formation using (primarily) detrital zircon (DZ) uranium-lead (U-Pb) and hafnium (Hf) isotopic geochronology and (secondarily) petrographic analysis. Recent DZ geochronology studies conducted on Paleozoic strata in the central and eastern United States published U-Pb and Hf data pertinent to this study, including studies conducted on Mississippian to Permian aged rocks in the Ouachita Mountains as well as the Anadarko, Arkoma, Fort Worth, Forest City, Illinois, Michigan, and Appalachian Basins (Sharrah, 2006; Alsalem et al., 2017; McGuire, 2017; Thomas et al., 2017; Kissock et al., 2017; Tunin, 2020; Thomas et al., 2020; Allred and Blum, 2021; Thomas et al., 2021). These studies aid in the interpretation of the sediment dispersal from the Appalachian orogen to the east-northeast and the northern Laurentian craton, which sourced sediments to subsiding Midcontinent basins via transcontinental fluvial systems during the Pennsylvanian (Tunin, 2020; Allred and Blum, 2021).

Important DZ U-Pb and Hf measurements, signatures, and interpretations that will be compared to this study (among others) include Allred and Blum (2021); McGuire (2017); and Sharrah (2006) who analyzed Mississippian to Pennsylvanian strata in the Ouachita Mountains of central to western Arkansas and southeast Oklahoma. These studies are relevant because the Ouachita Mountains are the widely accepted primary sediment source of the Cottage Grove Sandstone within the Anadarko Basin based on previous work conducted on paleogeography, petrology, and lithostratigraphy (Lalla, 1975; Rascoe, 1978; Towns, 1978; Waller, 1985; Wade, 1987; Fruit and Elmore, 1988). In terms of DZ U-Pb and Hf geochronology, this study is the first of its kind conducted on the Cottage Grove Sandstone in the Anadarko Basin and seeks to test the hypothesis of an Ouachita Mountains provenance by comparing geochronologic data herein to known ages of potential source terranes and recent studies, such as studies conducted in the Ouachitas, the surrounding Midcontinent, and basins to the northeast. Results and interpretations produced from this study have critical implications for sediment sources, routing, and paleogeographic reconstructions in the Anadarko Basin and surrounding Midcontinent of North America.

Two-hundred eighty-eight (288) new DZ U-Pb ages and 26 new εHf(t) (epsilon units of Hf at the timing of crystallization (U-Pb age)) measurements are presented from DZs collected from a subsurface Cottage Grove Sandstone sample located in the northern Anadarko Basin, Ellis County, Oklahoma (**Figure 1**). As discussed above, these new measurements compared to recently published, relevant DZ geochronology studies and known ages of positive, eroding source terranes of North America will not only give new insights into paleogeographic reconstructions, sediment source terranes, and dispersal systems/pathways, but it will also aid in creating a better understanding of spatial changes in detrital and overall rock composition within the Cottage Grove Sandstone, which directly correlates to reservoir quality and hydrocarbon producibility.

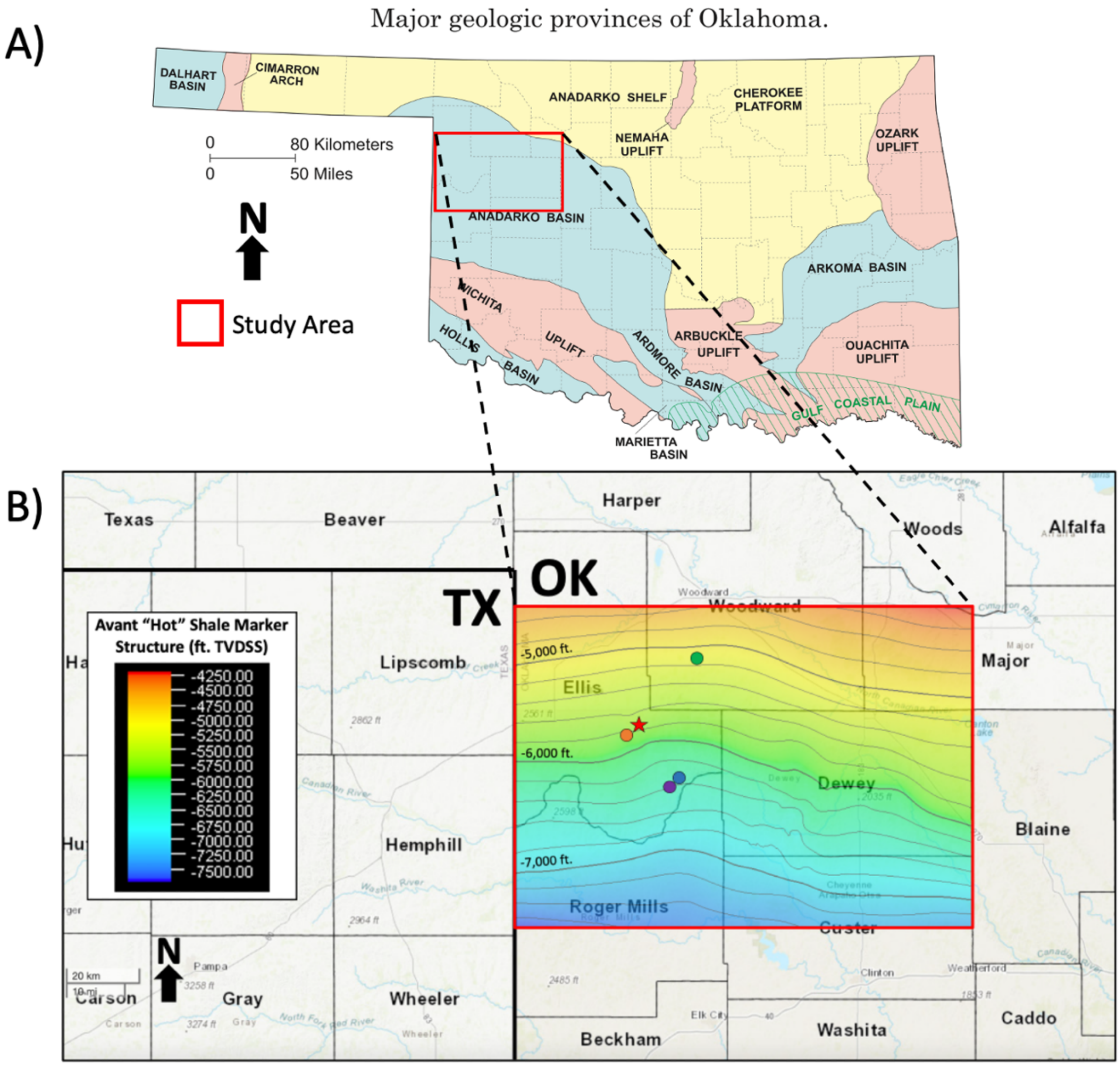

Figure 1. A) Map showing the location of the general study area in the northern Anadarko Basin, Oklahoma. Yellow represents shelf and platform settings, blue represents deeper basins, and pastel red represents uplifts (Modified after Northcutt and Campbell, 1995). B) Map showing the study area in greater detail with overlain Avant "hot" shale marker structure map in feet total vertical depth subsea (TVDSS) (C.I. = 200 feet). This map was constructed using 160 formation tops. Note the north to south dipping slope of the basin. The red star denotes the DZ sample well location: George Berryman C 1. The colored circles represent well locations used for petrographic analysis: green = Cole 28-A, orange = Berryman C 1, blue = Gillispie 3-2, and purple = Gillispie 1-3.

CHAPTER II

LITERATURE REVIEW

2.1 Previous Cottage Grove Sandstone Studies

Much of the previous work that has been conducted on the Cottage Grove Sandstone in the region includes theses and papers focused on depositional environments, petrology/petrography, sedimentology/diagenesis, and lithostratigraphy with the primary goal of mapping and characterizing reservoir facies. These studies all have one hypothesis in common that has never been scientifically tested or proven, which is that the Cottage Grove Sandstone is thought to be primarily sourced from the Ouachita Mountains (Lalla, 1975; Rascoe, 1978; Towns, 1978; Waller, 1985; Wade, 1987; Fruit and Elmore, 1988). It is proposed that Cottage Grove Sandstone sediments, sourced from the Ouachita Mountains, were distributed to the general study area through fluvial and deltaic processes in south-central Oklahoma (southeast of the study area) and were subsequently deposited in the study area as shallow marine/shelf deposits in northwest Oklahoma (**Figure 2**) (Towns, 1978; Rascoe and Adler, 1983; Waller, 1985; Fruit and Elmore, 1988). This study aims to fill the gap in terms of sedimentary provenance that exists between vintage (petrology/petrography) and modern (DZ geochronology) provenance studies with a goal of creating a better understand of the relative abundance and distribution of source terranes that contributed to the detrital composition of the Cottage Grove Sandstone.

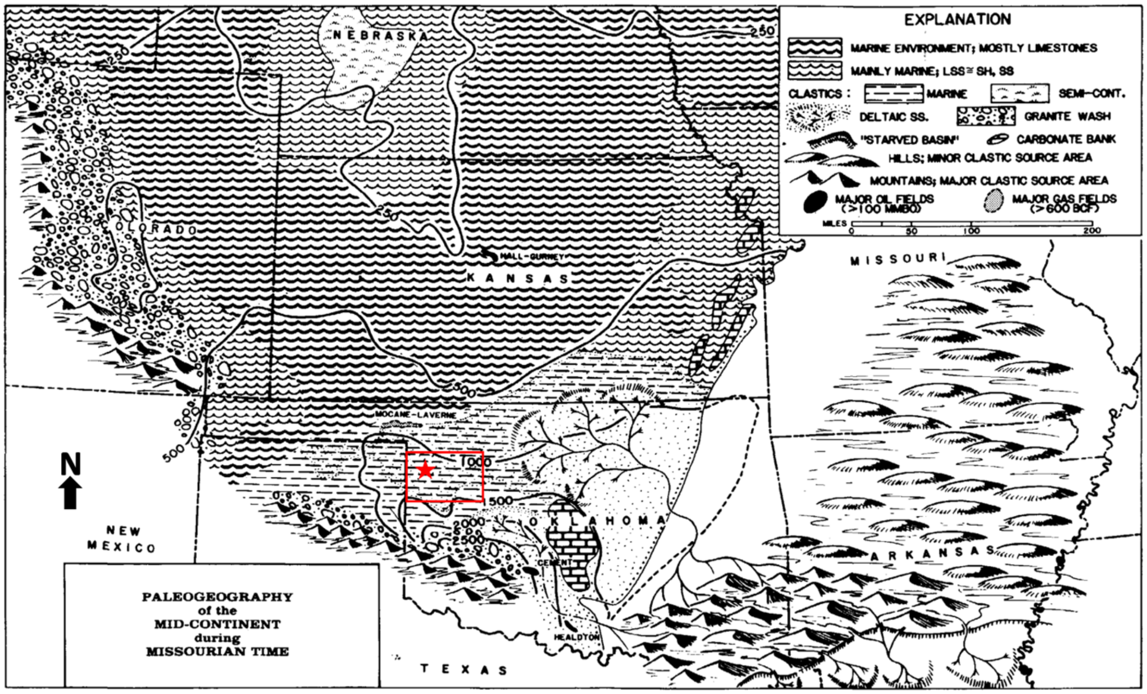

Figure 2. Paleogeographic reconstruction of the Midcontinent during Missourian time (Late Pennsylvanian) showing potential major and minor source terranes, sediment dispersal patterns, isopach contours of Missourian aged rocks, and the extent of the Midcontinent Sea. The zircon sampling location (George Berryman C 1) is marked with a red star and the general study area is denoted with a red rectangle (Modified after Rascoe and Adler, 1983).

Qualitative descriptions of detrital constituents and quantitative point counting using the Gazzi-Dickinson method are two forms of petrographic analysis conducted herein and by previous researchers (Towns, 1978; Waller, 1985; Wade 1987). These studies show that the Cottage Grove contains abundant phyllitic or schistose metamorphic rock fragments and less abundant, occasional granitic, plutonic rock fragments (Towns, 1978; Waller, 1985; Wade 1987). These findings regarding petrology of the Cottage Grove Sandstone create concern in terms of previous provenance hypotheses because the Ouachita Mountains are composed of almost entirely siliciclastic and carbonate sedimentary rocks with no known record of metamorphic or plutonic rocks (Wade, 1987; McGuire, 2017). Therefore, additional source terranes that host metamorphic and plutonic, igneous rocks must be considered, as well as possible sediment recycling and influence from crustal provinces that sourced the metamorphic and plutonic material that is observed in the Cottage Grove Sandstone in the Anadarko Basin.

A possible additional source area that hosts plutonic rocks is the proximal Wichita Mountains directly to the south of the study area. However, petrographic analysis shows only small, negligible contributions of plutonic rock fragments within the Cottage Grove, and the Wichita Mountains were initially ruled out as a possible source as the sediments shed from this province were thought to be confined to the deeper, axial portion of the Anadarko Basin, closer to the mountain front (Wade, 1987). However, this hypothesis was never adequately tested and sediments that were shed could have been transported to the study area by the fluvial-deltaic system that is thought to have existed on the northeastern edge of the Wichita Mountains. Similar systems are known to have existed during early Missourian time and resulted in deposition of the Cleveland Sandstone (Hentz, 1992; 1994).

Another possible additional source area for the Cottage Grove Sandstone that is discussed in previous literature is the Ancestral Rocky Mountains (ARMs) associated Apishapa-Sierra Grande Uplift to the northwest, as it was the second closest plutonic province during time of deposition. However, the Apishapa-Sierra Grande Uplift might be a less likely additional sediment source for the Cottage Grove Sandstone as it was more distal and separated from the study area by the carbonate rich platform associated with the Kansas-Lansing Group (Wade, 1987).

Based on the previous studies discussed above, it is inferred that the Cottage Grove Sandstone was sourced from terrains hosting a complex assemblage of sedimentary, metamorphic, and minor contributions of plutonic, igneous rocks. These rock types are a prime example of the type of formations that typically take place within sedimentary basins, and therefore strengthens the hypothesis of a recycled Ouachita Basin and subsequent Ouachita

Mountains source. Likewise, this also strengthens potential direct sourcing of recycled sediments to the Anadarko Basin from the Appalachian, Michigan, Illinois, and/or Forest City Basins to the north-northeast through previously suggest south-southwest flowing, transcontinental fluvial systems (Kissock et al., 2017; Chapman and Laskowski, 2019; Thomas et al., 2020; Tunin, 2020). It is important to note that not only does grain size for the Cottage Grove slightly increase to the southeast, but source proximal depositional environments such as fluvial-deltaic facies are observed southeast of the study area as well (Waller, 1985).

2.2 Relevant Detrital Zircon Geochronology Studies

Petrographic analysis continues to be a valuable tool for making inferences on sedimentary provenance based on characterization of detrital constituents, but with advancing technology and improved analytical methods, a modern provenance tool that is being widely used with impressive results is DZ geochronology. As briefly discussed above, recent U-Pb and Hf DZ geochronology studies are pivotal in creating a new understanding of Paleozoic sediment sourcing and pathways/systems throughout the Laurentian craton of North America. A topic of widespread interest that directly correlates to this study and that has been documented by studies from Sharrah (2006); Park et al. (2010); Gehrels et al. (2011); Alsalem et al. (2017); McGuire (2017); Thomas et al. (2017); Kissock et al. (2017); Chapman and Laskowski (2019); Thomas et al. (2020); Tunin (2020); Allred and Blum (2021); and Thomas et al. (2021) is the transcontinental transport of Appalachian orogenic system sourced sediments from the east-northeast United States to the Midcontinent and as far as the western United States during the Carboniferous. **Figure 3** shows inferred sediment dispersal systems stemming from the Appalachian orogen that are thought to have transported sediments to the Anadarko and Arkoma Basins during the Middle to Late Pennsylvanian as suggested by Kissock et al., 2017 and Tunin, 2020.

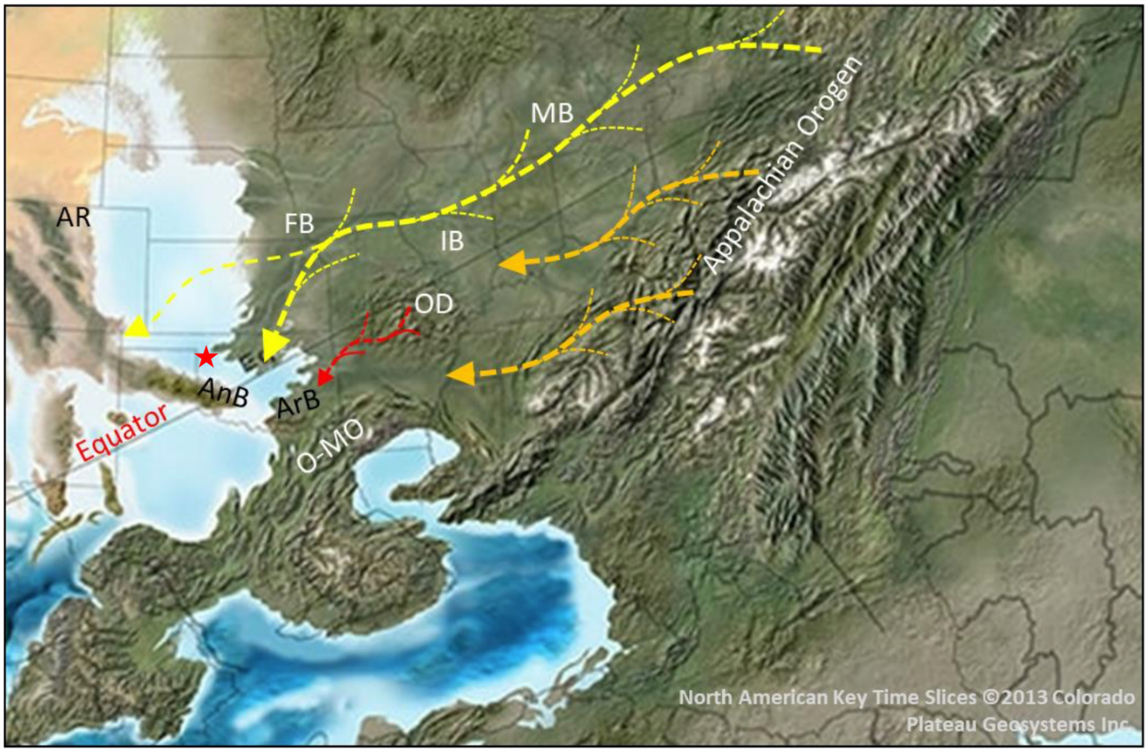

Figure 3. Middle to Late Pennsylvanian paleogeographic map showing inferred sediment dispersal systems that are thought to have provided sediments to the Anadarko and Arkoma Basins of the Midcontinent (modified after Tunin, 2020). Red star = general study area, yellow lines = dispersal pathway of fluvial systems from the northern Appalachians (Tunin, 2020), orange = transverse dispersal pathways from the central and southern Appalachians (Kissock et al., 2017), red = regional drainage pathways from the Ozark Dome. AR = Ancestral Rocky Mountains, AnB = Anadarko Basin, ArB = Arkoma Basin, O-MO = Ouachita-Marathon Orogeny, OD = Ozark Dome, FB = Forest City Basin, IB = Illinois Basin, MB = Michigan Basin.

The general workflow for DZ geochronology and provenance studies, such as those mentioned above and this study, is two-fold:

1. Comparisons and correlations are made between new U-Pb ages and known ages of major North American geologic provinces (**Figure 4**). New U-Pb age signatures and distributions are also compared to previously published, relevant signatures, data, and interpretations.

2. Hf isotopic measurements are used as a “fingerprint” by comparing new measurements to previously published, relevant Hf measurements in order to further delineate source provinces of

overlapping U-Pb ages and to differentiate source terranes with corresponding ages that span multiple locations.

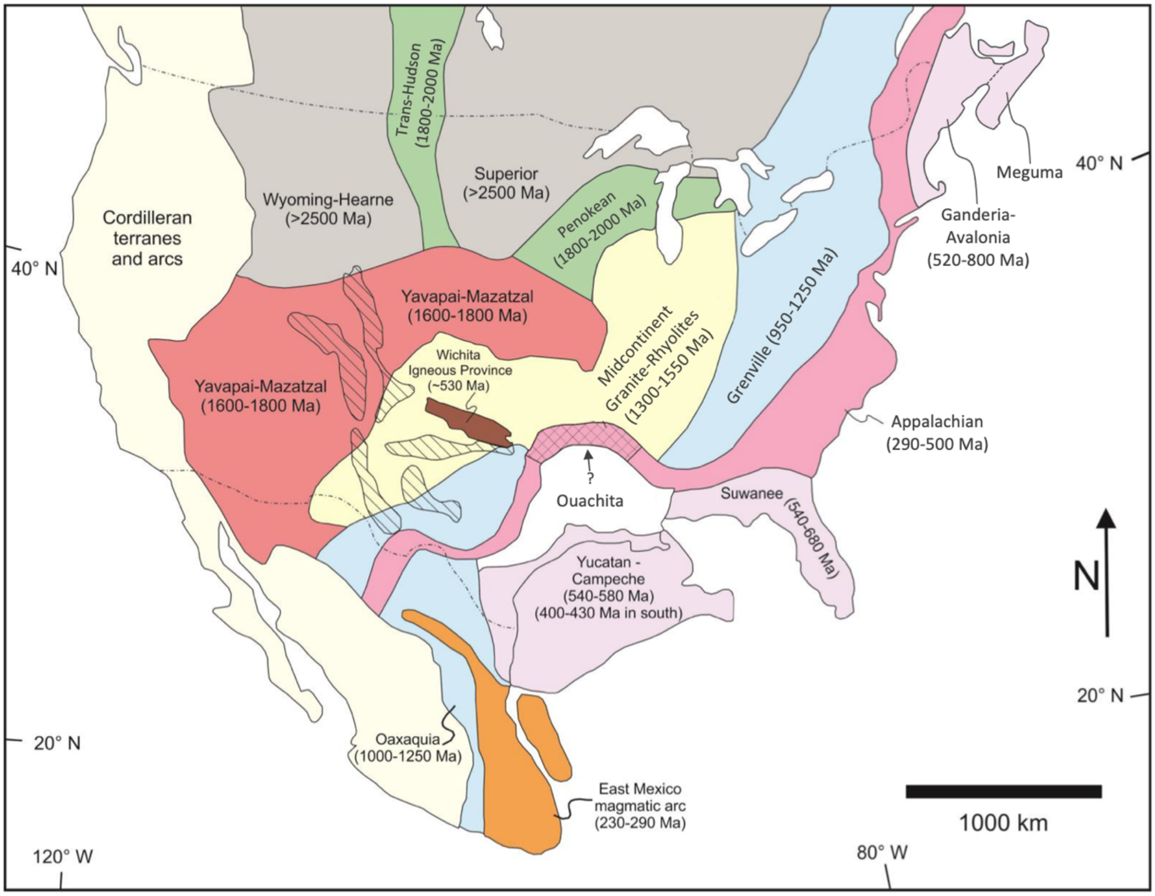

Figure 4. Basement map showing major North American geologic provinces with correlating ages. The Ancestral Rocky Mountains are denoted with the hachured areas (modified after McGuire, 2017).

A combination of the findings from recent and relevant DZ geochronology studies will be used in comparison with this study to make interpretations on provenance of the Cottage Grove Sandstone in the northern Anadarko Basin of Oklahoma. Important to this study are measurements and interpretations published on the proposed source of the Cottage Grove Sandstone, the Ouachita Mountains, as well as studies from the surrounding Midcontinent and studies related to the dispersal system that is thought to have sourced sediments to south-central North America from the north and east-northeast. Findings and interpretations are summarized from Sharrah (2006); McGuire (2017); and Allred and Blum (2021), all of which had the same goal of identifying the provenance of Paleozoic strata in the Ouachita Mountains. DZ U-Pb ages, εHf(t) measurements, and other geologic evidence such as sandstone petrography, depositional environment interpretations, and paleocurrent indicators from these studies show close correlations to data and interpretations published herein regarding the provenance of the Cottage Grove Sandstone.

Sharrah (2006) is a sedimentology, petrology/petrography, and DZ U-Pb geochronology and provenance study conducted on sandstones from the submarine fan (turbidite) deposited Middle Pennsylvanian Atoka Formation located in the Ouachita Mountains with outcrop samples taken from central Arkansas and southeast Oklahoma. Paleocurrent indicators suggest that deposition generally occurred in both north-northeast and south-southwest directions. Metamorphic rock fragments compose a significant portion of the framework grains for the south-southwest deposited Atokan rocks and indicate that a source of metamorphic rocks was exposed somewhere to the north-northeast of the Ouachita Basin, such as the Appalachian orogen. However, it is important to note that polycrystalline quartz grains were included in the metamorphic rock fragment point counts conducted in this study and therefore the abundance of low-grade metamorphic rock fragments is unclear, but the presence of these low-grade metamorphic rock fragments are mentioned. All samples display a dominant Grenville (950-1,250 Ma (Ma = mega-annum = million years ago)) age population, which is interpretated to reflect sediment influence into the Ouachita Basin from the southwest, east, and northeast. Subordinate peaks include ages that correlate to the Appalachian orogen (290-500 Ma), Yavapai-Mazatzal (1,600-1,800 Ma) terranes, and lesser craton-derived Archean (>2,500 Ma) provinces. Sharrah (2006) proposed that the origin of Neoproterozoic (500-800 Ma) aged peri-Gondwanan grains associated with the Pan-African orogeny were derived from the Yucatan-Campeche and/or Sabine terranes to the south of the Ouachita Basin and subsequent Ouachita Mountains. The comprehensive study documents the complex interplay of fluctuations in tectonics, sea level, and changes in sedimentary depositional systems, which directly correlate to provenance signals. Sediment source shifts tend to occur with the onset of tectonic plate collisions that form detritus shedding orogenic events or orogenies. The most relevant orogenic events to the study are the number of orogenies that affected the Appalachian and Ouachita Mountains. As a result of complications with data extraction, DZ U-Pb data from Sharrah (2006) are not included in the compiled normalized age probability plots compared herein. **Figure 5** shows the relative age probability density plots for the ten analyzed samples from the study. Similarities are noted between the Cottage Grove Sandstone sample analyzed herein with all U-Pb signatures presented by Sharrah (2006), however the northeast deposited Atoka samples taken from the west side of the Ouachita Mountains (in Oklahoma) show the closest correlation with the DZ U-Pb signature of the Cottage Grove Sandstone that is presented and discussed in chapter five and six, respectively. Based on DZ U-Pb geochronology it is interpreted that the samples analyzed by Sharrah (2006) from the western portion of the Ouachita Mountains (in Oklahoma) could potentially have a similar or the same provenance as the Cottage Grove Sandstone in the adjacent Anadarko Basin.

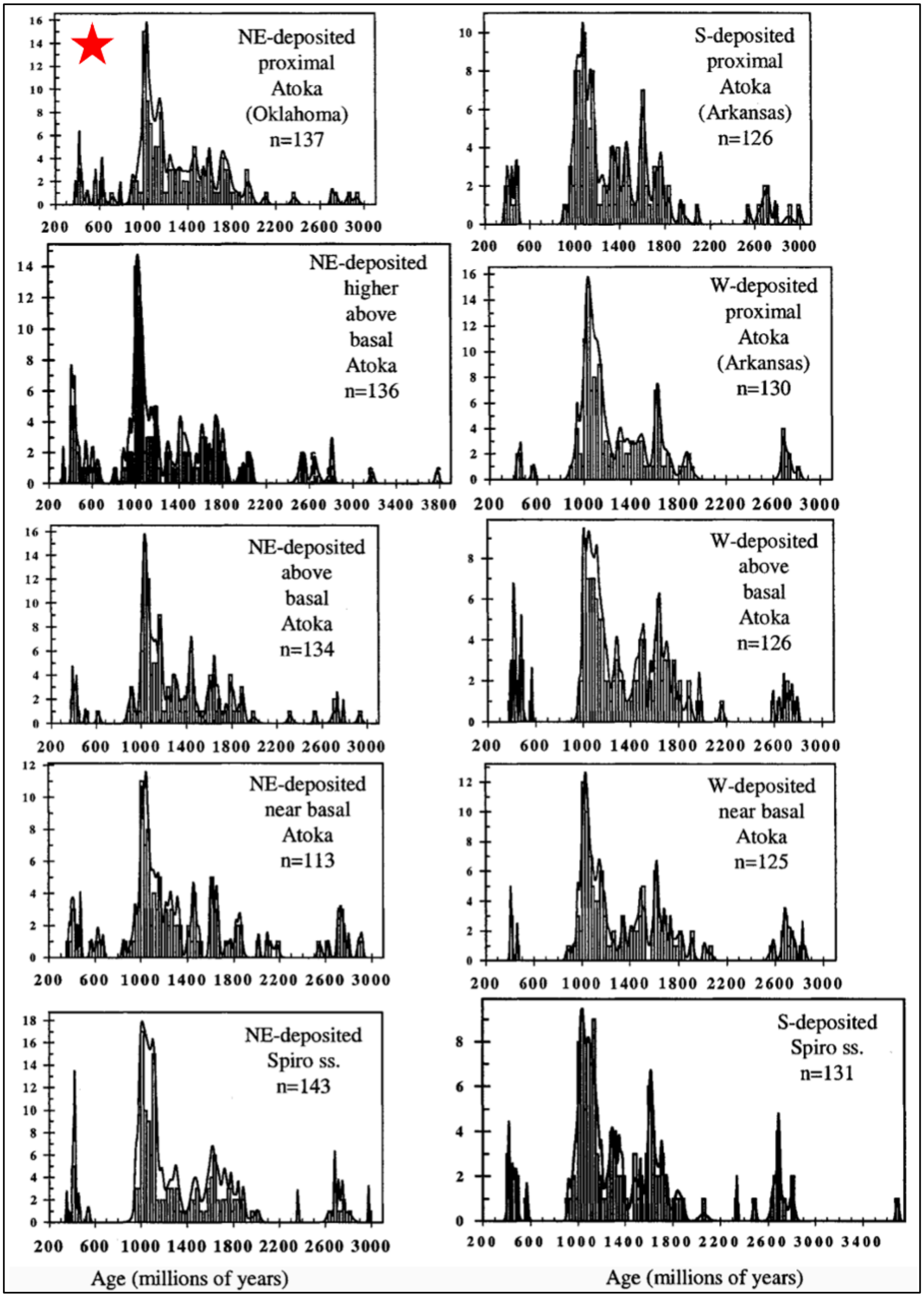

Figure 5. DZ U-Pb relative age probability density plots from the ten samples analyzed by Sharrah (2006). All samples show similarities with the Cottage Grove signature, however the sample denoted by the red star displays the closest correlation with the signature of the Cottage Grove (modified after Sharrah, 2006).

McGuire (2017) is a DZ U-Pb geochronology and provenance study conducted on Ordovician to Mississippian sandstones and sandstone intervals of shale formations in the Ouachita Mountains of western Arkansas. Seven samples were taken from outcrop and include the Ordovician Crystal Mountain Sandstone, Blakely Sandstone, Womble Shale, Polk Creek Shale, the Silurian Blaylock Sandstone, and the Mississippian Hot Springs Member and Stanley Group. These sandstones are interpreted to be turbidite deposits that were fed by deep marine fans and channels. The DZ U-Pb ages from the seven samples are generally characterized by 50% Grenville grains, 25% Midcontinent Granite-Rhyolite grains, and 25% as a combination of <950 Ma (Ma) (peri-Gondwanan, Wichita, and Appalachian terranes) and >2,500 Ma (Archean Superior province) aged grains. An important finding of the study is that based on the DZ U-Pb signatures it is interpreted that a major sediment source shift occurred after the deposition of the Silurian Blaylock Sandstone and before the deposition of the Mississippian Stanley Group. This major sediment source shift that occurred sometime after the Silurian and sometime before the Mississippian is thought to represent the Ouachita trough system evolving from a passive to an active margin. This is inferred to have caused the influx of sediments coming from peri-Gondwanan terranes and the Appalachian orogens to the northeast during the suturing of Laurentia and Gondwana. This sediment source shift can be noted by the general lack of peri-Gondwanan and Appalachian aged grains in Ordovician to Silurian samples with an increase in these ages in the Mississippian samples. A unique Midcontinent Granite-Rhyolite peak in the Womble Shale sample is thought to represent the initial uplift of the Ozark Dome. However, this sediment influence is brief as the Silurian samples suggest a return to Grenville dominated ages as well as the initial influence from the newly accreted Appalachian orogens to the northeast.

Allred and Blum (2021) incorporates both U-Pb ages and εHf(t) measurements, as well as taking into account the findings from most of the previous studies discussed above. Allred and Blum (2021) is a DZ U-Pb and Hf geochronology and provenance study conducted on Early

Pennsylvanian sandstones of the Jackfork Group and Johns Valley Shale with 12 outcrop samples taken from the Ouachita Mountains in central and southeast Arkansas. Combined U-Pb ages from all samples display prominent Grenville (37%), Appalachian (14%), Midcontinent Granite-Rhyolite (14%), and Yavapai-Mazatzal (15%) ages with minor contributions from peri-Gondwanan (3%), Penokean—Trans-Hudson (4%), and Archean Superior (6%) ages. In terms of εHf(t) measurements, four samples were used to further delineate grains with overlapping U-Pb ages, and these samples display mean εHf(t) values of -2.0 ± 1.0 (1σ error). The mean εHf(t) values for per-Gondwanan aged (500-800 Ma) grains are -2.8 ± 0.9 (1σ error) and -1.8 ± 1.0 (1σ error) for Appalachian aged (290-500 Ma) grains. Overall, the εHf(t) values correlate and show similarities with the εHf(t) values published by Thomas et al. (2017) from Late Mississippian to Early Permian samples in the Appalachian Basin, as well as εHf(t) values published by Thomas et al. (2020) from Middle Mississippian to Middle Permian samples in the Illinois and Forest City Basins. These correlations are interpreted to signify a connection of sediment dispersal systems stemming from the Appalachian margin and being deposited in the Ouachita Basin. Based on the U-Pb ages, εHf(t) values, and other geologic evidence it is interpreted that two distinct deep sea fan systems operated within the Ouachita Basin and were sourced from three distinct transcontinental feeder fluvial systems to the north and northeast (**Figure 6**). During the Early Pennsylvanian, the Ouachita Basin is thought to have served as a terminal sink for sediments derived from the Laurentian craton to the north as well as the Appalachian orogenic system to the east-northeast. These sediments are thought to have then been incorporated into the Ouachita Mountains after basin inversion and uplift occurred in the Late Pennsylvanian.

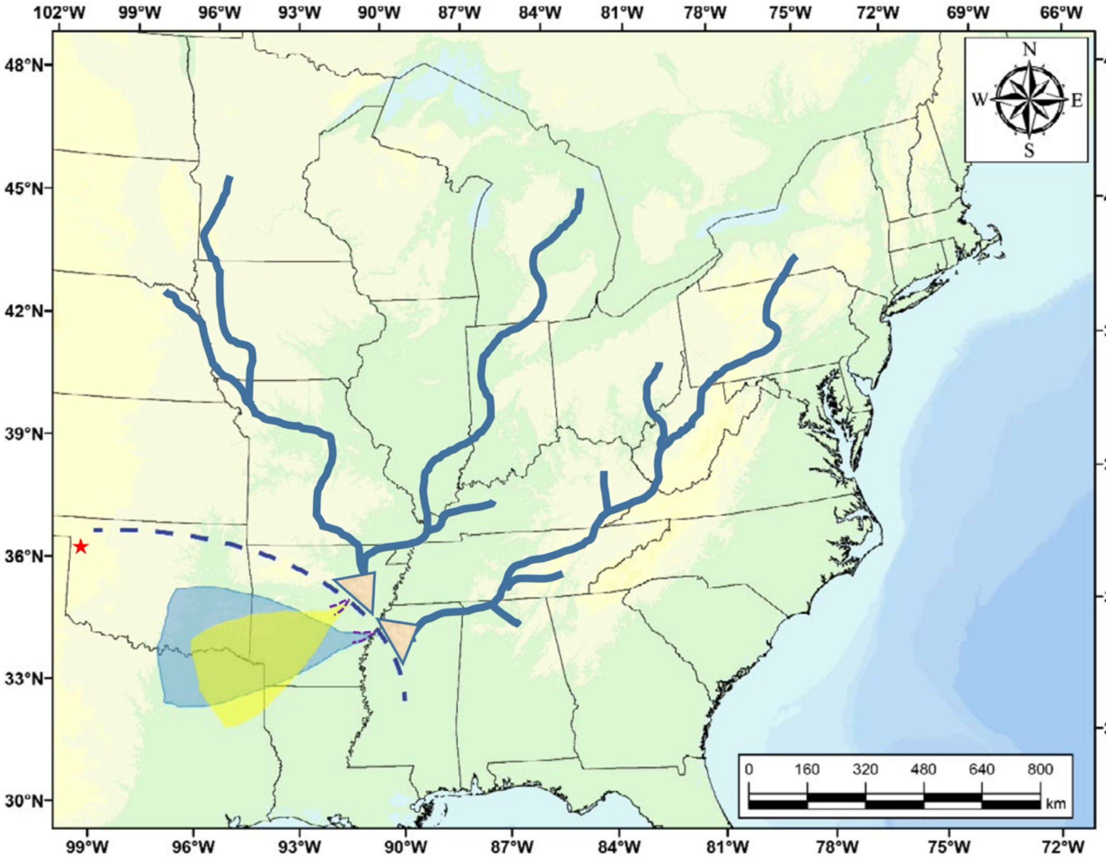

Figure 6. Schematic map showing the three fluvial dispersal systems that contributed detritus to the Ouachita Basin during the Early Pennsylvanian as interpreted by Allred and Blum (2021). The yellow and blue polygons represent the two separate deep marine fan systems, the blue dashed line represents the inferred lowstand shoreline, and the two triangles represent shelf margin deltas. The red star denotes the general location for this study (modified after Allred and Blum, 2021).

CHAPTER III

GEOLOGIC BACKGROUND

Geologic background pertinent to this study includes the relevant tectonic or orogenic events and Pennsylvanian paleogeography associated with the region (i.e., the Midcontinent of North America), as well as tectonic/orogenic events and associated geologic provinces that correlate to the age range of DZs measured and published herein. These DZ ages are discussed in greater detail in chapter five and range from the Paleozoic to the Archean. An overview of the general Anadarko Basin stratigraphy and depositional settings associated with the Cottage Grove Sandstone proximal to the study area are also discussed.

3.1 General Stratigraphy and Depositional Settings

The Late Pennsylvanian Cottage Grove Sandstone is part of the Ochelata Group and has been informally referred to as the Osage-Layton, Musselman and several other operational names for numerous decades by the oil and gas industry (Banken, 1998). Within the region of the general study area in northwest Oklahoma, the Cottage Grove interval is stratigraphically situated below the Avant Limestone and above the Hogshooter Limestone. It is important to note that while both limestone beds are intermittent throughout the basin and study area, the radioactive "hot" shale markers associated with these limestone beds are laterally extensive and serve as reliable indicators for the uppermost and lowermost formation contacts of the Cottage Grove interval. Generalized stratigraphic columns for the Anadarko Basin tend to focus on known, producing reservoirs and therefore the intermittent Avant and Hogshooter Limestones are often not included. While the Cottage Grove interval is generally denoted as lying between the upper Avant "hot" shale marker and the lower Hogshooter "hot" shale marker, the Cottage Grove Sandstone is generally referred to as the lower sandstone section that is the primary oil and gas producing, reservoir quality facies within the interval. Based on 160 formation tops from wireline logs within the study area, the Cottage Grove Sandstone is stratigraphically situated a mean 120 feet below the Avant "hot" shale marker and a mean 293 feet above the Hogshooter "hot" shale marker. The combined upper and lower Cottage Grove Sandstone unit is encased in black, marine shale/mudstone that has typical gamma-ray values that range from approximately 105 to 130 API units based on wireline logs. Gradational contacts are typically observed at the top of sandstone units (between the upper and lower Cottage Grove Sandstone), and sharp contacts are typically observed at the base of sandstone units. A generalized stratigraphic column for the Anadarko Basin showing Devonian to Lower Permian stratigraphy compared to a type log from the study area is shown in **Figure 7**.

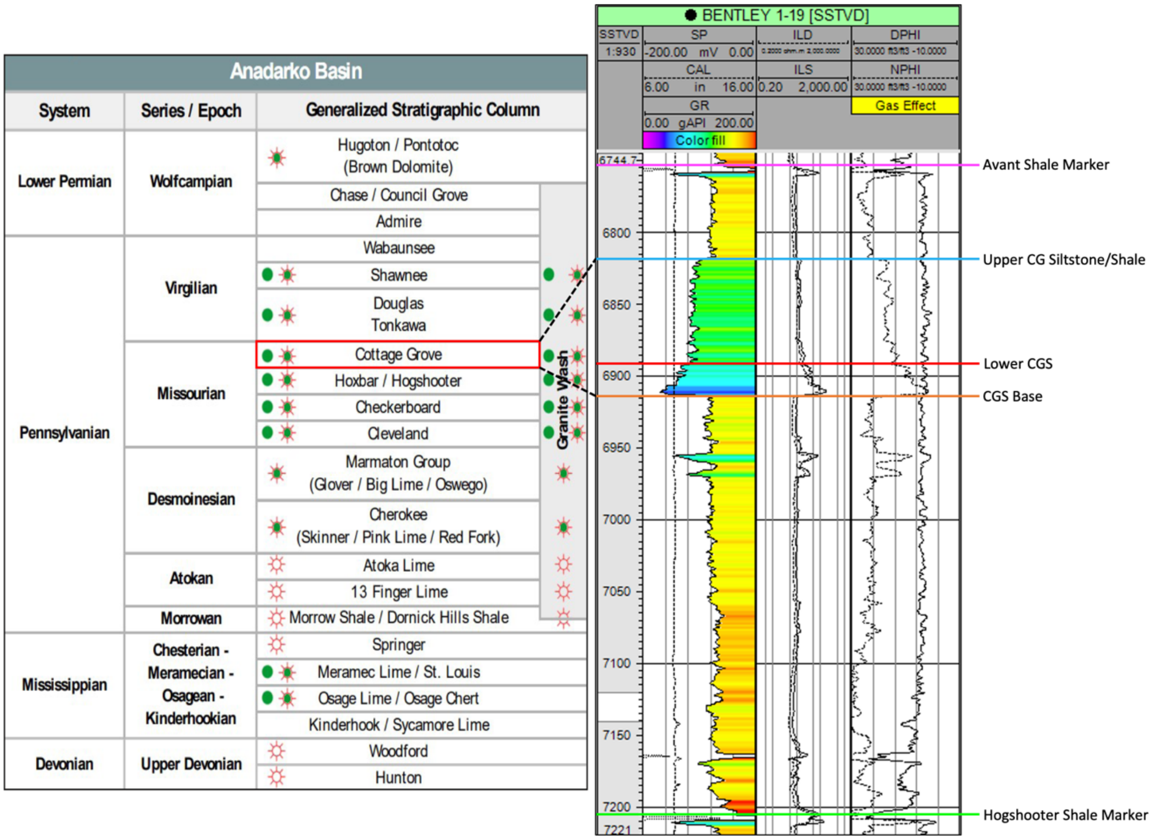

Figure 7. Generalized stratigraphic column for the Anadarko Basin showing Devonian to Lower Permian stratigraphy (left) (modified after LoCricchio, 2012) compared to the Bentley 1-19 type log from southwest Dewey County, Oklahoma within the study area (right). CG = Cottage Grove and CGS = Cottage Grove Sandstone.

Within the study area of the northern Anadarko Basin in northwest Oklahoma, the Cottage Grove Sandstone is described as a series of shoals that formed in a shallow marine, shelf environment. These shoals were thought to be heavily influenced by wave action during storm events denoted by the winnowing of crests and discontinuous geometries that have an overall trend of northeast-southwest (Fruit and Elmore, 1988). Based on core analysis and description of the Berryman C 1 well (orange circle in **Figure 1**), the upper Cottage Grove interval is generally characterized by alternating grey (siltstone) and black (shale), tidal influenced, lenticular/interbedded siltstone and shale with horizontal to low angle/inclined bedding and abundant horizontal burrows with occasional vertical burrows. Abundant bioclastic material in the upper Cottage Grove Sandstone is dominated by crinoids. The lower Cottage Grove Sandstone is the primary productive reservoir facies of the formation and is generally characterized by massive to low angle/inclined bedding of fine-grained, light grey sandstone. It is important to note that the Berryman C 1 is located just one mile southwest of the George Berryman C 1 (DZ sample location for this study – red star in **Figure 1**) and therefore core analysis conducted on the Berryman C 1 is analogues to the George Berryman C 1. A detailed core description for the Berryman C 1 is shown in **Figure 8**.

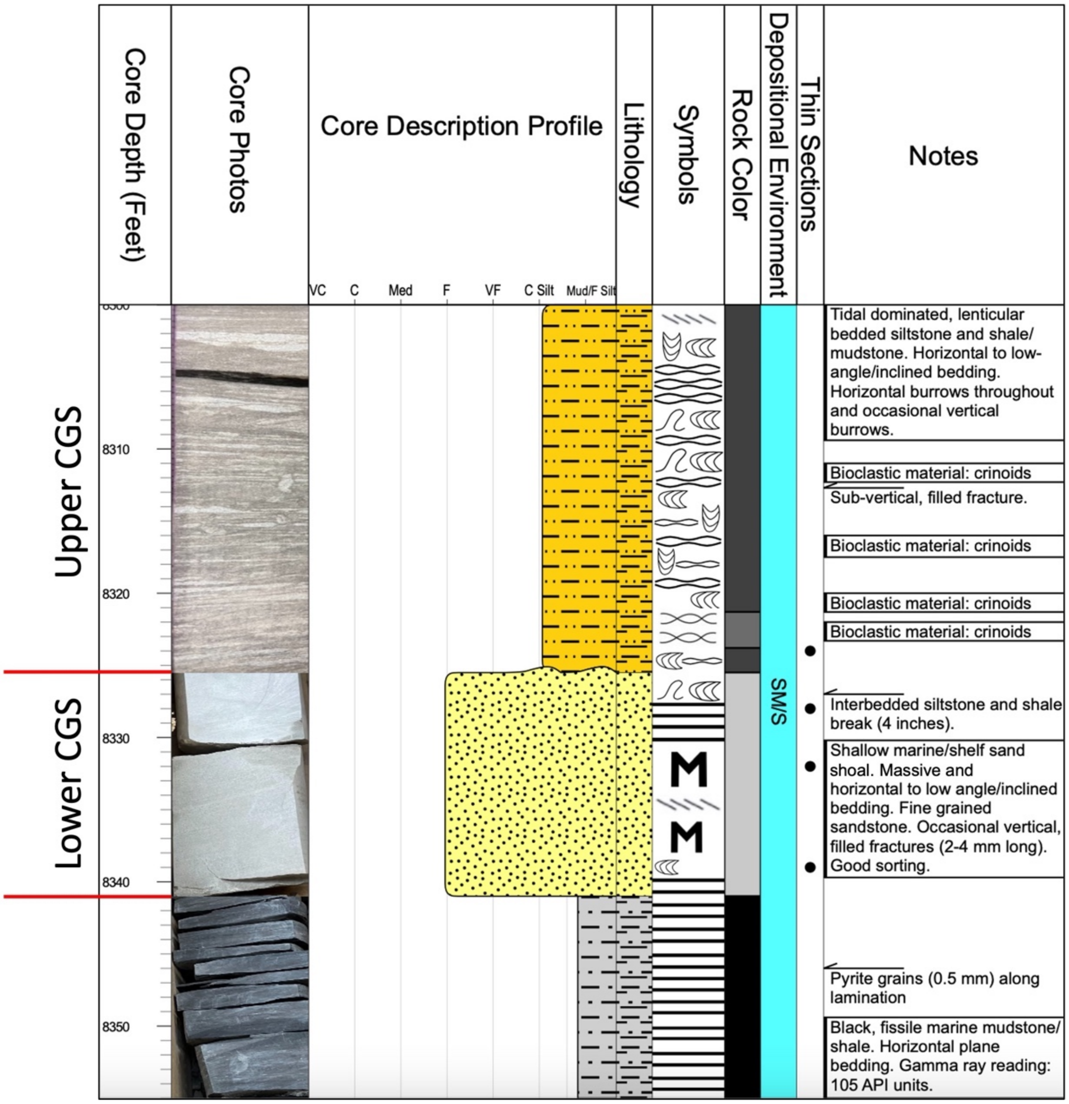

Figure 8. Detailed core description of the Berryman C 1 over the Cottage Grove interval. Depth is listed in measured depth (MD). SM/S = shallow marine/shelf and CGS = Cottage Grove Sandstone.

Two distinct wireline log signatures have been noted of the Cottage Grove Sandstone within the study area and include the primary fining-upward gamma-ray log signature (that can be seen in **Figure 7**) of the transgressive, shallow marine, shoal facies, and the secondary blocky, barrel-shaped gamma-ray log signature that is thought to represent channel fill associated with submarine channel facies (Wade, 1987). The blocky gamma-ray log signature of the submarine channel facies is sparse and ancillary to the primary shoal facies, but it is important to note the occurrence of both depositional styles and it is also important to note that the submarine channel facies tend to occur within the southern portion of the study area. To the southeast of the study area in Canadian County, central Oklahoma, Bryan Waller (1985) conducted a study on the Cottage Grove Sandstone and found that the coarsening upward gamma-ray log signature of this area is interpreted to be a high constructive, distal marine delta deposit. This single sandstone body is characterized by a general north-south oriented trend that was deposited in a regressive phase (Waller, 1985). The shallow marine shoal facies observed in this study is compared to the distal marine delta facies that is observed to the southeast in Canadian County, Oklahoma in **Figure 9**. Based on previous studies and evidence from analysis conducted herein regarding depositional settings of the Cottage Grove Sandstone, it seems reasonable that a potential source terrane and/or sediment dispersal system located to the east-southeast contributed sediments to the study area in northwest Oklahoma.

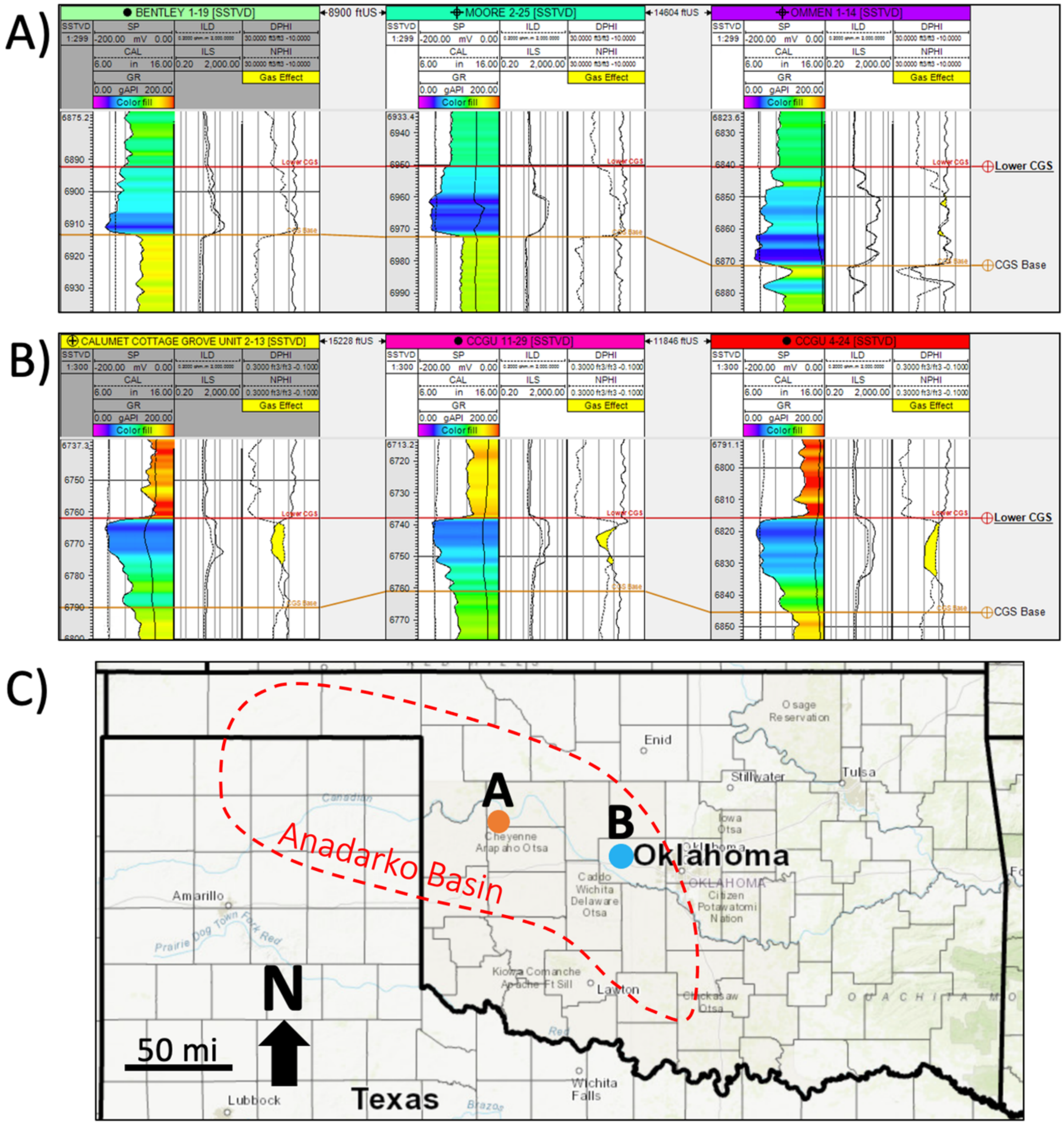

Figure 9. A) Cross section showing the fining upward gamma-ray (GR) log signature for the Cottage Grove Sandstone in this study (shallow marine/shelf shoal deposit). B) Cross section showing the coarsening upward gamma-ray (GR) log signature for the Cottage Grove Sandstone to the southeast of the study area (delta deposit). C) Map showing the locations for cross sections A (orange circle) in southwest Dewey County, Oklahoma, and B (blue circle) in Canadian County, Oklahoma. Well tops are flattened on the lower Cottage Grove Sandstone.

3.2 Paleogeography and Tectonic Setting

3.2.1 Sea Level Change and Depositional Processes

Pennsylvanian sedimentation in the Midcontinent was largely influenced by fluctuating climatic conditions during the Absaroka megasequence and are thought to be related to the waxing and waning of Gondwanan icesheets in the Southern Hemisphere (Heckel, 1994; Tunin, 2020). This caused cyclic sea level rise and fall of the expansive Upper Carboniferous (Pennsylvanian) Midcontinent Sea that repeatedly flooded and exposed basin shelf and platform areas of the Midcontinent (**Figure 10**) (Heckel, 1994; Algeo and Heckel, 2008; Tunin, 2020). During periods of low sea level, detritus shed from uplifted areas, such as the Ouachita and Appalachian Mountains, was thought to be deposited in proximal, rapidly subsiding basins, such as the Anadarko and Arkoma Basins for the Ouachita Mountains and the Appalachian and Illinois Basins for the Appalachian Mountains (Algeo and Heckel, 2008; Tunin, 2020). The geographical distribution and age for sources of DZs in the North America craton have been well studied over the past decades and generally record the episodic growth and deformation of Laurentia through time (Allred and Blum, 2021). This deformation was caused by orogenic/tectonic events that involved the southern, western, and eastern margins of Laurentia and in most cases resulted in the formation of uplifts (mountains) and accompanying adjacent basins.

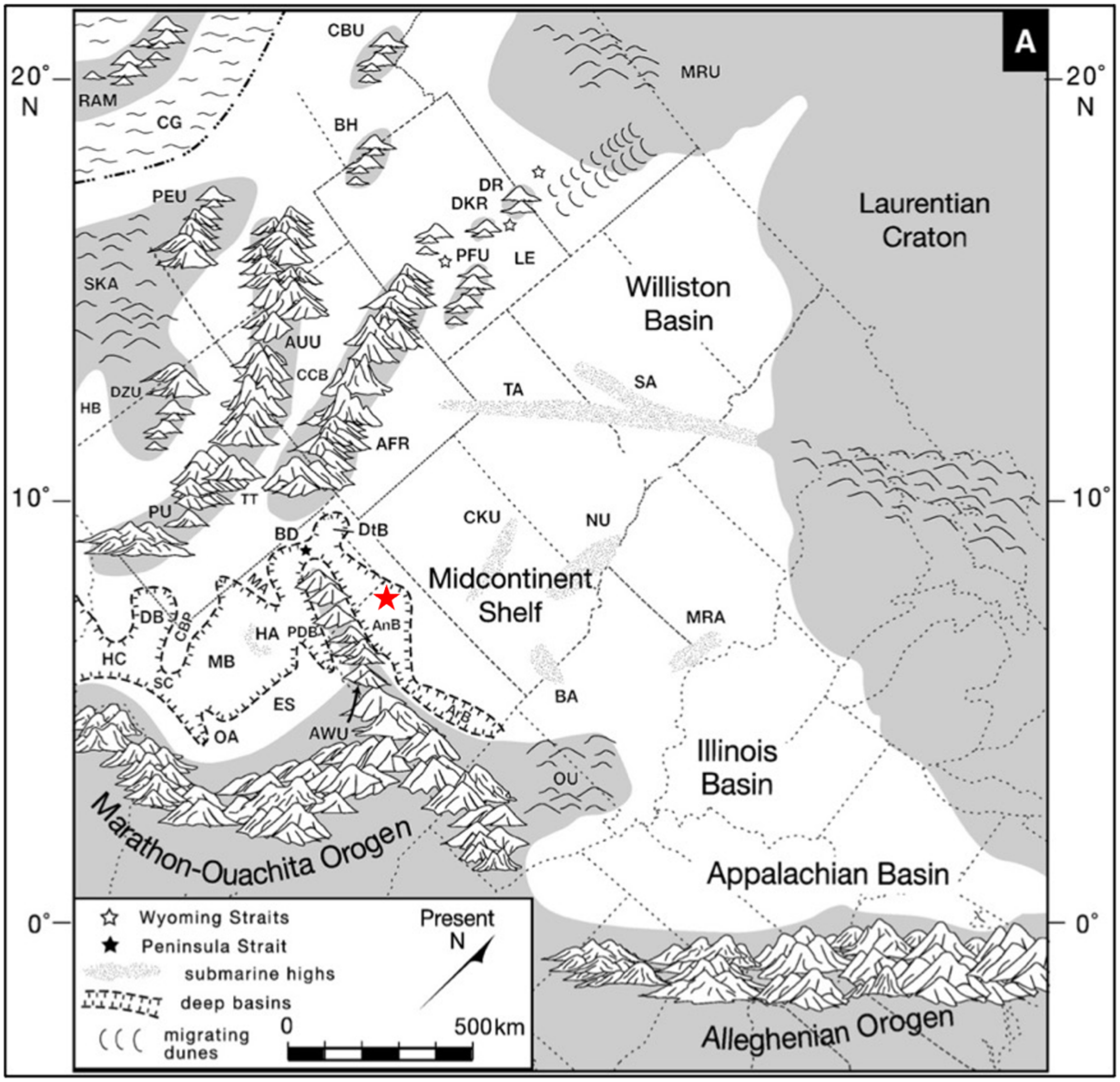

Figure 10. Paleogeographic reconstruction of the Laurentian craton during the Middle to Late Pennsylvanian showing the extent of the Late Pennsylvanian Midcontinent Sea (white areas) and uplifted areas. The red star denotes the general location for this study (modified after Algeo and Heckel, 2008).

3.2.2 Orogenic/Tectonic History

During the Proterozoic, the Laurentian craton underwent the incorporation and deformation of multiple terranes, which ultimately led to the assembly and ancillary rifting of supercontinents Columbia and Rodinia (Allred and Blum, 2021). These events produced the Paleoproterozoic Yavapai-Mazatzal orogeny (1,600-1,800 Ma), the Yavapai-Mazatzal intruding, anorogenic Midcontinent Granite-Rhyolite province (1,300-1,550 Ma), and the Mesoproterozoic Grenville orogenic cycle (950-1,250 Ma) (Allred and Blum, 2021). During the Neoproterozoic, the breakup of Rodinia first affected the western margin of the Laurentian craton, then the eastern margin and lastly the southern margin (Allred and Blum, 2021). During the Cambrian, the breakup along the southern margin of Laurentia rifted the Argentine Precordillera from the precursor to the Ouachita Basin, the Ouachita Embayment (Thomas and Astini, 1999; Allred and Blum, 2021). During the Paleozoic Late Mississippian to Early Pennsylvanian, the initial collision of Laurentia and Gondwana took place resulting in the inversion and reactivation of the Southern Oklahoma rift zone and Cambrian rift faults, respectively (Tunin, 2020). This crustal flexure is thought to have uplifted the Wichita Mountains and began the initial growth and subsidence of the adjacent Anadarko Basin (Tunin, 2020). During the Early Pennsylvanian, the collision with Gondwana is thought to have also resulted in the uplift of the Ancestral Rocky Mountains (ARMs) to the west of the Wichita Mountains in the western North American craton (Tunin, 2020).

The last series of orogenic events that took place in the Laurentian craton, and which greatly affected the terranes and tectonic systems pertinent to this study, include the Appalachian synorogenies and the Ouachita orogeny. The Paleozoic Appalachian orogen that took place on the eastern margin of Laurentia consisted of three primary orogenic events: 1) the succession of island arc terranes that were accreted to Laurentia during the Taconic orogeny (430-490 Ma); 2) the continental-margin magmatic arc that was accreted to Laurentia and which was associated with the Ganderia, Avalonia, and Carolina peri-Gondwanan superterranes known as the northern Acadian orogeny and the southern Neoacadian orogeny, both of which spanned from 345 Ma to 430 Ma; and 3) the final assembly of Pangea recorded by the north to south collision of Gondwana and Laurentia during the Alleghenian-Ouachita orogeny (290-330 Ma) (Allred and Blum, 2021). It is important to note that the Appalachian orogenic system collectively includes source terranes from the Mesoproterozoic Grenville, the Neoproterozoic peri-Gondwanan, and the Paleozoic Appalachian provinces with ages that range from 290-1,250 Ma (Allred and Blum, 2021).

As previously discussed, the deep marine Carboniferous basin known as the Ouachita Basin is thought to have represented a terminal sink for sediments derived from the north and northeast Laurentian craton (Allred and Blum, 2021). This basin, which was located near the Laurentia-Gondwana suture zone, is characterized as a remnant ocean basin that began to narrow over time with the advancement of the Ouachita magmatic arc from the south (Allred and Blum, 2021). During the Early Pennsylvanian, Appalachian orogen sourced sedimentation is thought to have increased in conjunction with the continued suturing of Pangea and subsequent inversion of the Ouachita Basin (Allred and Blum, 2021). This inversion resulted in deep marine, basin fill strata (including submarine fan and turbidite deposits) being uplifted and integrated into the northward propagating Ouachita Uplift or Ouachita fold and thrust belt during the Middle to Late Pennsylvanian (Allred and Blum, 2021). This uplift and subsequent flexural loading resulted in the formation of the adjacent Arkoma Basin to the north (Allred and Blum, 2021). As previously mentioned, during the Late Pennsylvanian the Ouachita Mountains are thought to have served as a dominant source of sediment for the Anadarko and Arkoma Basins.

CHAPTER IV

METHODOLOGY

U-Pb and Hf DZ geochronology and provenance analysis was conducted on a subsurface Cottage Grove Sandstone sample taken from the George Berryman C 1 well located in Ellis County, Oklahoma (red star in **Figure 1**). Zircon is a mineral that is often used for geochronology and provenance analysis as it is relatively common in crustal, silicate rocks and it is also highly resistant to weathering and alteration. Out of the 315 total zircon grains analyzed, 288 grains produced U-Pb concordant ages and therefore represent reliable age populations for conducting provenance analysis. 30 grains were then selected for Hf isotopic analysis out of the 288 concordant U-Pb ages in order to delineate source terranes of overlapping U-Pb ages and to disseminate source terranes with corresponding ages that span multiple locations. 26 zircons out of the 30 analyzed for Hf isotopes produced acceptable measurements and therefore are published herein. Two of the analyzed grains produced measurements with high uncertainty and were therefore omitted, and two were omitted due to grain burn through that took place during the laser ablating process. As previously alluded to, DZ geochronology has become the standard tool for provenance analysis over the last couple decades due to the technique being highly refined and understood, as well as it being able to yield precise (1-2 σ uncertainty) and rapid measurements for both U-Pb and Hf isotopic systems (Tunin, 2020). This reliable and accurate methodology has allowed for published, accessible data that provides ease of comparison and a better overall understanding of sedimentary provenance throughout the North America craton. This study follows the same general workflow (**Figure 11**) as Tunin (2020) and combines U-Pb and Hf DZ geochronology and provenance analysis with sandstone petrology/petrography to draw interpretations on distal and proximal source terranes as well as the associated sediment dispersal pathways/systems and depositional environments.

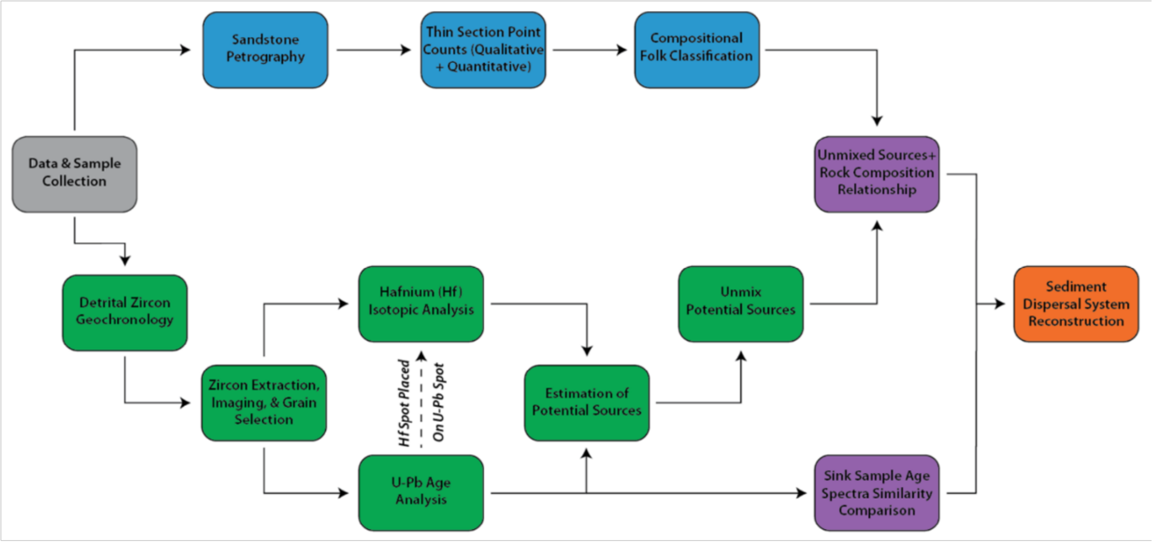

Figure 11. Flowchart from Tunin (2020) showing the general workflow followed for this study (chart reads from left to right).

4.1 Sample Collection and Preparation

One subsurface Cottage Grove Sandstone sample in the form of core chips was acquired from the George Berryman C 1 well located in the northern Anadarko Basin, Ellis County, Oklahoma (red star in **Figure 1**). The Cottage Grove Sandstone sample was taken from a very fine to fine grained sandstone at an approximate measured depth (MD) of 8,250 feet. The core chips were then disaggregated into sand sized particles using a rock hammer and subsequent SPEX ShatterBox 8530 at Oklahoma State University. After the sample was crushed, the resulting 2.6 kg of sand sized material was sent to the University of Arizona Laserchron Center (ALC) in Tucson Arizona for zircon extraction, mounting, and subsequent DZ geochronology analysis. Once at the ALC, the sample underwent zircon extraction/separation and mounting following the methods outlined by Gehrels et al. (2008) and Gehrels and Pecha (2014). Zircon extraction from the host material was done using a Wilfley table, heavy liquids, and a Frantz magnetic separator. After the zircons were extracted from the host material, a representative split of the final number of retained zircons was then mounted in a one-inch diameter epoxy plug along with both U-Pb zircon standards (Sri Lanka, FC, and R33) and Hf zircon standards (Mud Tank, Temora, 91500, R33, FC, Sri Lanka, and Plesovice). The mounts were sanded down to an approximate depth of 20 um and polished to expose the center of the zircon grains. The mounts were then imaged using both cathodoluminescence (CL) and back-scattered electron (BSE) microscopy. The CL and BSE images (**Figure 12**) were used for the remote selection of 315 zircon grains using the Photon Machines Chromium Offline Targeting 2.4 software (provided by the ALC) at Oklahoma State University. Utilization of CL and BSE images for identifying analysis locations/spots is critical as these images help to delineate non-zircon grains, fractured and/or cracked zircons, and non-homogenous and/or multiply zoned zircons, all of which should be avoided when selecting grains and spots on grains to target for analysis.

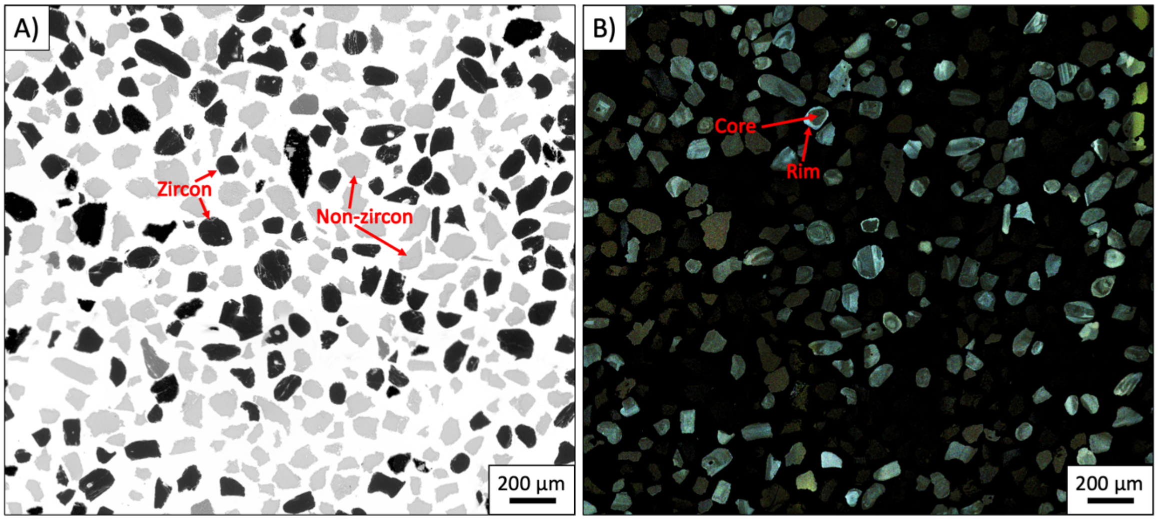

Figure 12. A) Back scatter electron (BSE) image showing how to identify zircon (dark) versus non-zircon (light) grains. B) Cathodoluminescence (CL) image showing how to identify zircon cores, which are a better representation of true zircon age, versus zircon rims, which tend to record younger, non-representative ages.

4.2 Sandstone Petrography

Sandstone petrography was conducted at Oklahoma State University on thin sections taken from the Cottage Grove Sandstone by using the traditional methods of thin sections cut from core and a petrographic microscope. Nine total thin sections from four different wells located within the general study area (colored circles in **Figure 1**) were analyzed to evaluate detrital constituents, Folk classification, provenance type, and diagenetic alteration that occurred after deposition. The diagenetic study of the Cottage Grove Sandstone is focused on thin sections taken from three of the four total wells: Cole 28-A, Gillispie 1-3, and Gillispie 3-2. A paragenetic sequence of diagenetic events was constructed based on petrographic analysis and interpretations and is presented in chapter five. As previously mentioned, qualitative descriptions of detrital components and quantitative point counting using the Gazzi-Dickinson method are two critical forms of petrographic analyses that provide a better understand of overall rock composition and fabric, which is directly correlated to provenance and reservoir quality. Thin sections were not cut from the zircon sample well (George Berryman C 1), however four thin sections from the Berryman C 1 well were analyzed and this well is located one mile southwest of the George Berryman C 1, and therefore thin sections from the Berryman C 1 serve as reliable analogues for petrology seen within the DZ sample. Petrographic point counts are displayed using Folk QFL (Folk, 1968) and provenance type QFL (Dickinson et al., 1983) ternary diagrams.

4.3 Detrital Zircon U-Pb Age Analysis

U-Pb isotopic age analysis of the Cottage Grove Sandstone sample was conducted at the ALC by laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) using the methods outlined by Gehrels et al. (2008); Gehrels (2012); and Gehrels and Pecha (2014). A Photon Machines Analyte G2 excimer laser was used to ablate a diameter of 20 um into the zircon grain to an approximate depth of 12 um. The ablated material is subsequently fed into a Thermo Element 2 HR ICPMS via an inert gas (typically helium) where it is then analyzed for U-Pb concentrations. For large number detrital zircon samples, such as the Cottage Grove sample of approximately 800 retained zircon grains, selection of 315 analysis locations was suggested. These 315 analysis locations (grains) were selected at random and evenly distributed throughout the entire sample. Grains were avoided if they were too small (<20 um), contained cracks/fractures or inclusions, or if they displayed non-homogenous or complex zonation. It is important to note that zircons start to crystalize from the center and therefore analysis locations are typically placed in the center of the grain (core) rather than on the margin (rim) to accurately measure the most mature portion and best representative age of the zircon.

Three measured U-Pb ratios including 206Pb/238U, 206Pb/207Pb, and 207Pb/235U were used for final age calculations using the AgeCalcML software from the ALC (http://www.laserchron.com) with an uncertainty filter of >10%. Other data filters applied include >20% discordance and >5% reverse discordance. The U-Pb radiometric dating method involves two paired decay systems including two isotopes from the same radioactive parent (238U and 235U) which decay to the two isotopes of the same radiogenic daughter (206Pb and 207Pb, respectively) (Vermeesch, 2020). This method provides two chronometers that can be used to verify if the isotopic system is free of primary or secondary disturbances (Vermeesch, 2020). Therefore, if the two chronometers are in agreeance the ages are said to be "concordant" and if the two chronometers disagree the ages are said to be "discordant" (Vermeesch, 2020). Reverse discordance is far less common and is defined as the occurrence when U-Pb ages are older than the 206Pb and 207Pb ages (Wiedenbeck, 1995). All data and correlating ages that did not meet the filtering requirements were excluded from the final dataset. Of the 315 total zircons analyzed, 288 grains produced concordant U-Pb ages and therefore are included in the results and interpretations presented herein. When utilizing U-Pb DZ geochronology, it is assumed that the concordant ages displayed by the analyzed grains are an accurate reflection of the entire sample and are representative of the age proportions correlating to the specific source terranes (Allred and Blum, 2021). This includes more distal sources that are not typically identified with traditional provenance methods (i.e., petrology/petrography) (Allred and Blum, 2021). U-Pb radiometric dating is possible because at the time of zircon crystallization, U-Pb concentrations are preserved in a generally closed geochemical system (Gehrels et al., 2008).

A relative probability density plot was constructed using the Isoplot 4 Microsoft Excel plugin from Ludwig (2012) to better visualize the age distribution and U-Pb signature of the Cottage Grove sample. Normalized age probability plots were constructed using a Microsoft Excel macro supplied by the ALC (http://www.laserchron.com) and were used to compare the Cottage Grove U-Pb age signature to relevant signatures from previous studies.

4.4 Detrital Zircon Hf Isotopic Analysis

Hf isotopic analysis of 30 zircon grains was conducted at the ALC using methods outlined by Gehrels and Pecha (2014). This analysis was performed utilizing a Photon Machines Analyte G2 excimer laser coupled to a Nu HR ICPMS. Hf analyses were conducted on top of the U-Pb pit in order to link the U-Pb and Hf measurements. The 30 Hf analysis locations were selected from the set of the 288 concordant U-Pb age spots and were placed on zircons with U-Pb ages that represent the main age groups or peaks, as well as zircons that displayed U-Pb ages that are common to more than one potential source terrane. The primary goal of the Hf isotopic analysis is to segregate grains from source terranes with overlapping ages and in this case further delineate zircons with U-Pb ages 290-800 Ma. A known solution of JMC475 and seven Hf zircon standards including Mud Tank, 91500, Temora, R33, FC, Plesovice, and Sri Lanka were analyzed during the same session as the unknowns to optimize and parameterize the Hf isotope data acquisition.

Of the 30 Hf analyses conducted, four zircons produced erroneous measurements (two due to high uncertainty and two due to the laser burning through the zircon grain) resulting in 26 total acceptable Hf isotope measurements, which are included in the final dataset and interpretations published herein. The Hf isotope results are reported as mean values of εHf(t) (epsilon units evaluated at the time of zircon crystallization or U-Pb age) with uncertainties at 2σ standard error. Hf isotopic data is commonly expressed in terms of epsilon units as it compares the Hf isotopic composition of the sample with the known Hf isotopic concentration of the bulk silicate earth or chondritic uniform reservoir (CHUR) (Allred and Blum, 2021).

Hf isotopic analysis of zircons is possible because when zircons crystallize (U-Pb age), the grain takes up relatively high concentrations of Hf (~15,000 ppm) and low concentrations of Lutetium (Lu) (~50 ppm). Therefore, the 176Hf/177Hf ratio provides information concerning the composition of the magma that produced the zircon (Tunin, 2020). This becomes useful when delineating zircons of overlapping U-Pb ages (i.e., crystallization ages) because the 176Hf/177Hf ratio records the magmatic differentiation and can be used for fingerprinting each zircon to a specific source terrane (Tunin, 2020). For this study, Hf measurements were primarily used to further delineate DZ U-Pb ages that correlate to the Paleozoic aged Appalachian synorogenies (290-500 Ma) and the Neoproterozoic aged peri-Gondwanan terranes (500-800 Ma) that were sutured to Laurentia. These source provinces comprise multiple locations, have similar U-Pb ages, and can be pinpointed by comparing Hf signatures published herein to previously published Hf signatures. Hf measurements were also placed on the primary U-Pb age peaks or groups to either strengthen or weaken provenance interpretations.

Hf results from the Cottage Grove sample analyzed herein and results from previous, relevant studies are presented using two-dimensional (2D) bivariate kernel density estimates (KDEs) with the Hafnium Plotter 1.8 MATLAB algorithm using methods described by Sundell et al. (2019). KDEs help visualize Hf data by highlighting data density displayed by a sample in a Cartesian coordinate system/space. For this study, kernel bandwidths for the Cottage Grove sample and for the samples from the previous, compared studies were set at 50 Ma for the x-axis and 2ε for the y-axis and contours are calculated at 95% (2σ) peak density. 95% (2σ) peak density contours from previous studies are plotted and compared to the Cottage Grove sample to further delineate and interpret provenance.

CHAPTER V

RESULTS

5.1 Sandstone Petrography

Sandstone petrography using the Gazzi-Dickinson method of point counting was conducted on nine thin sections from four wells within the study area (colored circles in **Figure 1**) with the primary goal of identifying and describing the allogenic (detrital) and authigenic constituents, classifying the sandstone using Folk classification and provenance type, and to construct a paragenetic sequence of diagenetic events. Two thin sections were analyzed from the Gillispie 1-3: S60.5 at a measured depth of 8,560.5 feet and S75.7 at a measured depth of 8,575.7 feet. Two thin sections were analyzed from the Gillispie 3-2: G52.5 at a measured depth of 8,552.5 feet and G59.3 at a measured depth of 8,559.3 feet. One thin section was analyzed from the Cole 28-A: R47.9 at a measured depth of 7,447.9 feet. Four thin sections were analyzed from the Berryman C 1 located one mile southwest of the zircon sampling location (George Berryman C 1) and include thin sections from measured depths of 8,324 feet, 8,328 feet, 8,332 feet, and 8,339 feet. The diagenetic study of the Cottage Grove Sandstone was conducted using all listed thin sections except for the thin sections from the Berryman C 1 due to the diagenetic study being conducted prior to thin sectioning of Berryman C 1 core.

Common constituents noted in the Cottage Grove Sandstone include monocrystalline quartz, feldspar (plagioclase and orthoclase), muscovite, chert, dolomite, schistose metamorphic rock fragments, carbonate rock fragments, plutonic rock fragments (granophyre), opaque heavy minerals (such as zircon and apatite), calcite cement, and dolomite cement (in no order). The Cottage Grove Sandstone is well sorted and is composed of very fine to fine, subangular to rounded, well sorted, and mature quartz grains. Seven out of the nine thin section point counts fall within the sublitharenite classification (Folk, 1968) with one of the analyzed thin sections from the Berryman C 1 at a measured depth of 8,324 feet being classified as subarkose and another from the Berryman C 1 at a measured depth of 8,332 feet being classified as feldspathic litharenite based on Folk (1968) (**Figure 13**). In terms of the Dickinson et al. (1983) model relating provenance to tectonic provinces, eight out of the nine thin sections fall within the recycled orogen classification, with the only exception being the Berryman C 1 thin section at a measured depth of 8,324 feet falling within the craton interior classification (**Figure 14**). Based on previous petrographic studies conducted on the Cottage Grove by Waller (1985) and Wade (1987), Folk classification of the Cottage Grove Sandstone ranges from sublitharenite to litharenite within and around the study area with the most common, highest porosity, and best reservoir being sublitharenite.

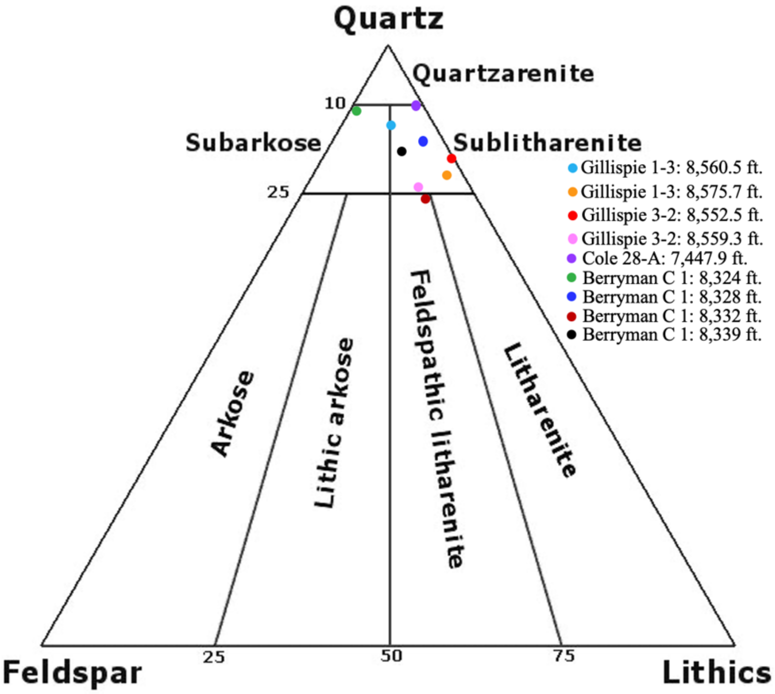

Figure 13. Compiled point counts from the nine thin sections analyzed in this study plotted on a QFL ternary diagram using Folk (1968) classification.

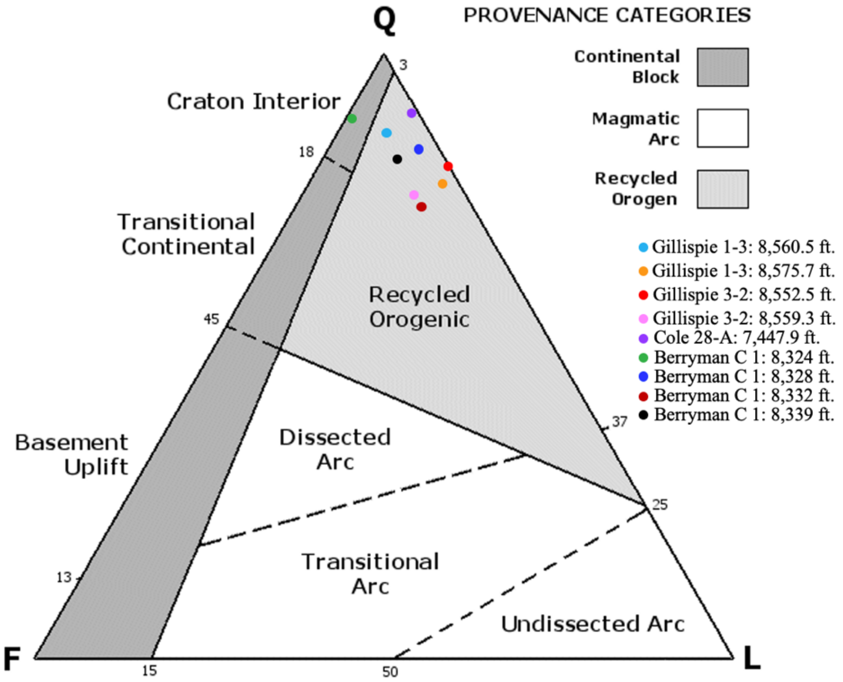

Figure 14. Compiled point counts from the nine thin sections analyzed in this study plotted on a QFL ternary diagram using Dickinson et al. (1983) classification of provenance type.

5.2 Diagenetic Study

5.2.1 Gillispie 1-3

Sample S60.5 at a measured depth of 8,560.5 feet displays a distinct diagenetic boundary between calcite cement and ferroan dolomite cement. Scattered, negligible amounts of porosity are noted and likely formed due to the dissolution of metastable or labile constituents forming moldic pores and what looks to be primary, intergranular porosity, but is thought to be the result of partially dissolved carbonate cements. This interval displays poor reservoir quality with core measured porosity of 8.5% and permeability of 0.1 mD. Normalized percentages of quartz, feldspar, and rock fragments equal 92%, 4%, and 4%, respectively. The average quartz grain size noted in the sample is 0.15 mm (fine sand).

Sample S75.7 at a measured depth of 8,575.7 feet is characterized by one side of the thin section being distinctly calcite cemented and the other side of the thin section being a mix of spotty calcite cement and ferroan dolomite cement with ferroan dolomite being the primary cement (**Figure 15**). Spatial relationships between grains and cement support the inference that ferroan dolomite cement was replaced by late-stage calcite cement. Due to pervasive cementation, no porosity was observed throughout the entirety of the thin section. This interval displays poor reservoir quality with core measured porosity of 3.4% and permeability of 0.1 mD. Normalized percentages of quartz, feldspar, and rock fragments equal 78%, 3%, and 19%, respectively. The average quartz grain size noted in the sample is 0.20 mm (fine sand).

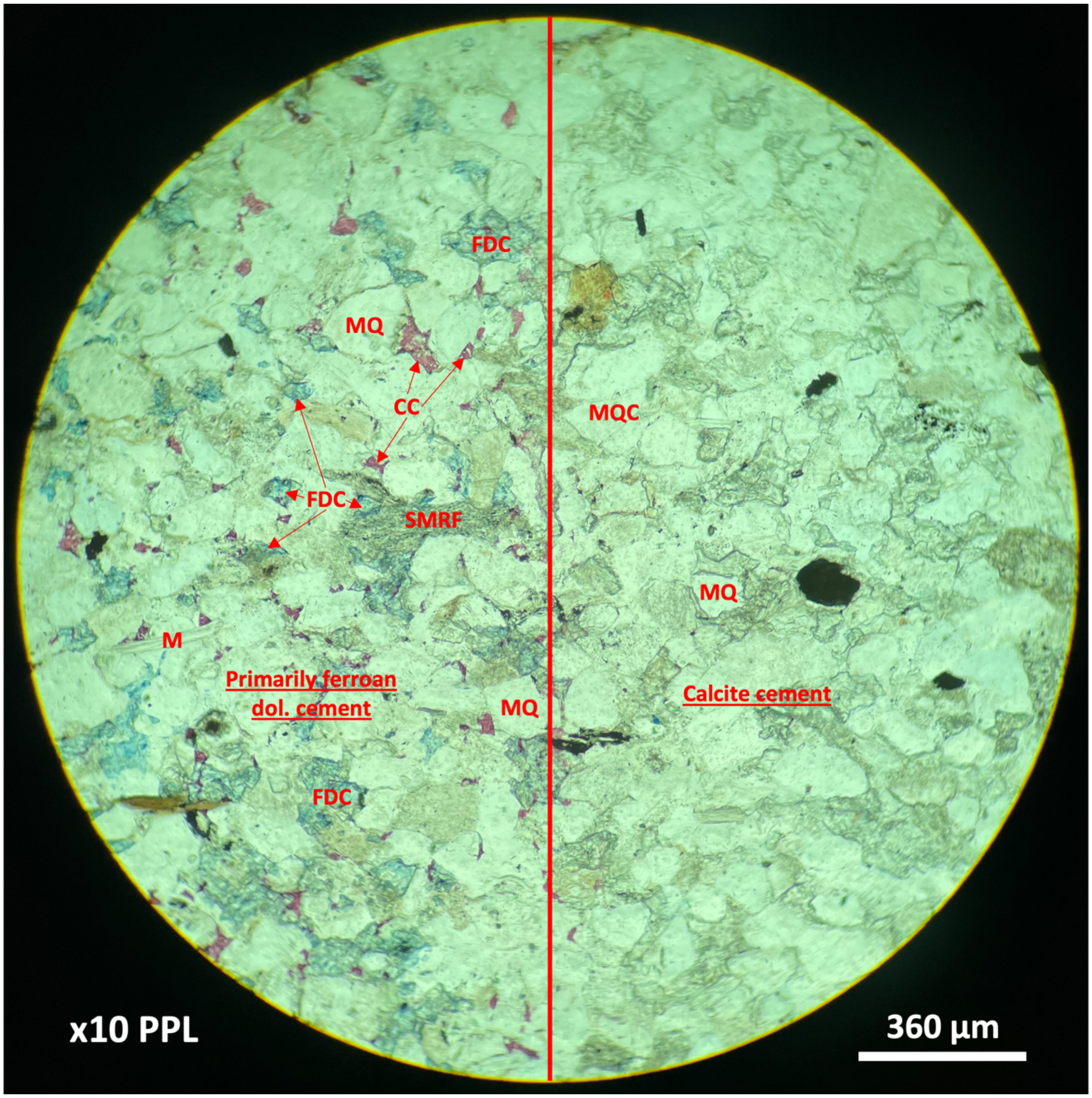

Figure 15. Thin section S75.7 from the Gillispie 1-3 showing a diagenetic boundary (red vertical line) between ferroan dolomite cement (stained blue) and calcite cement (stained red). The left side of the thin section is primarily ferroan dolomite cemented with spotty calcite cement and the right side is completely calcite cemented. It is important to note that the left side is stained, and the right side is not. FDC = ferroan dolomite cement, CC = calcite cement, MQ = monocrystalline quartz, MQC = monocrystalline quartz cluster, and SMRF = schistose metamorphic rock fragment, M = muscovite.

5.2.2 Gillispie 3-2

Sample G52.5 at a measured depth of 8,552.5 feet is characterized by a distinct diagenetic boundary that exists between calcite cement and ferroan dolomite cement. One side of the thin section is completely calcite cemented and the other side is completely ferroan dolomite cemented. Sparse fossil fragments and carbonate rock fragments occur throughout the thin section. Very little to no porosity is evident as a result of the calcite and ferroan dolomite cements. This interval displays poor reservoir quality with core measured porosity of 2.3% and permeability of 3 mD. Normalized percentages of quartz, feldspar, and rock fragments equal 81%, 0%, and 19%, respectively. The average quartz grain size noted in the sample is 0.17 mm (fine sand).

Sample G59.3 at a measured depth of 8,559.3 feet is characterized by being almost entirely calcite cemented except for occasional and quantitatively negligible ferroan dolomite cement (**Figure 16**). Little to no visible porosity is detected during point counting and this lack of porosity is used as evidence to support the inference that this sample is representative of poor reservoir quality for this interval. Sparse grain-coating illite is evident. Occasional glauconite grains and fossil fragments are observed and used to support the premise that deposition occurred in a marine environment. This interval displays poor reservoir quality with core measured porosity of 3.3% and permeability of 0.1 mD. Normalized percentages of quartz, feldspar, and rock fragments equal 76%, 8%, and 16%, respectively. The average quartz grain size noted in the sample is 0.15 mm (fine sand).

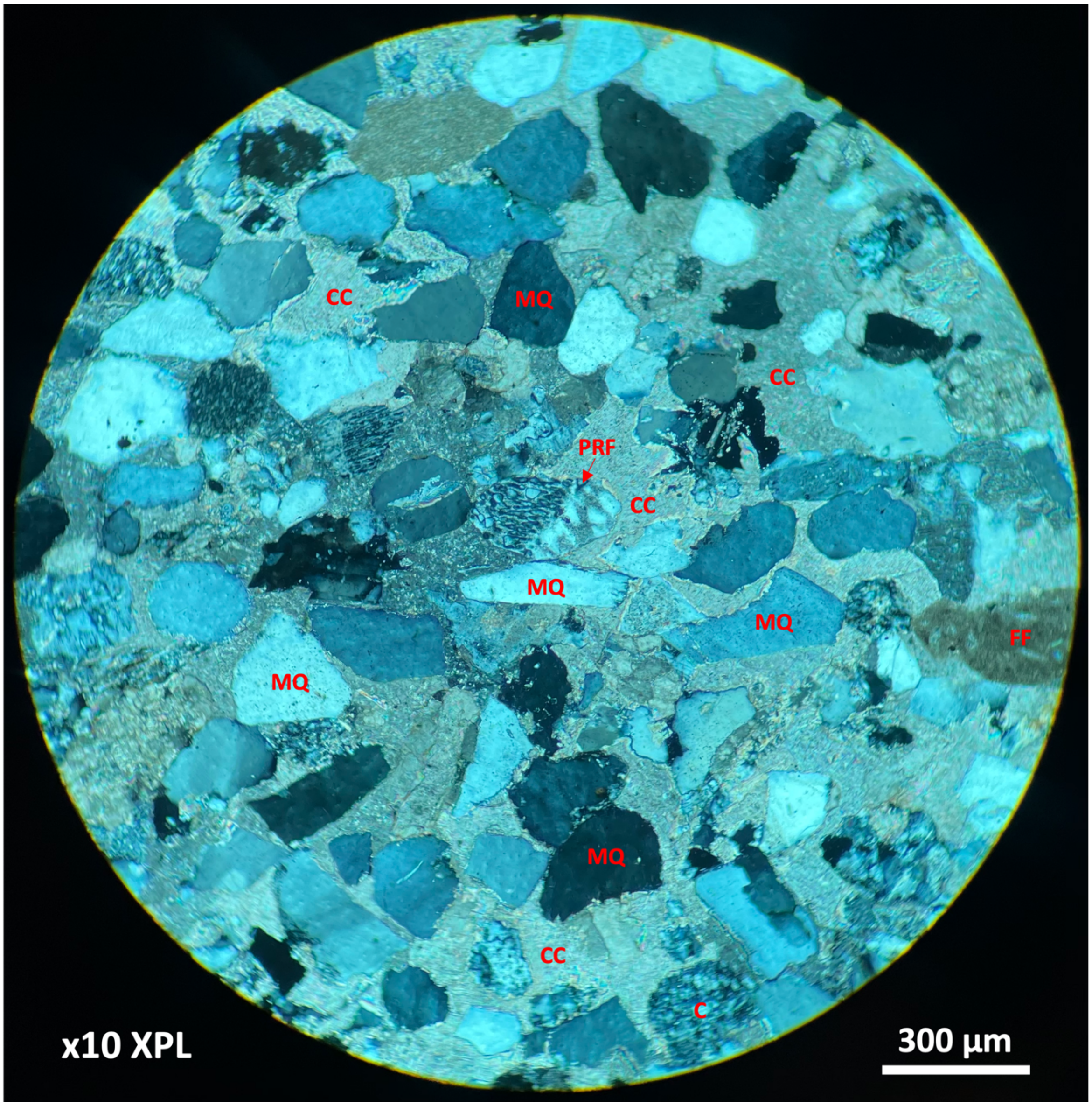

Figure 16. Thin section G59.3 from the Gillispie 3-2 showing complete calcite cementation with little to no visible porosity resulting in poor reservoir quality. Corroded quartz grains reflect dissolution during calcite precipitation. CC = calcite cement, MQ = monocrystalline quartz, C = chert, and PRF = plutonic rock fragment (granophyre), FF = fossil fragment.

5.2.3 Cole 28-A

Thin section R47.9 at a measured depth of 7,447.9 feet is characterized by the general lack of pore-filling cements, however small amounts of spotty ferroan dolomite cement were observed (**Figure 17**). With the decrease in cements, there is corresponding increase in visible, blue-stained epoxy filled porosity and inferred permeability. Most of the porosity is oversized suggesting possible late-stage dissolution of carbonate cements and gives the rock fabric a “floating grains” appearance. This interval displays good reservoir quality with core measured porosity of 18% and permeability of 80 mD. Normalized percentages of quartz, feldspar, and rock fragments equal 95%, 1%, and 4%, respectively. The average quartz grain size noted in the sample is 0.14 mm (fine sand).

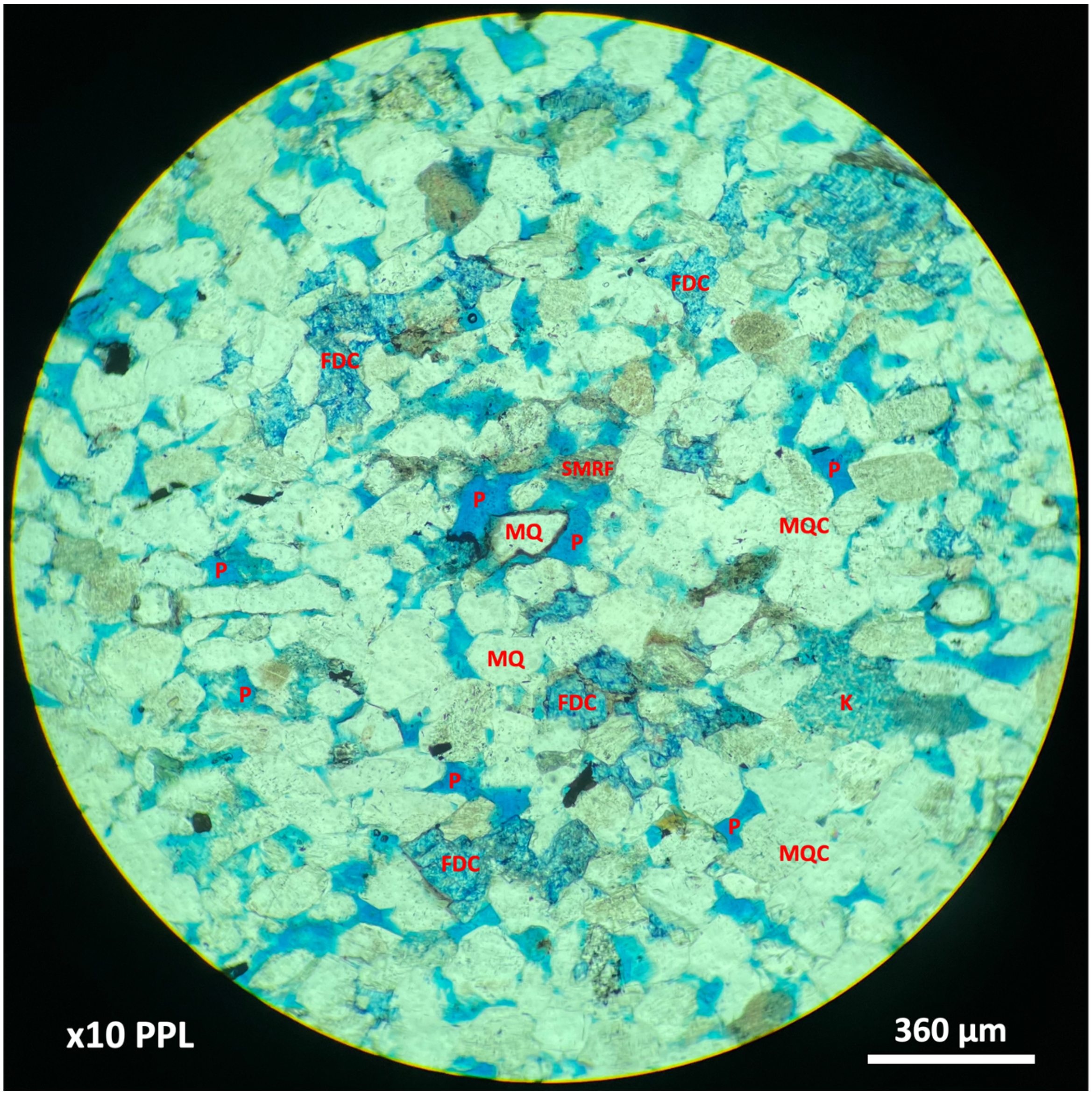

Figure 17. Thin section R47.9 from the Cole 28-A showing a general lack of cementation resulting in higher porosity and good reservoir quality as compared to the Gillispie 1-3 and 3-2. FDC = ferroan dolomite cement, P = porosity, MQ = monocrystalline quartz, and MQC = monocrystalline quartz cluster, K = pore-filling kaolinite, SMRF = schistose metamorphic rock fragment.

5.2.4 Paragenetic Sequence of Diagenetic Events

Based on petrographic evidence and subsequent interpretations, a paragenetic sequence of diagenetic events was constructed for the Cottage Grove Sandstone (**Figure 18**) within the study area using thin sections from the Gillispie 1-3, Gillispie 3-2, and Cole 28-A. The following sequence of events denotes the series in which diagenetic alteration took place after final deposition and mechanical compaction from burial occurred:

1. Early phase precipitation of calcite cement likely sourced from detrital carbonate material, such as bioclasts including crinoid, echinoderm, bryozoan, and other unidentified fossil fragments. These bioclasts are more prevalent near the upper and lower contacts of sandstone units.
2. Early phase grain coating by illite that is possibly detrital in origin.
3. Early phase dissolution related to biodegradation and early carbonic acid formation.
4. Precipitation of syntaxial quartz overgrowths.
5. Precipitation of syntaxial feldspar overgrowths.
6. Precipitation of illite.
7. Precipitation of kaolinite.
8. Precipitation of chlorite.
9. Precipitation of ferroan dolomite cement that likely formed from the effects of deep burial and influence of regionally migrating pore waters high in Mg^{++}/Ca^{++} ratios.
10. Late phase precipitation of calcite cement likely replacing ferroan dolomite cement.
11. Late phase dissolution of carbonate cements, feldspars, rock fragments, and detrital matrix forming porosity and giving the rock a “floating grains” appearance.
12. Migration of hydrocarbons into porosity.

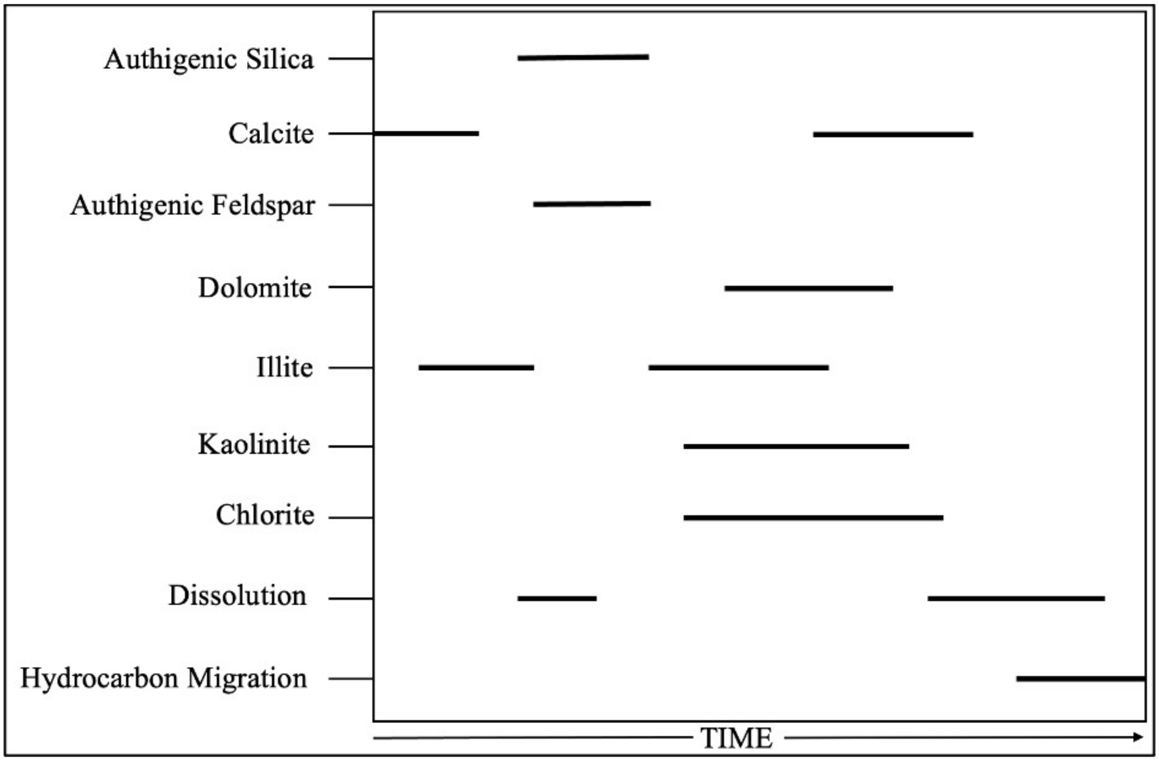

Figure 18. Paragenetic sequence of diagenetic events for the Cottage Grove Sandstone within the general study area of the northern Anadarko Basin, northwest Oklahoma.

5.2.5 Diagenetic Study Summary

Based on the five analyzed thin sections from three wells within the northern portion of the Anadarko Basin, porosity, permeability, and productive reservoir facies of the Cottage Grove Sandstone is largely controlled by detrital framework grain composition, abundance of bioclast/fossil grains, and diagenetic alteration. Specifically, the absence or presence of carbonate cements and absence or presence of labile grains that are essential to porosity occlusion or enhancement and that provide for the generation of dissolution or secondary porosity, respectively. The porosity observed within the Cottage Grove Sandstone is almost entirely secondary due to the dissolution of labile grains, carbonates, and detrital matrix by organic and carbonic acids during the generation of hydrocarbons. The highest porosity seen within the analyzed thin sections was from thin section R47.9 from the Cole 28-A. It is interpretated that late-stage dissolution likely removed carbonate cements leaving a “floating grains” appearance in the rock fabric. This interval displays core measured porosity of 18% and permeability of 80 mD, creating for good reservoir quality.

Distinct diagenetic boundaries between calcite and ferroan dolomite cement take place in thin sections from both the Gillispie 1-3 and Gillispie 3-2. These distinct boundaries were observed at the upper and lower contacts of sandstone units and are thought to be due to higher carbonate influence and infiltration at the top and base of sand shoals. Based on core analysis of the Berryman C 1 and petrographic analysis of five thin sections from three wells within the study area, bioclastic/fossiliferous deposits, and trace fossils in the form of burrows are commonly observed both at the upper and lower contacts of sandstone units. In the middle of sandstone units, mixed or spotty cement contacts were observed, and it is interpreted that ferroan dolomite cement was being replaced by late-stage calcite cement based on grain and cement spatial relationships. Porosity and permeability tend to be higher in the middle of sandstone units and this is interpreted to represent either late-stage dissolution of carbonate cements and/or the lack of infiltration of carbonate influence from the observed upper and lower bioclastic/fossiliferous deposits. The observed calcite cement was likely sourced from bioclastic deposits of carbonate fossil debris that typically take place at the uppermost and lowermost portions of sandstone units. The observed ferroan dolomite cement was likely formed under deep burial conditions and influx of regionally migrating pore waters.

5.3 Detrital Zircon U-Pb Age Distribution

DZ U-Pb geochronology analysis resulted in 288 concordant ages from the subsurface Cottage Grove Sandstone sample located in the northern Anadarko Basin, Ellis County, Oklahoma (red star in **Figure 1**). The U-Pb data for the sample displays major age peaks that correlate to Grenville (950-1250 Ma), Midcontinent Granite-Rhyolite (1,300-1,550 Ma), Appalachian synorogenies (290-500 Ma), and peri-Gondwanan (500-800 Ma) terranes with minor contributions from Yavapai-Mazatzal (1,600-1,800 Ma), Penokean (1,800-2,000 Ma), and Superior (>2,500 Ma) terranes. Overall, the sample is dominated by 950-1,250 Ma aged zircons indicative of sourcing from Grenville terranes associated with the Grenville orogen. The Grenville aged zircons represent 44% of the total concordant ages produced by the sample set. Besides Grenville ages, 16% correlate with Midcontinent Granite-Rhyolite ages, 10% are Appalachian ages, 9% are peri-Gondwanan, 7% Yavapai-Mazatzal, 6% Superior ages, and 1% Penokean (**Figure 19**). Only two zircon grains (<1%) display ages correlating to the nearby Wichita Mountains (530-540 Ma), evidence that supports the hypotheses stating that detritus shed from this province was likely confined to the deeper, axial portion of the basin. Like a majority of the published DZ U-Pb data from Late Paleozoic aged samples located in the Midcontinent and eastern United States that suggest detrital influence from the Appalachian orogenic system, Grenville aged zircons dwarf all other age groups within the Cottage Grove sample. The youngest DZ U-Pb age displayed by the sample is 353 Ma (Appalachian) and the oldest is 2,862 Ma (Superior). **Figure 20** shows a relative age probability density plot constructed for the Cottage Grove sample using the produced 288 concordant DZ U-Pb ages.

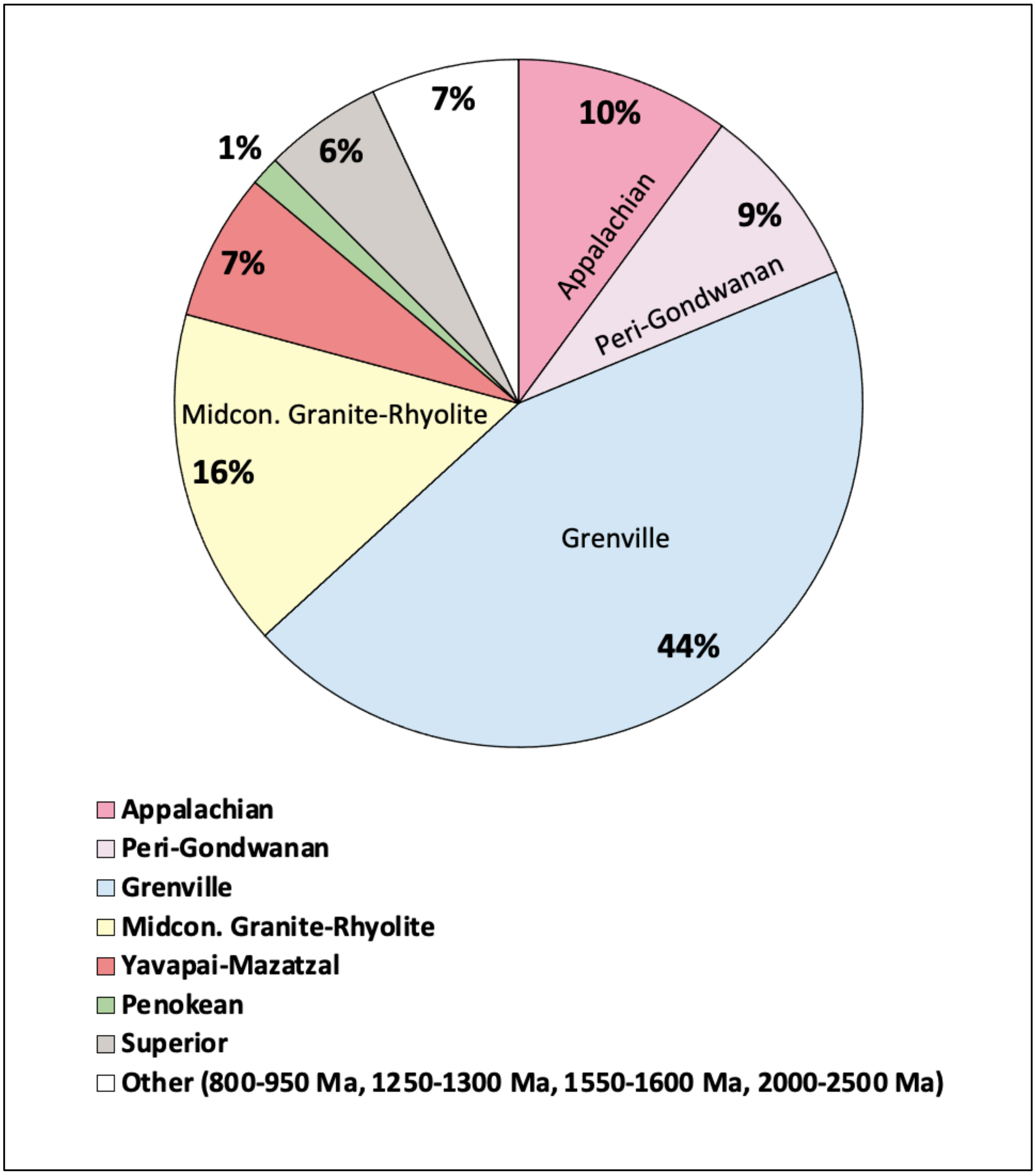

Figure 19. Pie chart showing the DZ U-Pb age contributions from different source terranes within the Cottage Grove sample. Colors are correlated to the basement map of North America in **Figure 4**.

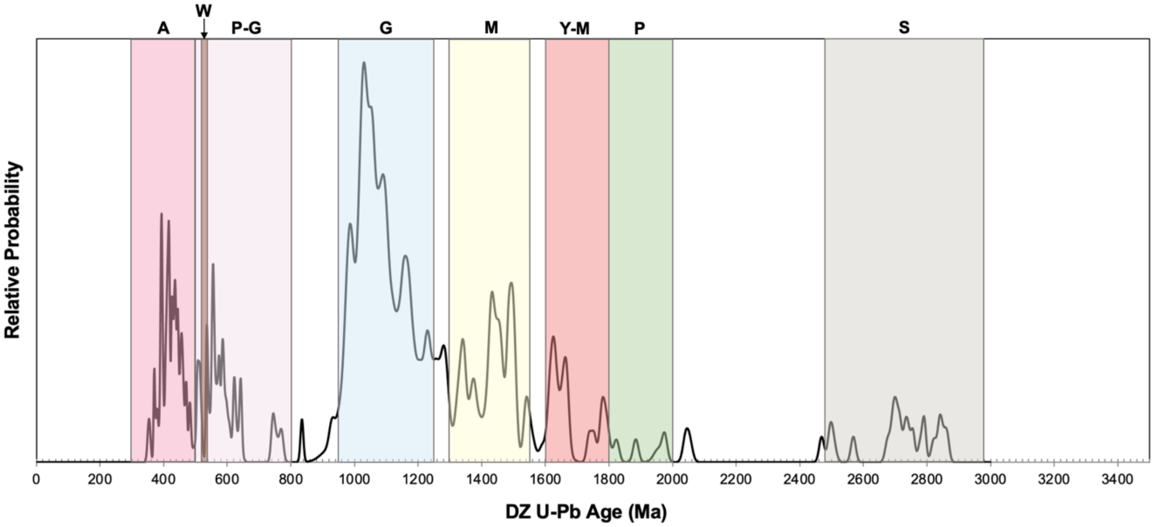

Figure 20. Relative age probability density plot for the Cottage Grove sample showing the results of the 288 DZ U-Pb analyses. The plot is colored in coordination with the basement map of North America displayed in **Figure 4**. A = Appalachian synorogenies, W = Wichita Mountains, P-G = peri-Gondwanan, G = Grenville, M = Midcontinent Granite-Rhyolite, Y-M = Yavapai-Mazatzal, P = Penokean, and S = Superior.

5.4 Detrital Zircon Hf Isotopic Measurements

The 26 DZ Hf isotopic measurements for the Cottage Grove sample are plotted in **Figure 21** in the form of a εHf(t)-U-Pb KDE plot. Seven measurements were produced from zircons within the Appalachian synorogenies DZ U-Pb age group (290-500 Ma) with a mean εHf(t) value of -2.1 and a mean standard error of ± 1.7 (2σ). Seven measurements were also produced from zircons within the peri-Gondwanan DZ U-Pb age group (500-800 Ma) with a mean εHf(t) value of 0.1 and a mean standard error of ± 1.7 (2σ). Four measurements were produced from zircons within the Grenville DZ U-Pb age group (950-1,250 Ma) with a mean εHf(t) value of 6.4 and a mean standard error of ± 1.7 (2σ). Five measurements were produced from zircons within the Midcontinent Granite-Rhyolite DZ U-Pb age group (1,300-1,550 Ma) with a mean εHf(t) value of 5.0 and a mean standard error of ± 2.0 (2σ). Lastly, three measurements were produced from zircons within the Yavapai-Mazatzal DZ U-Pb age group (1,600-1,800 Ma) with a mean εHf(t) value of 4.7 and a mean standard error of ± 1.4 (2σ). Overall, the Cottage Grove sample produced a total mean εHf(t) value of 2.0 with a mean standard error of ± 1.7 (2σ).

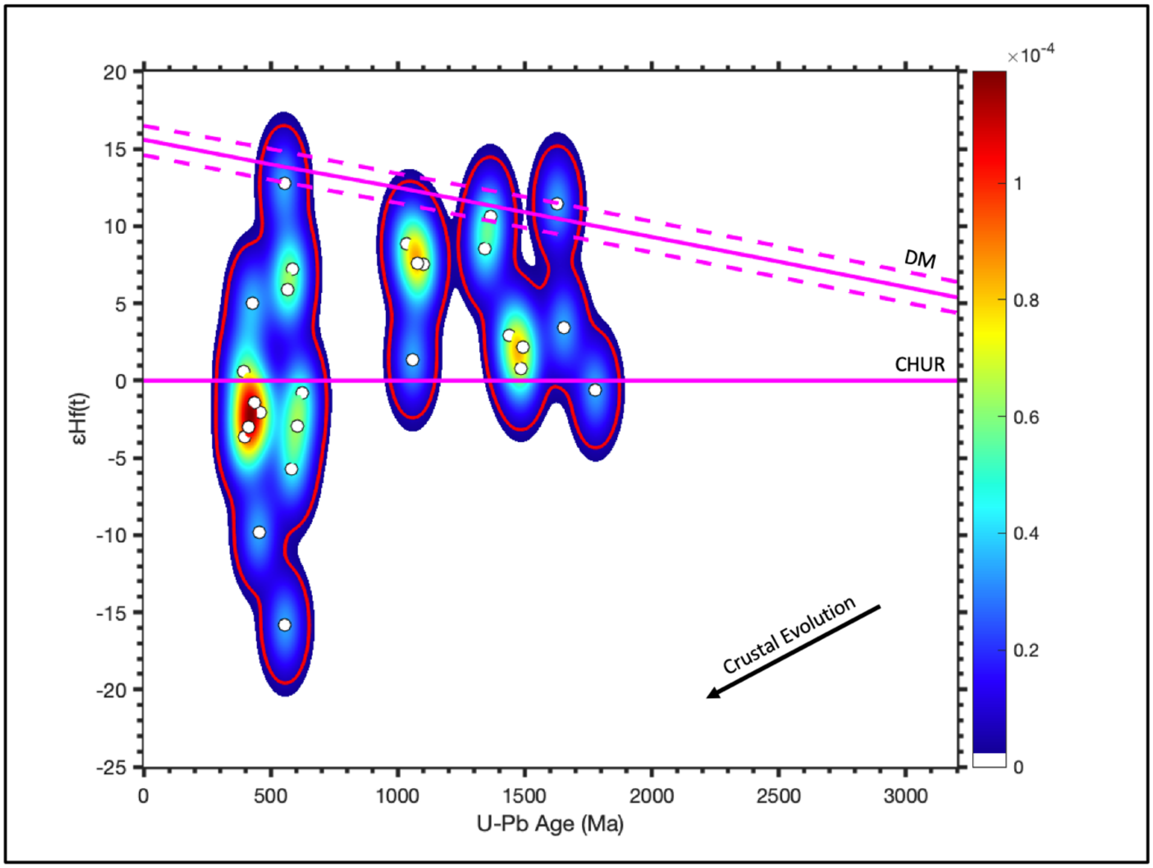

Figure 21. εHf(t)-U-Pb results for the Cottage Grove sample plotted as a two-dimensional bivariate kernel density estimate (KDE) with red contour lines at 95% peak density. DM = depleted mantle and CHUR = chondritic uniform reservoir.

When evaluating εHf(t) data it is important to note that Hf isotopes provide the average mantle extraction age of the source material and because of uncertainty εHf(t) values are typically used as a fingerprint rather than a geochronometer such as U-Pb ages. Therefore, the εHf(t) results displayed by the Cottage Grove sample will be compared to relevant, previous studies in the form of εHf(t)-U-Pb KDE plots with contours at 95% peak densities serving as comparable signatures in chapter six. These comparisons, which following chapter six (6), are carried out to relate similarities and/or dissimilarities between the datasets and therefore potential source terranes. εHf(t) data is generally characterized by three main groups that aid in the interpretation of maturity of zircon grains. εHf(t) measurements are said to be “juvenile” (closer to mantle extraction i.e., DM = depleted mantle) and therefore immature when displaying positive to zero values. εHf(t) measurements are said to be “intermediate” and therefore sub-mature when displaying zero to slightly negative values. εHf(t) measurements are said to be “evolved” and therefore mature when displaying slightly negative to highly negative values. Based on this designation, the mean εHf(t) value for the Appalachian aged (290-500 Ma) zircons of -2.1 ± 1.7 (2σ) suggests intermediate or sub-mature zircon grains. The mean εHf(t) value for the peri-Gondwanan aged (500-800 Ma) zircons of 0.1 ± 1.7 (2σ) suggests slightly juvenile or immature zircon grains. The mean εHf(t) value for the Grenville aged (950-1,250 Ma) zircons of 6.4 ± 1.7 (2σ) suggests juvenile or immature zircon grains. The mean εHf(t) value for the Midcontinent Granite-Rhyolite aged (1,300-1,550 Ma) zircons of 5.0 ± 2.0 (2σ) suggests juvenile or immature zircon grains. The mean εHf(t) value for the Yavapai-Mazatzal aged (1,600-1,800 Ma) zircons of 4.7 ± 1.4 (2σ) suggests juvenile or immature zircon grains. Overall, the mean εHf(t) values from the Appalachian aged (290-500 Ma) and peri-Gondwanan aged (500-800 Ma) zircons show a slight trend toward more evolved values as compared to the Grenville (950-1,250 Ma), Midcontinent Granite-Rhyolite (1,300-1,550 Ma), and Yavapai-Mazatzal (1,600-1,800 Ma) aged zircons. The total mean εHf(t) value for the Cottage Grove sample of 2.0 ± 1.7 (2σ) suggests that overall, the zircon grains are slightly juvenile or immature. Peri-Gondwanan aged zircons from the Cottage Grove sample show the greatest range of εHf(t) values from 12.8 ± 2.4 (2σ) (juvenile) to -15.8 ± 1.9 (2σ) (evolved).

CHAPTER VI

DISCUSSION

6.1 Diagenetic Study Interpretations

Heavy cementation observed in thin sections S60.5 and S75.7 from the Gillispie 1-3, and thin sections G52.5 and G59.3 from the Gillispie 3-2 could have prevented dissolution of metastable grains by protecting them from corrosive fluids including organic and carbonic acids associated with the generation of hydrocarbons. Based on spatial relationships between grains and cements, sparse grain-coating illite likely formed before carbonate cementation and is thought to be detrital in origin. Most of the porosity observed in thin section R47.9 from the Cole 28-A is oversized suggesting possible late-stage dissolution of carbonate cements and gives the rock fabric a “floating grains” appearance. An ancillary interpretation for the lack of carbonate cements observed in the Cole 28-A thin section is that this well is located more than 20 miles to the north and is approximately 1,400 feet shallower than the two Gillispie wells/thin sections analyzed in this study. Different deposition conditions to the north could have resulted in less bioclastic and/or fossiliferous input in this location, which is thought to be the primary source for much of the carbonate cements observed in the Cottage Grove Sandstone.

6.2 Provenance Interpretations

Numerous recent DZ geochronology studies have been conducted on Mississippian to Permian aged samples from the southern United States and include samples from the Fort Worth, Anadarko, and Arkoma Basins and the Ouachita Mountains (Alsalem et al., 2017; McGuire, 2017; Tunin, 2020; Allred and Blum, 2021; Thomas et al., 2021). These studies as well as studies conducted on samples from more northerly basins including the Forest City, Illinois, Michigan, and Appalachian Basins (Thomas et al., 2017; Kissock et al., 2017; Thomas et al., 2020), provide analogous DZ U-Pb age and εHf(t) isotopic signatures to compare to the Late Pennsylvanian Cottage Grove Sandstone signatures presented herein. Comparisons made between the Cottage Grove sample and select samples analyzed from these relevant studies enhance the interpretation of sedimentary provenance by not only displaying similarities between the datasets, but also dissimilarities that are believed to reflect relationships in sediment sourcing and associated processes.

Comparisons between U-Pb age data from the Cottage Grove sample and select samples from the relevant studies listed above (Alsalem et al., 2017; McGuire, 2017; Thomas et al., 2017; Kissock et al., 2017; Thomas et al., 2020; Tunin, 2020; Allred and Blum, 2021; Thomas et al., 2021) are shown in **Figure 22** and **Figure 23** with normalized age probability plots. U-Pb age signatures are compared to the Cottage Grove signature in two separate groups: the southern group that includes select samples from the proximal Fort Worth, Anadarko, and Arkoma Basins and the Ouachita Mountains, and a north-northeastern group which includes select samples from the distal Forest City, Illinois, Michigan, and Appalachian Basins. Comparisons between εHf(t) measurements from the Cottage Grove sample and available εHf(t) data from select samples from the following studies are shown in **Figure 24, Figure 25, Figure 26,** and **Figure 27** with εHf(t)-U-Pb KDE plots with contours at 95% peak density: Thomas et al. (2017), Tunin (2020), Thomas et al. (2020), Allred and Blum (2021), and Thomas et al. (2021). Just as with the U-Pb age signatures, the εHf(t)-U-Pb signatures (correlated using 95% peak density contours) compared to the Cottage Grove sample are separated into the southern group of samples and the north-northeastern group.

Similarities in U-Pb age signatures are noted between all samples including both southern and north-northeastern groups. These similarities suggest possible connections between source terranes, sedimentary basins, and associated sediment dispersal systems, such as the fluvial routing systems that are thought to have flowed from the northern Laurentian craton and the east-northeast Appalachian orogen to the Midcontinent during the Late Mississippian to Late Pennsylvanian as suggested by Kissock et al. (2017), Thomas et al. (2020), Tunin (2020), Allred and Blum (2021), and Thomas et al. (2021). During the Early Pennsylvanian the Ouachita Basin is thought to have represented a terminal sink for sediments coming from multiple provinces to the north-northeast and east via three distinct fluvial routing systems (**Figure 5**) (Allred and Blum, 2021). During the Middle to Late Pennsylvanian the Anadarko and Arkoma Basins are thought to have also served as terminal sinks for sediments coming from source provinces to the north-northeast and east via transcontinental south-southwest and west flowing fluvial systems (**Figure 3**) (Kissock et al., 2017; Tunin, 2020).

Grenville (950-1,250 Ma) aged zircons are the dominant age group in the majority of all samples (both southern and north-northeastern groups). However, samples from Tunin, 2020 (Bartlesville and Red Fork, northeast Oklahoma and Anadarko Basin samples, respectively) and Thomas et al., 2021 (Fort Worth Basin samples) display deflated Grenville (950-1,250 Ma) aged peaks with more robust peri-Gondwanan, Neoproterozoic (500-800 Ma) aged peaks as compared to the rest of the 12 signatures. This suggests that these samples likely experienced major sourcing from the number of exotic, peri-Gondwanan terranes (Coahuila, Sabine, Suwannee, Yucatan-Campeche, Carolinia, Ganderia, Avalonia, and Meguma) that were accreted to the southern, eastern, and northeastern margin of Laurentia just before the collision with Gondwana occurred. Overall, the southern group of samples seem to display more prominent peri-Gondwanan (500-800 Ma) aged peaks as compared to the north-northeastern group, which seem to display more prominent Paleozoic, Appalachian synorogenic (290-500 Ma) aged peaks. Another common theme amongst all samples (both southern and north-northeastern) is that zircons with older U-Pb ages seem to become more depleted through time. Meaning that after the Grenville (950-1,250 Ma) aged peaks, the concentrations of DZs with ages 1,250-3,200 Ma decrease with progressing time. This is likely due to these older aged zircons being recycled multiple times and finally being dropped out of the dispersal system(s). Therefore, the older the zircon grain is, typically the less abundant it is within the sample.

Similarities in εHf(t)-U-Pb signatures (95% peak density contours) are also noted between all samples including both southern and north-northeastern groups. However, similarities (and dissimilarities) between the εHf(t)-U-Pb signatures are more subtle than comparisons noted in U-Pb age signatures, and εHf(t) measurements alone do not directly indicate differentiation of specific source terranes. Nevertheless, these similarities are thought to suggest possible connections between source terranes, sedimentary basins, and associated sediment dispersal systems much like the U-Pb age data. As previously stated, the primary goal of the Hf isotopic analyses of the Cottage Grove sample was to further delineate source terranes that might be difficult to separate solely based on the U-Pb ages. Therefore, for the purpose of this study εHf(t)-U-Pb signatures help to characterize potential source terranes for zircons with ages of 290-800 Ma (Appalachian and peri-Gondwanan provinces).

In terms of εHf(t)-U-Pb signatures for Paleozoic (290-500 Ma) aged zircons, both the southern (**Figure 24** and **Figure 25**) and north-northeastern (**Figure 26** and **Figure 27**) groups show close correlations to the Cottage Grove sample. Slight differences are noted in the form of signatures that are both somewhat less evolved and somewhat more evolved than the Cottage Grove sample in terms of 290-500 Ma aged zircons. However, both instances are noted in the southern and north-northeastern groups and these dissimilarities are interpreted to be negligible. This interpretation suggests that Paleozoic (290-500 Ma) aged zircons were likely sourced from similar terranes for both the southern (including the Cottage Grove sample) and north-northeastern groups. These 290-500 Ma aged zircons are interpreted to be sourced from the Appalachian synorogenies of the east-northeast Laurentian margin.

εHf(t)-U-Pb signatures for the southern group of samples (**Figure 24** and **Figure 25**) seem to show a closer correlation to the Cottage Grove sample in terms of Neoproterozoic (500-800 Ma) aged zircons as compared to north-northeastern group of samples (**Figure 26** and **Figure 27**). This interpretation is based on 500-800 Ma aged zircons for the southern group that display both a wider range (juvenile – intermediate – evolved) and that also display more evolved εHf(t) measurements as compared to the north-northeastern group of εHf(t) measurements. However, based on these εHf(t)-U-Pb signatures, petrographic analysis, and interpretations from Tunin (2020) (orange contours in **Figure 24** and **Figure 25**), whose data is included in the southern group of samples, evidence suggests that exposed peri-Gondwanan terranes in the northern Appalachian orogen, specifically the Ganderia and Avalonia terranes, are the source of Neoproterozoic (500-800 Ma) peri-Gondwanan aged zircons. Considering that the εHf(t)-U-Pb signature from Tunin (2020) has the closest correlation to Neoproterozoic (500-800 Ma) aged zircons in the Cottage Grove εHf(t)-U-Pb signature, it is possible that these zircons are sourced from the same Ganderia and Avalonia terranes of the northern Appalachians. It is important to note that rocks from the Ganderia and Avalonia terranes generally display evolved and a wide range of εHf(t) values (Tunin, 2020). Based on εHf(t)-U-Pb signatures from Thomas et al. (2021) (light purple, grey, and olive contours in **Figure 24** and **Figure 25**), who suggested that Neoproterozoic aged, peri-Gondwanan zircons were sourced from the proximal Sabine terrane on the southern Laurentian margin, a possible secondary source of these zircons in the Cottage Grove sample is the Sabine terrane to the south-southeast of the Anadarko Basin. Sourcing from both northeastern and southern peri-Gondwanan terranes is possible, but the correlation between Thomas et al. (2021) and this study regarding εHf(t)-U-Pb signatures is lacking compared to the closer correlation observed between Tunin (2020) and this study. This interpretation is based on the comparison between the Cottage Grove sample and the samples analyzed by Tunin (2020) that show both evolved and a wide range of εHf(t) values. Therefore, a northern Appalachian, Ganderia and Avalonia, peri-Gondwanan source is preferred over a southern Sabine source.

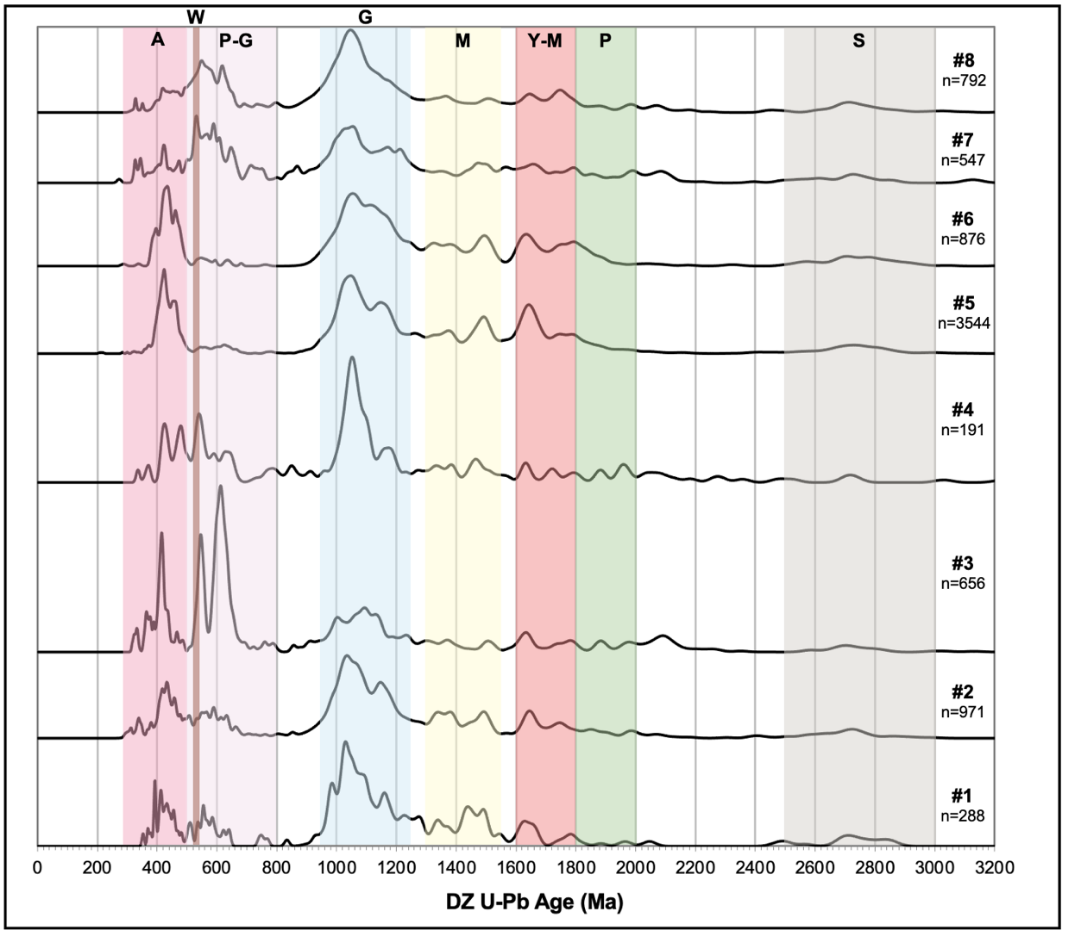

Figure 22. Normalized age probability plot for the southern group DZ U-Pb age signatures compared to the #1 Cottage Grove sample from this study. Other signatures shown include #2 Thomas et al., 2021 (Anadarko Basin and Oklahoma samples), #3 Tunin, 2020 (Bartlesville and Red Fork, Oklahoma and Anadarko Basin samples), #4 McGuire, 2017 (Stanley and Hot Springs, Ouachita samples), #5 Allred and Blum, 2021 (Ouachita samples), #6 Thomas et al., 2021 (Arkoma Basin samples), #7 Thomas et al., 2021 (Fort Worth Basin samples), and #8 Alsalem et al., 2017 (Fort Worth Basin samples). Vertical color bars denoting potential source terranes are correlated to **Figure 4**. A = Appalachian synorogenies, W = Wichita Mountains, P-G = peri-Gondwanan, G = Grenville, M = Midcontinent Granite-Rhyolite, Y-M = Yavapai-Mazatzal, P = Penokean, and S = Superior.

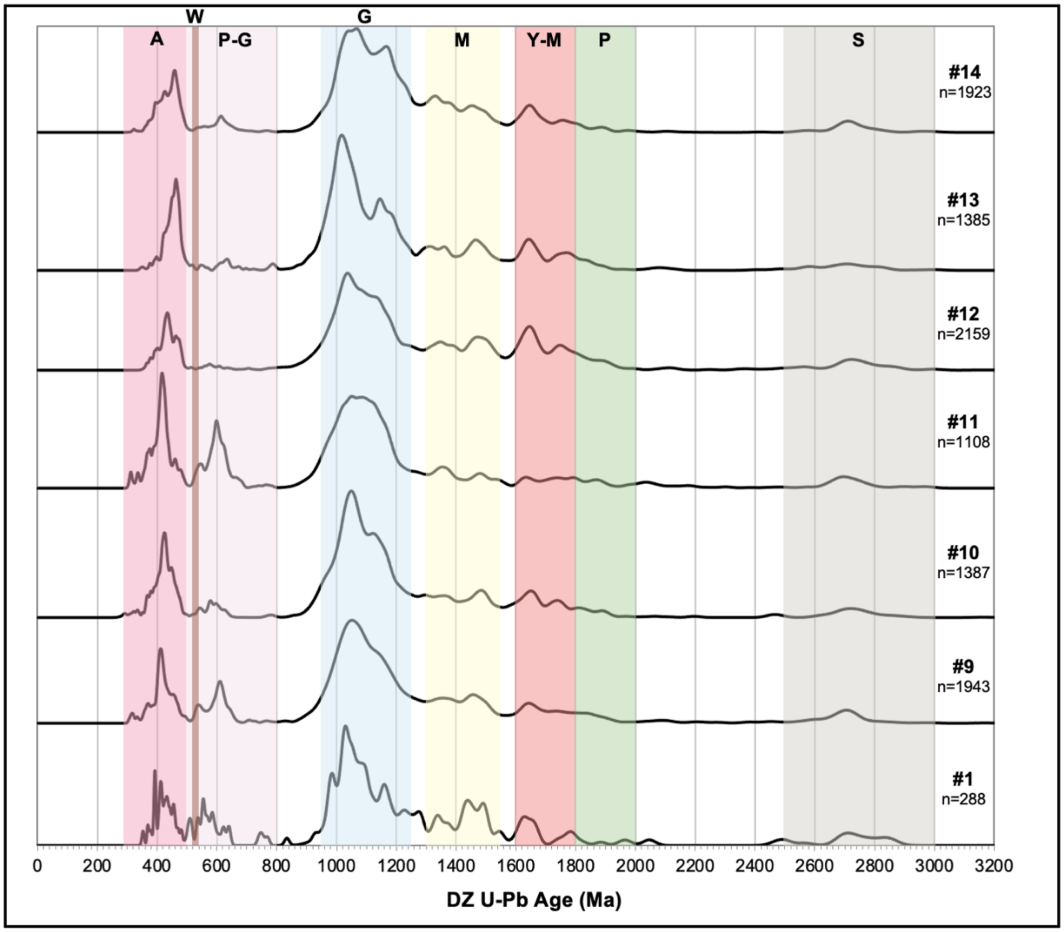

Figure 23. Normalized age probability plot for the north-northeastern group DZ U-Pb age signatures compared to the #1 Cottage Grove sample from this study. Other signatures shown include #9 Kissock et al., 2017 (Forest City Basin samples), #10 Thomas et al., 2020 (Forest City Basin samples), #11 Kissock et al., 2017 (Illinois Basin samples), #12 Thomas et al., 2020 (Illinois Basin samples), #13 Thomas et al., 2020 (Michigan Basin samples), and #14 Thomas et al., 2017 (Appalachian Basin samples). Vertical color bars denoting potential source terranes are correlated to **Figure 4**. A = Appalachian synorogenies, W = Wichita Mountains, P-G = peri-Gondwanan, G = Grenville, M = Midcontinent Granite-Rhyolite, Y-M = Yavapai-Mazatzal, P = Penokean, and S = Superior.

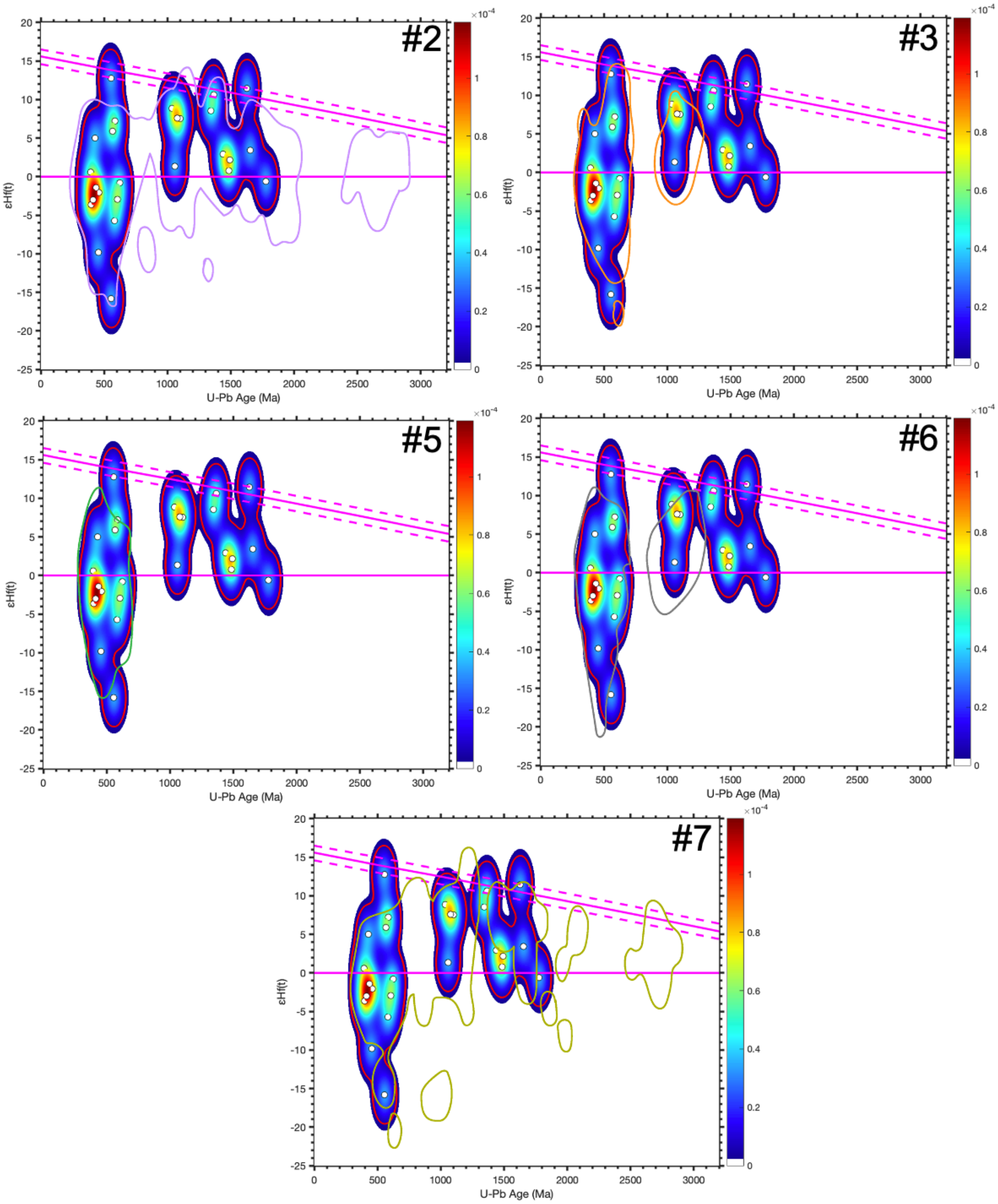

Figure 24. εHf(t)-U-Pb KDE plots with contours at 95% peak density showing the available Hf data from the southern group of samples overlain on the Cottage Grove sample. Plot numbers correlate to the southern group numbers in **Figure 23**. #2 (light purple) Thomas et al., 2021 (Anadarko Basin and Oklahoma samples), #3 (orange) Tunin, 2020 (Bartlesville and Red Fork, Oklahoma and Anadarko Basin samples, #5 (green) Allred and Blum, 2021 (Ouachita samples), #6 (grey) Thomas et al., 2021 (Arkoma Basin samples), #7 (olive) Thomas et al., 2021 (Fort Worth Basin samples).

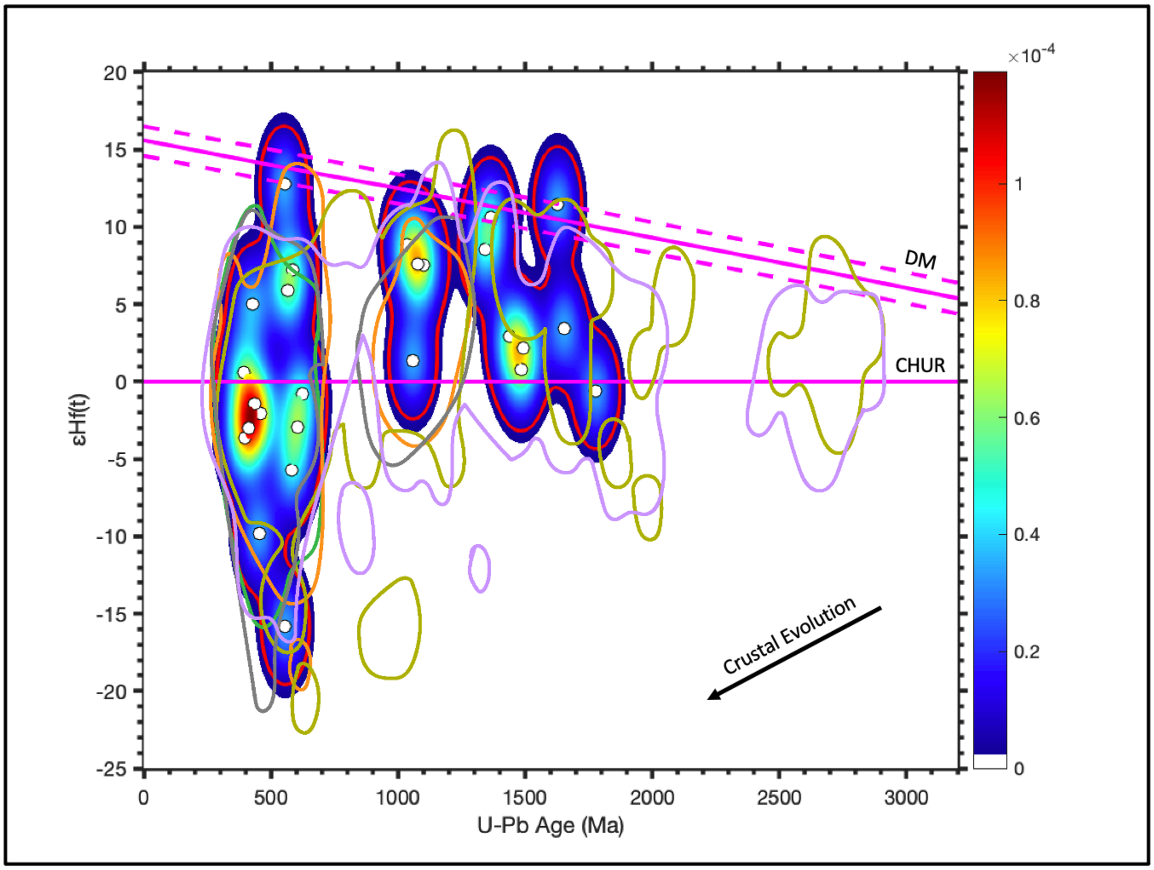

Figure 25. Compiled εHf(t)-U-Pb KDE plot with contours at 95% peak density showing the available Hf data from all southern group samples overlain on the Cottage Grove sample. Light purple = Thomas et al., 2021 (Anadarko Basin and Oklahoma samples), orange = Tunin, 2020 (Bartlesville and Red Fork, Oklahoma and Anadarko Basin samples, green = Allred and Blum, 2021 (Ouachita samples), grey = Thomas et al., 2021 (Arkoma Basin samples), olive = Thomas et al., 2021 (Fort Worth Basin samples). DM = depleted mantle and CHUR = chondritic uniform reservoir.

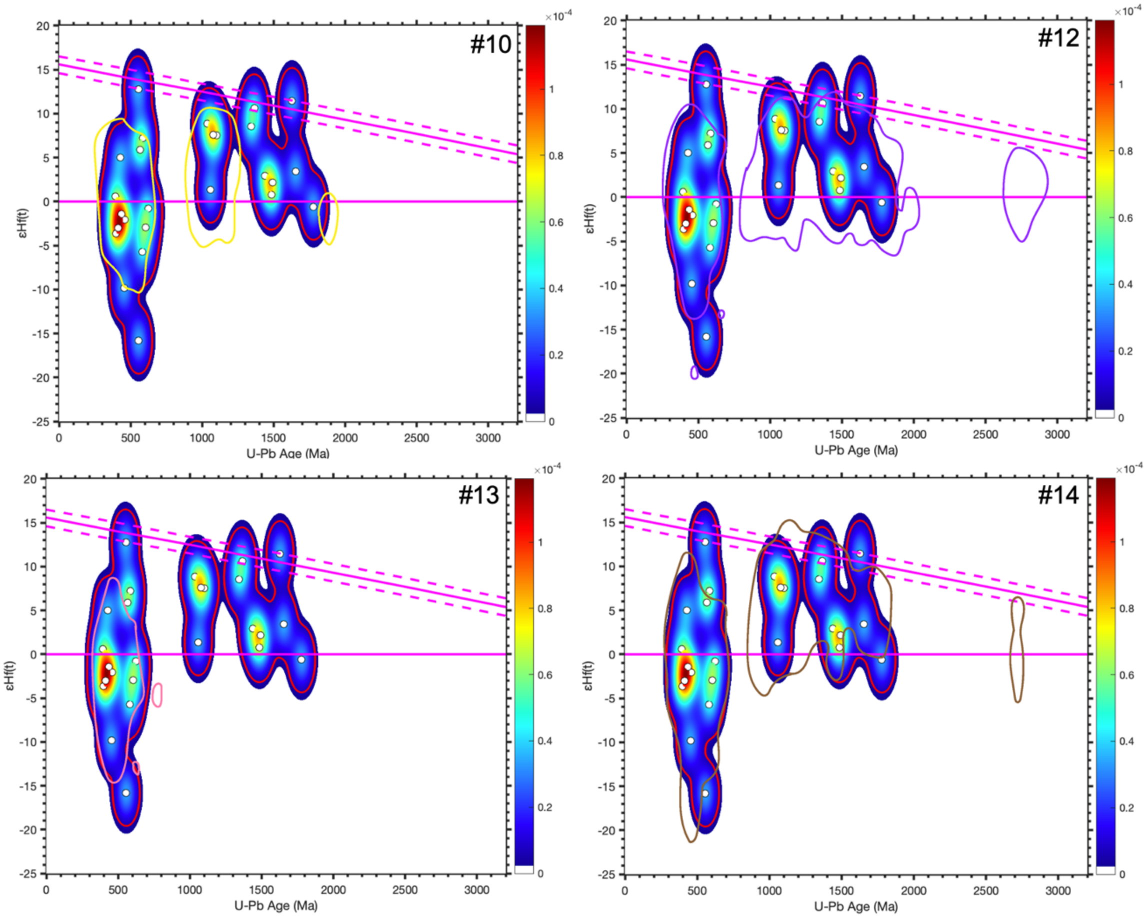

Figure 26. εHf(t)-U-Pb KDE plots with contours at 95% peak density showing the available Hf data from the north-northeastern group of samples overlain on the Cottage Grove sample. Plot numbers correlate to the north-northeastern group numbers in **Figure 24**. #10 (yellow) Thomas et al., 2020 (Forest City Basin samples), #12 (purple) Thomas et al., 2020 (Illinois Basin samples), #13 (pink) Thomas et al., 2020 (Michigan Basin samples), and #14 (brown) Thomas et al., 2017 (Appalachian Basin samples).

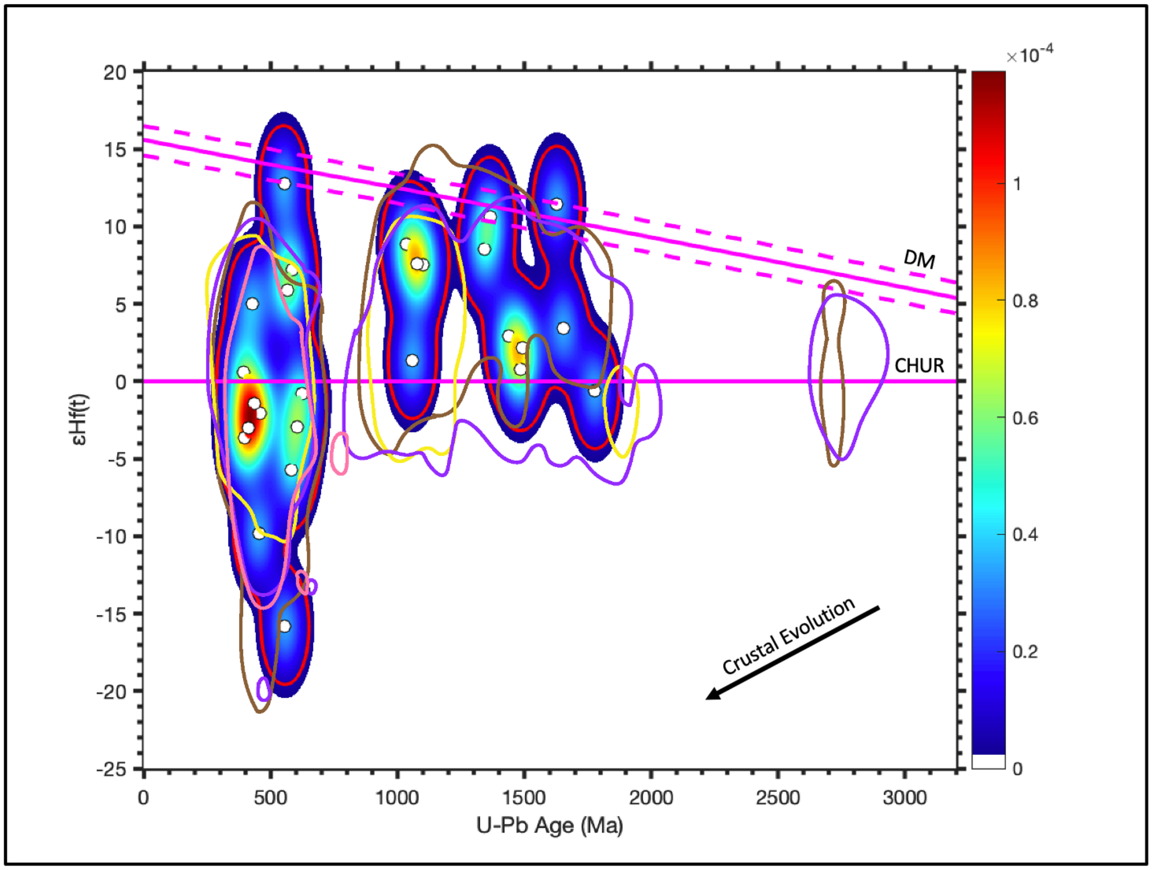

Figure 27. Compiled εHf(t)-U-Pb KDE plot with contours at 95% peak density showing the available Hf data from all north-northeastern group samples overlain on the Cottage Grove sample. Yellow = Thomas et al., 2020 (Forest City Basin samples), purple = Thomas et al., 2020 (Illinois Basin samples), pink = Thomas et al., 2020 (Michigan Basin samples), and brown = Thomas et al., 2017 (Appalachian Basin samples). DM = depleted mantle and CHUR = chondritic uniform reservoir.

6.2.1 Archean-Early Paleoproterozoic (>2,500-1,800 Ma)

The source terranes that are thought to have provided DZs to the Cottage Grove sample with U-Pb ages of >2,500 Ma are found in the northern Laurentian craton. These terranes include the Superior and Wyoming-Hearne provinces, but due to the Wyoming-Hearne province being buried during the Paleozoic, a Superior province is interpreted as being a more likely source of grains with ages of >2,500 Ma (McGuire, 2017). DZs with ages >2,500 Ma contribute 6% (16 grains) of the total, identifiable ages produced from the Cottage Grove sample.

The source terranes that are interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages of 1,800-2,000 Ma include the Penokean and Trans-Hudson provinces, also located in the northern Laurentian craton. However, during the Paleozoic and with the same case as the Wyoming-Hearne basement rocks, the Trans-Hudson basement was buried during the Paleozoic and therefore a Penokean source terrane is favored for this study (McGuire, 2017). DZs with ages ranging from 1,800 Ma to 2,000 Ma contribute 1% (4 grains) of the total, identifiable ages produced from the Cottage Grove sample. DZs with U-Pb ages ranging from >2,500 Ma to 1,800 Ma are interpreted to be sourced from the northern Laurentian craton from the Superior and Penokean provinces.

6.2.2 Late Paleoproterozoic (1,600-1,800 Ma)

The source terrane that is interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages that range from 1,600-1,800 Ma is the Yavapai-Mazatzal province that is composed of metavolcanic and metasedimentary rocks that are observed to take place across north-central and southwest North America (McGuire, 2017). DZs with ages ranging from 1,600 Ma to 1,800 Ma contribute 7% (20 grains) of the total, identifiable ages produced from the Cottage Grove sample. It is interpreted that DZs from this province were sourced from north-central North America.

6.2.3 Early Mesoproterozoic (1,300-1,550 Ma)

The source terrane that is interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages that range from 1,300-1,550 Ma is the Midcontinent Granite-Rhyolite province. This province consists of scattered plutons that formed by anorogenic magmatism and are located throughout the Midcontinent and Midwest (McGuire, 2017). DZs with ages ranging from 1,300 Ma to 1,550 Ma contribute 16% (46 grains) of the total, identifiable ages produced from the

Cottage Grove sample. It is interpreted that DZs from this province were sourced from terranes proximal to the Midcontinent or from the Midwest, or a combination of the two.

6.2.4 Middle-Late Mesoproterozoic (950-1,250 Ma)

The source terrane that is interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages that range from 950-1,250 Ma is the Grenville province associated with the Appalachian orogenic system of east-northeastern North America. Grenville aged terranes are also found in present day western Texas and northwest Mexico, but evidence from correlating U-Pb age and εHf(t)-U-Pb signatures presented herein and evidence from previous studies seem to suggest an Appalachian, east-northeast provenance over a southern provenance. DZs with ages ranging from 950 Ma to 1,250 Ma contribute 44% (128 grains) of the total, identifiable ages produced from the Cottage Grove sample. It is interpreted that DZs from this province were sourced from eastern and northeastern North America.

6.2.5 Neoproterozoic-Early Paleozoic (500-800 Ma)

The source terranes that are interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages that range from 500-800 Ma are the peri-Gondwanan Ganderia (including the Gander Group mica schist) and Avalonia terranes of the northern Appalachian orogen located from the New York promontory to the Newfoundland embayment (Tunin, 2020). This interpretation is based on evidence suggested by correlating εHf(t)-U-Pb signatures and petrographic analysis between this study and Tunin (2020). As discussed above, the εHf(t)-U-Pb signature from Tunin (2020) shows the closest correlation in terms of Neoproterozoic aged zircons to the Cottage Grove sample, which display both a wide range of εHf(t) values from juvenile to evolved and somewhat more evolved values than the other samples compared to the Cottage Grove sample. Petrographic evidence also supports this interpretation as the abundant schistose metamorphic rock fragments observed in the Cottage Grove Sandstone are also observed in the Desmoinesian Cherokee Group Sandstones of the Anadarko Basin and northeast Oklahoma by Tunin (2020). Considering that the Midcontinent has little to no known sources of metamorphic rocks, it is inferred that these zircons and metamorphic material were transported to the Midcontinent by transcontinental, southwest flowing fluvial systems that likely flowed from the northern Appalachians through the Michigan, Illinois, and Forest City Basins before being deposited in the Anadarko Basin in the Middle to Late Pennsylvanian as suggested by Tunin (2020) (**Figure 3**). It is important to note that Neoproterozoic aged zircons are not common in the Paleozoic clastic wedges associated with the southern and central portions of the Appalachian Basin, which is interpreted to strengthen a northern Appalachian provenance (Tunin, 2020). As discussed above, a possible secondary source of Neoproterozoic aged zircons is the Sabine terrane that was accreted to the southern Laurentian margin and that was located to the south-southeast of the Anadarko Basin. Studies conducted by Sharrah (2006), McGuire (2017), and Thomas et al. (2021) have suggested the Sabine terrane as a possible source of Neoproterozoic aged zircons for Mississippian to Permian aged samples located in the Ouachitas (Sharrah, 2006; McGuire, 2017), southern Anadarko Basin, and central Oklahoma (Thomas et al., 2021). Therefore, it is possible that Neoproterozoic aged zircons were also sourced from the south but based on εHf(t)-U-Pb signatures and petrographic evidence discussed above, a northern Appalachian, Ganderia and Avalonia source is favored over a Sabine source. DZs with ages ranging from 500 Ma to 800 Ma contribute 9% (25 grains) of the total, identifiable ages produced from the Cottage Grove sample.

This age range (500-800 Ma) also correlates to the localized igneous activity associated with the Wichita Mountains (530-540 Ma) of southern Oklahoma (McGuire, 2017). The Cottage Grove sample displays only two ages (<1%) representative of this province and therefore insignificant sourcing is interpreted from the Wichita Mountains. This interpretation of negligible sourcing from the Wichitas is thought to be correlated to the occasional, sparse proportions of plutonic (granitic) rock fragments that are observed by both qualitative and quantitative petrographic analysis of the Cottage Grove Sandstone. DZs correlating to the Wichita Mountains were likely directly sourced to the Anadarko Basin, however previous research and DZ geochronology evidence presented herein supports that there was likely minor sourcing from the Wichita Mountains, as the majority of sediments shed from this province were likely confined to the deeper, axial portion of the basin.

6.2.6 Paleozoic (290-500 Ma)

The source terranes that are interpreted to have provided DZs to the Cottage Grove sample with U-Pb ages that range from 290-500 Ma are the Alleghenian (275-330 Ma), Acadian (345-430 Ma), and Taconic (430-490 Ma) orogenies associated with the east-northeast Appalachian orogenic system. The southern portion of the peri-Gondwanan Yucatan-Campeche province also displays DZ U-Pb ages that fall within the 290-500 Ma age range therefore making it a potential source for 290-500 Ma aged zircons. However, based on DZ geochronology data presented herein (specifically εHf(t) signatures), an Appalachian provenance is favored over a southern, peri-Gondwanan provenance. DZs with ages ranging from 290 Ma to 500 Ma contribute 10% (29 grains) of the total, identifiable ages produced from the Cottage Grove sample. It is interpreted that DZs from the Appalachian orogen were sourced from the east-northeast portion of North America.

6.2.7 Provenance Summary

Relevant, previous studies and associated data compared to the Cottage Grove Sandstone sample analyzed herein suggest that sedimentation to the Anadarko Basin was complex and primarily derived from the northern (Superior, Penokean, and Yavapai-Mazatzal), northeastern (Midcontinent Granite-Rhyolite, Grenville, Appalachian synorogenies, peri-Gondwanan), and central (Midcontinent Granite-Rhyolite) portions of North America during the Middle to Late

Pennsylvanian via transcontinental fluvial routing systems. Based on the observed Cottage Grove depositional settings that transition from shallow marine deposits in the study area to fluvial-deltaic deposits in central Oklahoma, it is inferred that sediments that sourced the Cottage Grove Sandstone entered the Oklahoma region from the north, northeast, and/or east and were deposited west-northwest along the northwest-southeast axial trend of the Anadarko Basin. This evidence, along with observed DZ geochronology signatures, is thought to also suggest that sediments deposited in the deep-water Ouachita Basin during the Early Pennsylvanian were uplifted and incorporated into the northward propagating Ouachita Mountains and subsequently shed into the proximal Anadarko Basin during the Middle to Late Pennsylvanian via localized drainage systems. These localized drainage systems likely followed the same depositional trends of fluvial-deltaic environments in central Oklahoma and shallow marine environments in northwest Oklahoma. However, based on the abundant schistose metamorphic rock fragments observed in the Cottage Grove Sandstone, which are not observed in the same quantities in the Ouachita sedimentary rocks, it is inferred that the Ouachita Mountains were a restricted source, likely only providing the more resistant grains, such as quartz and associated zircons, to the study area. Based on DZ geochronology conducted herein, it is unclear what proportion of the zircons were recycled with the Ouachita Basin and subsequent Ouachita Mountains versus the detritus that was directly transported to the Anadarko Basin from the north-northeast and east. The similarities observed in the compared DZ geochronologic data are interpreted to reflect possible connections in source areas and/or dispersal systems between the Anadarko Basin and the Ouachita Basin. Sediments originating from the northern Laurentian craton and the east-northeast Appalachian orogen were likely recycled in sedimentary basins while being transported south and southwest to the Midcontinent. This includes possible recycling that occurred in the Appalachian, Michigan, Illinois, and Forest City Basins before the sediments were either deposited directly into the Anadarko Basin and/or deposited into the Ouachita Basin and subsequently shed into the Anadarko Basin after basin inversion and uplift.

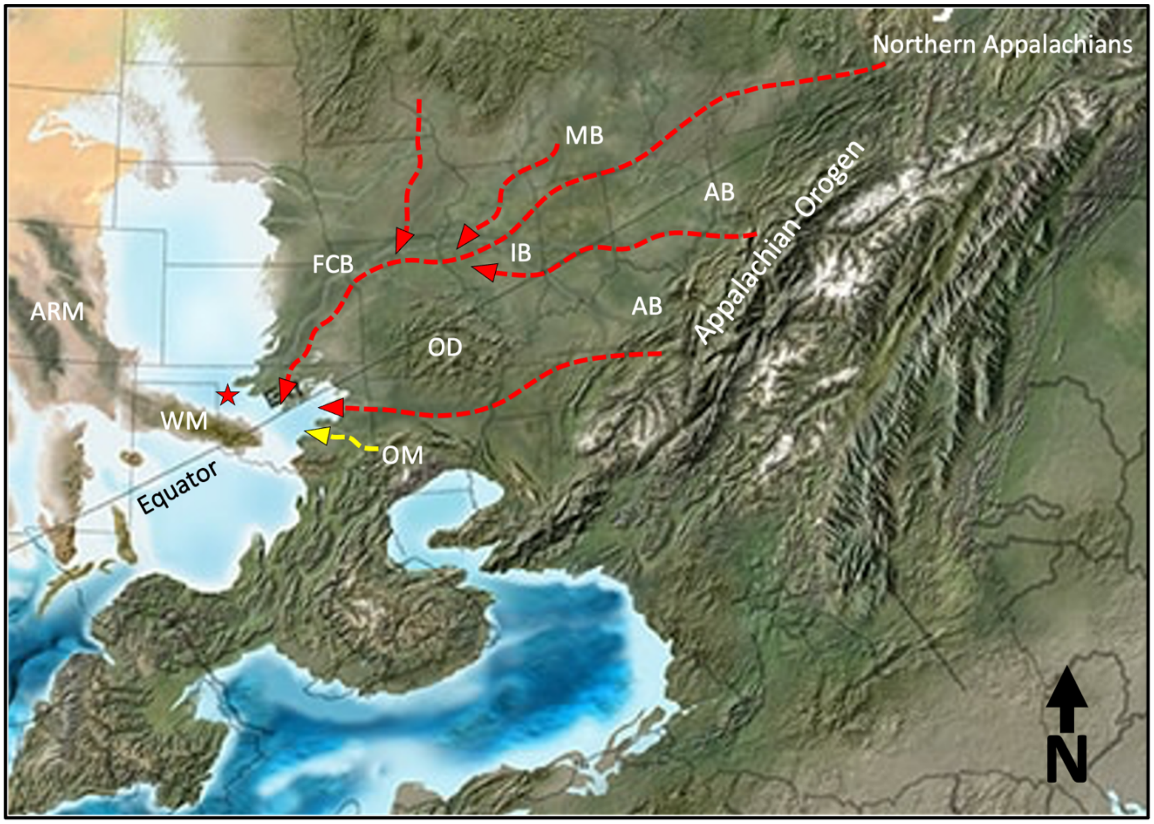

Figure 28. Middle to Late Pennsylvanian paleogeography (modified from North American Key Time Slices 2013 Colorado Plateau Geosystems Inc.) with interpreted sediment dispersal pathways for the Cottage Grove Sandstone in the Missourian. Red lines = transcontinental fluvial dispersal pathways originating from the northern Laurentian craton, northern Appalachians (Tunin, 2020), and the central and southern Appalachian orogen (Kissock et al., 2017). Yellow line = localized drainage pathway(s) from the Ouachita Mountains. Red star = general study area. ARM = Ancestral Rocky Mountains, WM = Wichita Mountains, OM = Ouachita Mountains, FCB = Forest City Basin, OD = Ozark Dome, IB = Illinois Basin, MB = Michigan Basin, AB = Appalachian Basin.

CHAPTER VII

CONCLUSIONS

This study presents 288 new DZ U-Pb ages and 26 new εHf(t) measurements for the Late Pennsylvanian Missourian series Cottage Grove Sandstone collected from subsurface samples in the northern Anadarko Basin, Ellis County, Oklahoma. Based on these new DZ geochronology data and similarities and dissimilarities observed when comparing pertinent DZ geochronology data from previous studies conducted on Mississippian to Permian formations from the Midcontinent and more north-northeasterly located basins of the United States, as well as interpretations based on petrographic analysis and depositional systems of the Cottage Grove Sandstone, the main conclusions from this study include:

1. Based on the petrographic analysis of nine thin sections within the study area, the primary Folk (1968) classification for the Cottage Grove Sandstone is sublitharenite and the primary Dickinson et al. (1983) provenance classification is recycled orogenic. The Cottage Grove Sandstone is composed of very fine to fine, subangular to rounded, well sorted, mature quartz grains suggesting a possible distal and/or recycled provenance.

2. Based on the composition and diagenetic history of five thin sections from three wells within the study area, evolution of porosity, permeability, and reservoir facies is largely controlled by detrital composition and diagenesis. The abundance of bioclasts facilitated generation of carbonate cements, and porosity occlusion. Most porosity observed in the Cottage Grove Sandstone is secondary and results from dissolution, therefore the presence of labile constituents is critical for the development of secondary porosity.

3. Distinct diagenetic boundaries between calcite and ferroan dolomite cement are common in the upper and lower sections of sandstone units and are interpreted to be the result of local carbonate supply in the form of bioclastic/fossiliferous deposits near the uppermost and lowermost contacts of sandstone units. Near the middle of sandstone units, carbonate is less prevalent and spatial relationships support the interpretation that ferroan dolomite cement was replaced by late-stage calcite cement. Porosity and permeability tend to be higher toward the middle of sandstone units, a relationship attributed to possible late-stage dissolution of carbonate cements and/or the lack of infiltration of carbonate-saturated fluids originating in the bioclast-rich zones near the contacts.

4. Wireline log signatures and distribution patterns support the interpretation that the Cottage Grove Sandstone represents shallow marine shoal depositional settings in northwest Oklahoma, whereas the Cottage Grove Sandstone bodies in central Oklahoma are interpreted to represent fluvial-deltaic depositional settings. This interpretation suggests that dispersal of sediments likely took place from the east and/or southeast. Sediments accumulating in the study area were likely transported to the west-northwest subparallel to the axial trend of the Anadarko Basin.

5. Overall, the DZ U-Pb ages represented by the Cottage Grove sample are characterized by 44% Grenville (950-1,250 Ma), 16% Midcontinent Granite-Rhyolite (1,300-1,550 Ma), 10% Appalachian synorogenies (290-500 Ma), 9% peri-Gondwanan (500-800 Ma), 7% Yavapai-Mazatzal (1,600-1,800 Ma), 6% Superior (>2,500 Ma), 1% Penokean (1,800-2,000 Ma), and <1% Wichita Mountains (530-540 Ma) aged zircons. This U-Pb age distribution is interpreted to reflect sediment sourcing from provinces located in the northern, northeastern, and central regions of North America.

6. Similarities in DZ U-Pb age signatures are noted between all samples including both southern and north-northeastern groups. These similarities suggest possible connections between source terranes, sedimentary basins, and associated sediment dispersal systems, such as transcontinental fluvial routing systems that are thought to have flowed from the northern Laurentian craton and the east-northeast Appalachian orogenic system to the Midcontinent during the Late Mississippian to Late Pennsylvanian.

7. Based on comparisons made between DZ εHf(t)-U-Pb signatures displayed by 290-500 Ma aged zircons from both the southern and north-northeastern groups of samples from previous studies and the Cottage Grove sample, it is interpreted that all samples (including the Cottage Grove sample) were sourced from the Appalachian synorogenies of the east-northeast Laurentian craton. These 290-500 Ma aged zircons were likely recycled from the Appalachian, Illinois, and Forest City Basins before being deposited into the Anadarko Basin and/or the Ouachita Basin. If deposited into the Ouachita Basin, these sediments were then uplifted and incorporated into the Ouachita Mountains and then shed into the proximal Anadarko Basin.

8. Based on comparisons of DZ εHf(t)-U-Pb signatures displayed by 500-800 Ma aged zircons analyzed by Tunin (2020) and the Cottage Grove sample, as well as petrographic evidence in the form of the abundant schistose metamorphic rock fragments observed in the Cottage Grove Sandstone and Desmoinesian Cherokee Group Sandstones (Tunin, 2020), it is proposed that Neoproterozoic aged zircons and metamorphic rock fragments were sourced from the Ganderia and Avalonia terranes in the northern Appalachians. These sediments were likely transported via transcontinental, southwest flowing fluvial systems that likely flowed through the Michigan, Illinois, and Forest City Basins before being deposited into the Anadarko Basin during the Middle to Late Pennsylvanian.

9. During the Early Pennsylvanian the Ouachita Basin is thought to have represented a terminal sink for sediments coming from multiple provinces to the north and northeast via transcontinental fluvial routing systems. These sediments were buried, lithified, and uplifted as the Ouachita Mountains. Erosion subsequently shed detritus into the proximal Anadarko Basin during the Late Pennsylvanian. Any recycled Ouachita sediment reaching the study area was mature and made up of more resistant grains, such as quartz and associated zircons.

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APPENDICES

APPENDIX A: Detrital Zircon U-Pb Data

Table 1. Detrital zircon U-Pb data for the Cottage Grove Sandstone.

	Isotope ratios						Apparent ages (Ma)						
Analysis	207Pb*	±	206Pb*	±	error	206Pb*	±	207Pb*	±	206Pb*	±	Best age	±
CG	235U	(%)	238U	(%)	corr.	238U	(Ma)	235U	(Ma)	207Pb*	(Ma)	(Ma)	(Ma)
Spot 1	2.2136	0.9	0.1998	0.9	0.90	1174.4	9.1	1185.4	6.6	1205.5	8.0	1205.5	8.0
Spot 2	5.9602	1.2	0.3604	0.9	0.74	1984.1	15.5	1970.1	10.7	1955.3	14.7	1955.3	14.7
Spot 3	2.3795	0.8	0.2118	0.6	0.74	1238.2	6.5	1236.5	5.6	1233.5	10.2	1233.5	10.2
Spot 4	1.9949	0.9	0.1900	0.8	0.88	1121.2	8.2	1113.8	6.1	1099.4	8.6	1099.4	8.6
Spot 5	1.7775	1.2	0.1743	0.8	0.64	1035.6	7.6	1037.2	8.0	1040.7	19.2	1040.7	19.2
Spot 6	1.7722	1.0	0.1687	0.8	0.77	1004.9	7.2	1035.3	6.5	1100.3	12.9	1100.3	12.9
Spot 7	1.8448	0.8	0.1803	0.6	0.84	1068.8	6.4	1061.6	5.1	1046.7	8.5	1046.7	8.5
Spot 8	4.3590	0.8	0.2890	0.6	0.70	1636.5	8.1	1704.6	6.7	1789.4	10.5	1789.4	10.5
Spot 9	1.7980	1.6	0.1758	1.3	0.85	1043.8	12.8	1044.7	10.2	1046.7	16.9	1046.7	16.9
Spot 10	3.4838	0.8	0.2641	0.6	0.81	1510.7	8.7	1523.5	6.3	1541.4	8.8	1541.4	8.8
Spot 11	3.2896	1.2	0.2563	1.1	0.89	1471.0	14.5	1478.6	9.6	1489.5	10.4	1489.5	10.4
Spot 12	3.3601	1.0	0.2603	0.9	0.91	1491.6	12.2	1495.1	7.9	1500.1	7.9	1500.1	7.9
Spot 13	2.7213	1.0	0.2246	0.8	0.80	1306.3	9.6	1334.3	7.5	1379.5	11.7	1379.5	11.7
Spot 14	2.9977	0.8	0.2438	0.6	0.75	1406.3	7.2	1407.0	5.8	1408.1	9.8	1408.1	9.8
Spot 15	0.5135	0.8	0.0667	0.6	0.77	416.5	2.5	420.8	2.8	444.2	11.4	416.5	2.5
Spot 16	0.5094	1.6	0.0633	1.0	0.59	395.7	3.7	418.0	5.6	543.1	28.9	395.7	3.7
Spot 17	2.6897	1.1	0.2234	1.0	0.89	1300.1	11.3	1325.6	8.0	1367.1	9.4	1367.1	9.4
Spot 18	2.2612	1.6	0.1971	0.8	0.48	1159.9	8.0	1200.3	11.0	1273.6	26.6	1273.6	26.6
Spot 19	1.8393	0.9	0.1764	0.8	0.88	1047.2	7.4	1059.6	5.7	1085.2	8.2	1085.2	8.2
Spot 20	2.8020	0.7	0.2359	0.5	0.67	1365.2	6.1	1356.1	5.5	1341.7	10.6	1341.7	10.6

Spot 21	2.2557	0.9	0.2019	0.7	0.81	1185.5	7.8	1198.6	6.2	1222.1	10.1	1222.1	10.1
Spot 22	1.8744	1.0	0.1824	0.9	0.91	1080.2	8.6	1072.1	6.3	1055.6	8.2	1055.6	8.2
Spot 23	14.1206	0.9	0.5135	0.7	0.81	2671.6	15.8	2757.8	8.4	2821.6	8.4	2821.6	8.4
Spot 24	2.6661	0.8	0.2265	0.6	0.75	1316.3	6.8	1319.1	5.7	1323.6	9.9	1323.6	9.9
Spot 25	3.9652	0.8	0.2829	0.6	0.80	1605.9	8.7	1627.1	6.2	1654.6	8.4	1654.6	8.4
Spot 26	1.9433	1.0	0.1852	0.8	0.86	1095.1	8.5	1096.1	6.5	1098.3	9.8	1098.3	9.8
Spot 27	1.5998	0.7	0.1593	0.5	0.70	953.1	4.5	970.1	4.5	1008.9	10.5	1008.9	10.5
Spot 28	1.8889	1.0	0.1798	0.9	0.89	1066.1	8.5	1077.2	6.4	1099.8	8.6	1099.8	8.6
Spot 29	2.5018	1.5	0.2081	0.8	0.56	1218.6	9.3	1272.6	10.9	1364.8	24.1	1364.8	24.1
Spot 30	1.5029	1.9	0.1552	0.8	0.46	929.9	7.3	931.6	11.4	935.6	34.0	935.6	34.0
Spot 31	1.7321	0.9	0.1710	0.7	0.78	1017.4	6.6	1020.5	5.8	1027.2	11.3	1027.2	11.3
Spot 32	4.8787	1.1	0.3175	1.0	0.90	1777.6	15.8	1798.6	9.5	1823.0	8.7	1823.0	8.7
Spot 33	1.4749	2.0	0.1483	1.9	0.97	891.4	16.1	920.2	12.1	989.9	9.9	989.9	9.9
Spot 34	0.5031	1.0	0.0663	0.8	0.79	413.9	3.2	413.8	3.4	413.1	13.6	413.9	3.2
Spot 35	2.4187	0.8	0.2137	0.6	0.82	1248.5	7.1	1248.2	5.5	1247.5	8.4	1247.5	8.4
Spot 36	2.1329	0.7	0.1964	0.5	0.73	1155.9	5.4	1159.5	4.8	1166.2	9.5	1166.2	9.5
Spot 37	2.4871	0.8	0.2173	0.5	0.68	1267.5	6.1	1268.3	5.6	1269.7	11.1	1269.7	11.1
Spot 38	2.8775	1.6	0.2280	1.5	0.95	1324.2	18.2	1376.0	12.0	1457.5	9.3	1457.5	9.3
Spot 39	2.0866	1.2	0.1941	0.7	0.64	1143.6	7.7	1144.4	7.9	1145.8	17.5	1145.8	17.5
Spot 40	1.6105	1.1	0.1630	1.0	0.87	973.4	8.7	974.3	6.9	976.3	10.9	976.3	10.9
Spot 41	0.5961	1.2	0.0776	0.8	0.65	481.8	3.6	474.7	4.5	440.7	20.2	481.8	3.6
Spot 42	3.9030	0.8	0.2827	0.7	0.87	1604.8	9.9	1614.3	6.5	1626.7	7.3	1626.7	7.3
Spot 43	4.0475	0.7	0.2911	0.6	0.80	1646.9	8.5	1643.8	5.9	1639.8	8.1	1639.8	8.1
Spot 44	0.7418	1.0	0.0896	0.7	0.68	553.2	3.5	563.4	4.1	604.8	15.0	553.2	3.5
Spot 45	13.2073	0.8	0.5077	0.7	0.88	2647.0	16.0	2694.6	7.9	2730.5	6.7	2730.5	6.7
Spot 46	0.8692	0.8	0.1047	0.6	0.67	641.8	3.5	635.1	4.0	611.5	13.6	641.8	3.5
Spot 47	2.0991	0.9	0.1935	0.7	0.77	1140.4	7.1	1148.5	6.0	1163.9	11.1	1163.9	11.1
Spot 48	1.8266	0.9	0.1761	0.6	0.71	1045.6	5.9	1055.1	5.7	1074.8	12.2	1074.8	12.2
Spot 49	1.8340	2.1	0.1746	2.0	0.97	1037.2	19.6	1057.7	13.8	1100.3	9.3	1100.3	9.3
Spot 50	0.4689	1.1	0.0625	0.9	0.78	391.1	3.3	390.4	3.6	386.7	15.8	391.1	3.3
Spot 51	2.9553	1.3	0.2332	1.1	0.85	1351.3	13.5	1396.2	9.8	1465.5	12.8	1465.5	12.8
Spot 52	1.8852	0.9	0.1844	0.9	0.91	1090.8	8.6	1075.9	6.3	1045.9	8.0	1045.9	8.0
Spot 53	1.9297	1.0	0.1804	0.8	0.75	1068.9	7.5	1091.4	6.7	1136.7	13.1	1136.7	13.1
Spot 54	1.8265	0.9	0.1805	0.7	0.79	1069.7	6.7	1055.0	5.6	1024.7	10.5	1024.7	10.5
Spot 55	3.9471	0.9	0.2818	0.7	0.84	1600.3	10.4	1623.4	7.1	1653.4	8.7	1653.4	8.7

Spot 56	1.6397	1.0	0.1613	1.0	0.91	964.1	8.6	985.6	6.6	1033.7	8.6	1033.7	8.6
Spot 57	4.0690	0.8	0.2956	0.6	0.75	1669.2	8.6	1648.1	6.4	1621.3	9.7	1621.3	9.7
Spot 58	4.3906	0.7	0.2996	0.6	0.84	1689.1	9.1	1710.6	6.1	1737.0	7.3	1737.0	7.3
Spot 59	1.9366	0.9	0.1791	0.7	0.79	1062.2	7.1	1093.8	6.2	1157.3	11.3	1157.3	11.3
Spot 60	3.9144	0.8	0.2832	0.7	0.81	1607.7	9.8	1616.7	6.8	1628.3	9.2	1628.3	9.2
Spot 61	0.5641	1.0	0.0712	0.6	0.68	443.3	2.8	454.2	3.5	509.7	15.3	443.3	2.8
Spot 62	1.8630	0.8	0.1784	0.7	0.89	1058.3	7.2	1068.1	5.5	1087.9	7.6	1087.9	7.6
Spot 63	2.9792	1.2	0.2390	1.0	0.82	1381.6	12.3	1402.3	9.3	1434.0	13.5	1434.0	13.5
Spot 64	0.5362	1.1	0.0695	0.8	0.75	432.9	3.4	435.9	3.8	452.1	16.0	432.9	3.4
Spot 65	1.3280	1.6	0.1382	0.6	0.37	834.2	4.6	858.0	9.2	920.0	30.5	834.2	4.6
Spot 66	2.8717	1.2	0.2230	1.0	0.85	1297.8	11.8	1374.5	8.9	1495.8	11.8	1495.8	11.8
Spot 67	1.7943	0.9	0.1751	0.7	0.81	1040.2	6.7	1043.4	5.6	1050.0	10.4	1050.0	10.4
Spot 68	1.6268	0.8	0.1640	0.7	0.81	979.0	6.1	980.6	5.2	984.1	9.8	984.1	9.8
Spot 69	2.3745	1.0	0.2072	0.7	0.75	1213.8	8.1	1235.0	7.0	1272.1	12.5	1272.1	12.5
Spot 70	1.7809	1.0	0.1759	0.8	0.87	1044.6	8.0	1038.5	6.2	1025.6	9.3	1025.6	9.3
Spot 71	1.7635	0.8	0.1738	0.5	0.70	1032.8	5.1	1032.1	4.9	1030.7	10.9	1030.7	10.9
Spot 72	1.7134	0.9	0.1716	0.6	0.68	1020.9	5.8	1013.6	5.8	997.8	13.4	997.8	13.4
Spot 73	0.5180	0.8	0.0681	0.7	0.86	424.9	2.9	423.8	2.8	417.6	9.4	424.9	2.9
Spot 74	2.1957	1.4	0.1982	0.9	0.61	1165.7	9.3	1179.7	9.9	1205.4	22.2	1205.4	22.2
Spot 75	1.9476	1.3	0.1781	1.2	0.90	1056.4	11.4	1097.6	8.7	1180.3	11.2	1180.3	11.2
Spot 76	0.7298	0.9	0.0901	0.7	0.79	556.3	3.8	556.4	3.9	556.9	12.1	556.3	3.8
Spot 77	4.1573	0.8	0.3007	0.5	0.65	1694.5	7.5	1665.6	6.3	1629.4	10.9	1629.4	10.9
Spot 78	2.1392	0.9	0.1966	0.9	0.92	1157.0	9.3	1161.6	6.6	1170.0	7.3	1170.0	7.3
Spot 79	2.3317	0.8	0.2074	0.7	0.87	1215.1	7.9	1222.0	5.8	1234.3	7.9	1234.3	7.9
Spot 80	1.7086	1.6	0.1575	1.5	0.93	943.1	13.2	1011.8	10.3	1163.5	11.7	1163.5	11.7
Spot 81	1.8429	0.9	0.1813	0.6	0.69	1074.2	6.0	1060.9	5.8	1033.6	12.8	1033.6	12.8
Spot 82	3.9714	0.8	0.2814	0.7	0.86	1598.2	9.3	1628.4	6.2	1667.5	7.1	1667.5	7.1
Spot 83	2.8027	1.0	0.2355	0.6	0.65	1363.3	7.9	1356.3	7.4	1345.2	14.6	1345.2	14.6
Spot 84	3.9818	0.7	0.2902	0.6	0.79	1642.4	8.6	1630.5	6.1	1615.2	8.5	1615.2	8.5
Spot 85	1.8937	0.9	0.1832	0.8	0.88	1084.6	7.7	1078.9	5.8	1067.3	8.4	1067.3	8.4
Spot 86	1.8895	0.9	0.1818	0.8	0.87	1076.8	8.0	1077.4	6.1	1078.7	9.0	1078.7	9.0
Spot 87	1.8218	0.9	0.1781	0.7	0.79	1056.4	7.2	1053.3	6.1	1047.0	11.6	1047.0	11.6
Spot 88	2.3892	0.8	0.2135	0.7	0.86	1247.6	8.2	1239.4	6.0	1225.0	8.5	1225.0	8.5
Spot 89	12.4329	0.6	0.4824	0.5	0.82	2537.9	11.1	2637.7	6.1	2715.2	6.1	2715.2	6.1
Spot 90	1.6777	1.1	0.1647	0.6	0.53	982.6	5.5	1000.1	7.3	1038.7	19.7	1038.7	19.7

Spot 91	0.5848	0.9	0.0757	0.6	0.73	470.6	2.9	467.5	3.3	452.2	13.3	470.6	2.9
Spot 92	0.7918	1.0	0.0968	0.8	0.81	595.9	4.4	592.2	4.3	577.9	12.4	595.9	4.4
Spot 93	3.0851	0.9	0.2444	0.7	0.77	1409.5	8.8	1429.0	6.9	1458.1	10.9	1458.1	10.9
Spot 94	0.8353	1.1	0.1017	0.9	0.79	624.5	5.1	616.5	5.0	587.5	14.6	624.5	5.1
Spot 95	1.9127	0.9	0.1803	0.6	0.63	1068.7	5.6	1085.5	6.0	1119.3	14.0	1119.3	14.0
Spot 96	4.1814	0.9	0.2791	0.8	0.91	1586.9	11.5	1670.4	7.4	1776.9	6.9	1776.9	6.9
Spot 97	0.5496	1.2	0.0713	0.7	0.59	444.2	3.0	444.7	4.2	447.6	21.1	444.2	3.0
Spot 98	3.1691	1.0	0.2534	0.9	0.84	1456.0	11.4	1449.7	8.0	1440.4	10.6	1440.4	10.6
Spot 99	2.5865	1.0	0.2206	0.7	0.79	1285.3	8.7	1296.8	7.0	1316.0	11.5	1316.0	11.5
Spot 100	10.1049	0.8	0.4013	0.6	0.77	2174.9	11.0	2444.4	7.2	2677.0	8.3	2677.0	8.3
Spot 101	2.1286	0.9	0.2004	0.6	0.64	1177.3	5.9	1158.1	6.0	1122.4	13.3	1122.4	13.3
Spot 102	1.7259	1.0	0.1732	0.7	0.65	1029.5	6.2	1018.2	6.4	994.2	15.4	994.2	15.4
Spot 103	1.5897	1.2	0.1532	1.2	0.95	919.1	10.1	966.2	7.7	1074.9	8.0	1074.9	8.0
Spot 104	1.9130	0.8	0.1847	0.6	0.81	1092.8	6.2	1085.6	5.1	1071.2	9.0	1071.2	9.0
Spot 105	14.6121	1.0	0.5447	0.8	0.85	2803.2	19.2	2790.3	9.5	2781.0	8.6	2781.0	8.6
Spot 106	1.7076	1.0	0.1694	0.5	0.57	1008.6	5.1	1011.4	6.2	1017.4	16.2	1017.4	16.2
Spot 107	12.8829	0.8	0.5029	0.7	0.85	2626.1	14.4	2671.1	7.4	2705.4	6.9	2705.4	6.9
Spot 108	15.5201	0.8	0.5749	0.7	0.88	2928.0	15.6	2847.7	7.2	2791.4	5.8	2791.4	5.8
Spot 109	2.0702	0.9	0.1847	0.7	0.83	1092.5	7.3	1139.0	6.0	1228.8	9.6	1228.8	9.6
Spot 110	1.8793	1.3	0.1796	1.0	0.82	1064.9	10.1	1073.8	8.4	1091.9	14.6	1091.9	14.6
Spot 111	0.4535	1.4	0.0604	1.1	0.79	378.2	4.0	379.7	4.4	388.7	19.0	378.2	4.0
Spot 112	1.8540	0.9	0.1785	0.7	0.84	1058.9	7.1	1064.8	5.7	1077.0	9.4	1077.0	9.4
Spot 113	2.5290	0.8	0.2223	0.7	0.83	1293.9	8.3	1280.4	6.1	1257.9	9.1	1257.9	9.1
Spot 114	3.2951	0.8	0.2612	0.7	0.77	1495.7	8.7	1479.9	6.6	1457.2	10.2	1457.2	10.2
Spot 115	1.7027	1.0	0.1718	0.7	0.69	1022.3	6.5	1009.5	6.3	982.1	14.5	982.1	14.5
Spot 116	1.6967	0.8	0.1718	0.7	0.80	1022.1	6.2	1007.3	5.2	975.2	9.9	975.2	9.9
Spot 117	1.6085	1.3	0.1569	1.2	0.89	939.4	10.1	973.5	8.2	1051.3	12.3	1051.3	12.3
Spot 118	2.1546	0.7	0.1998	0.6	0.84	1174.3	6.2	1166.5	4.7	1152.2	7.3	1152.2	7.3
Spot 119	14.9491	0.7	0.5378	0.6	0.84	2774.1	13.8	2812.0	6.9	2839.3	6.4	2839.3	6.4
Spot 120	2.7206	2.8	0.2201	1.1	0.40	1282.2	13.0	1334.1	20.7	1418.3	48.7	1418.3	48.7
Spot 121	0.7657	0.9	0.0953	0.6	0.65	586.7	3.4	577.3	4.1	540.3	15.7	586.7	3.4
Spot 122	2.3430	0.9	0.2035	0.8	0.87	1194.3	8.8	1225.4	6.6	1280.7	8.9	1280.7	8.9
Spot 123	2.7931	0.8	0.2310	0.7	0.88	1339.7	9.0	1353.7	6.3	1375.8	7.7	1375.8	7.7
Spot 124	0.5538	2.3	0.0735	1.9	0.81	457.2	8.4	447.5	8.5	398.2	31.0	457.2	8.4
Spot 125	3.4095	0.9	0.2650	0.7	0.76	1515.4	8.8	1506.6	6.7	1494.3	10.5	1494.3	10.5

Spot 126	1.6606	0.7	0.1679	0.5	0.67	1000.5	4.4	993.6	4.4	978.5	10.6	978.5	10.6
Spot 127	1.7409	0.9	0.1719	0.6	0.76	1022.8	6.1	1023.8	5.5	1025.9	11.2	1025.9	11.2
Spot 128	1.8735	0.8	0.1805	0.7	0.79	1069.6	6.4	1071.8	5.5	1076.3	10.1	1076.3	10.1
Spot 129	3.2640	0.8	0.2539	0.7	0.86	1458.5	8.5	1472.5	5.9	1492.8	7.4	1492.8	7.4
Spot 130	2.2929	0.9	0.2086	0.8	0.82	1221.2	8.4	1210.1	6.5	1190.5	10.4	1190.5	10.4
Spot 131	2.1559	1.7	0.2002	1.0	0.58	1176.6	10.9	1167.0	12.1	1149.1	28.2	1149.1	28.2
Spot 132	3.9465	1.1	0.2912	0.9	0.84	1647.3	13.6	1623.3	9.0	1592.3	11.1	1592.3	11.1
Spot 133	4.8040	1.4	0.3200	1.3	0.88	1789.8	19.9	1785.6	12.1	1780.6	12.3	1780.6	12.3
Spot 134	1.7644	0.7	0.1753	0.6	0.80	1041.4	5.6	1032.5	4.7	1013.5	8.8	1013.5	8.8
Spot 135	0.5262	1.1	0.0683	0.8	0.70	425.6	3.1	429.3	3.8	449.1	17.3	425.6	3.1
Spot 136	1.7621	0.8	0.1647	0.7	0.87	983.0	6.3	1031.6	5.1	1136.3	7.7	1136.3	7.7
Spot 137	2.0360	1.9	0.1851	1.5	0.75	1095.0	14.6	1127.6	13.2	1191.0	25.2	1191.0	25.2
Spot 138	3.8459	1.0	0.2787	0.9	0.87	1584.7	12.3	1602.4	8.1	1625.8	9.4	1625.8	9.4
Spot 139	3.3177	0.9	0.2625	0.7	0.71	1502.9	8.8	1485.2	7.2	1460.1	12.2	1460.1	12.2
Spot 140	0.7394	1.5	0.0920	1.0	0.71	567.4	5.6	562.0	6.3	540.3	22.3	567.4	5.6
Spot 141	15.9955	0.9	0.5723	0.8	0.85	2917.1	18.9	2876.5	9.0	2848.2	8.0	2848.2	8.0
Spot 142	2.7260	0.7	0.2293	0.6	0.85	1331.0	7.4	1335.6	5.4	1343.0	7.4	1343.0	7.4
Spot 143	0.4873	1.0	0.0650	0.7	0.71	406.1	2.8	403.1	3.3	385.5	15.5	406.1	2.8
Spot 144	0.6651	1.5	0.0834	0.9	0.55	516.5	4.2	517.7	6.2	523.2	28.1	516.5	4.2
Spot 145	0.9312	4.6	0.0806	2.4	0.52	499.9	11.7	668.2	22.7	1286.9	76.9	499.9	11.7
Spot 146	0.7642	1.0	0.0945	0.6	0.63	582.3	3.6	576.4	4.5	553.3	17.3	582.3	3.6
Spot 147	9.6891	0.9	0.4359	0.7	0.85	2332.3	14.6	2405.7	8.0	2468.3	7.7	2468.3	7.7
Spot 148	4.2074	0.8	0.2983	0.7	0.82	1682.7	10.0	1675.5	6.7	1666.4	8.6	1666.4	8.6
Spot 149	0.7549	0.9	0.0931	0.5	0.59	574.1	2.9	571.0	3.9	559.1	15.7	574.1	2.9
Spot 150	4.1464	1.2	0.2947	0.8	0.66	1664.9	11.4	1663.5	9.7	1661.7	16.5	1661.7	16.5
Spot 151	0.4708	5.1	0.0564	1.3	0.25	353.4	4.5	391.7	16.6	624.7	106.6	353.4	4.5
Spot 152	1.8142	0.7	0.1762	0.5	0.71	1046.2	4.5	1050.6	4.3	1059.9	9.4	1059.9	9.4
Spot 153	1.7561	1.6	0.1724	1.4	0.93	1025.5	13.7	1029.4	10.0	1037.8	11.5	1037.8	11.5
Spot 154	1.4976	0.8	0.1552	0.7	0.86	929.9	6.0	929.4	4.9	928.3	8.5	928.3	8.5
Spot 155	1.6803	1.0	0.1641	0.7	0.69	979.6	6.0	1001.1	6.1	1048.4	14.0	1048.4	14.0
Spot 156	0.6966	2.2	0.0878	0.9	0.40	542.8	4.6	536.7	9.0	511.2	43.6	542.8	4.6
Spot 157	11.2883	1.1	0.4786	1.0	0.91	2521.1	21.3	2547.2	10.4	2568.1	7.6	2568.1	7.6
Spot 158	1.8026	1.1	0.1749	1.0	0.90	1038.9	9.7	1046.4	7.3	1062.2	9.6	1062.2	9.6
Spot 159	1.7416	0.9	0.1712	0.7	0.79	1018.9	6.7	1024.1	5.8	1035.2	11.2	1035.2	11.2
Spot 160	2.0230	1.3	0.1884	1.3	0.94	1112.4	12.9	1123.3	9.1	1144.2	9.1	1144.2	9.1

Spot 161	0.5003	1.1	0.0659	0.6	0.57	411.4	2.6	411.9	3.9	414.6	21.0	411.4	2.6
Spot 162	2.9770	1.2	0.2361	1.1	0.92	1366.5	13.8	1401.8	9.2	1455.8	9.0	1455.8	9.0
Spot 163	1.7275	0.8	0.1740	0.6	0.75	1034.3	6.1	1018.8	5.4	985.8	11.3	985.8	11.3
Spot 164	2.9310	0.8	0.2402	0.6	0.77	1387.9	7.5	1389.9	5.9	1393.0	9.5	1393.0	9.5
Spot 165	3.5958	0.7	0.2731	0.6	0.83	1556.4	8.5	1548.6	5.9	1538.0	7.7	1538.0	7.7
Spot 166	2.5341	0.8	0.2224	0.5	0.69	1294.7	6.1	1281.9	5.5	1260.4	10.7	1260.4	10.7
Spot 167	1.6661	1.0	0.1672	0.8	0.80	996.4	7.2	995.7	6.2	994.2	11.8	994.2	11.8
Spot 168	5.7387	0.8	0.3308	0.6	0.75	1842.4	9.1	1937.2	6.5	2040.2	8.7	2040.2	8.7
Spot 169	0.5232	1.0	0.0697	0.8	0.78	434.3	3.4	427.3	3.6	389.5	14.6	434.3	3.4
Spot 170	0.5626	1.1	0.0729	0.9	0.81	453.8	4.1	453.2	4.2	450.1	14.8	453.8	4.1
Spot 171	1.7306	1.0	0.1711	0.9	0.87	1017.9	8.3	1020.0	6.6	1024.4	10.2	1024.4	10.2
Spot 172	1.7628	1.2	0.1714	1.1	0.95	1019.9	10.5	1031.9	7.5	1057.3	7.0	1057.3	7.0
Spot 173	1.6168	0.8	0.1656	0.6	0.71	988.0	5.5	976.7	5.3	951.4	12.2	951.4	12.2
Spot 174	0.4283	1.1	0.0591	0.6	0.55	369.8	2.2	362.0	3.4	311.7	21.6	369.8	2.2
Spot 175	3.5632	1.0	0.2694	0.7	0.68	1537.7	9.4	1541.4	8.0	1546.4	13.8	1546.4	13.8
Spot 176	1.6067	0.8	0.1625	0.5	0.64	970.6	4.4	972.8	4.7	978.0	11.8	978.0	11.8
Spot 177	0.4967	1.9	0.0657	1.1	0.57	410.2	4.3	409.5	6.3	405.2	34.3	410.2	4.3
Spot 178	2.0858	0.9	0.1909	0.8	0.85	1126.5	8.1	1144.1	6.3	1177.7	9.4	1177.7	9.4
Spot 179	1.7726	0.7	0.1726	0.6	0.79	1026.6	5.4	1035.5	4.7	1054.3	8.8	1054.3	8.8
Spot 180	2.5737	0.8	0.2234	0.6	0.70	1299.9	6.7	1293.2	5.9	1282.0	11.3	1282.0	11.3
Spot 181	0.7578	1.5	0.0901	0.8	0.56	555.9	4.4	572.7	6.5	640.0	26.3	555.9	4.4
Spot 182	1.6788	1.0	0.1693	0.8	0.78	1008.4	7.1	1000.5	6.2	983.4	12.3	983.4	12.3
Spot 183	1.0666	1.1	0.1221	0.8	0.69	742.7	5.4	737.1	5.8	720.0	17.0	742.7	5.4
Spot 184	1.5757	1.2	0.1611	0.7	0.57	962.8	6.3	960.7	7.6	955.8	20.6	955.8	20.6
Spot 185	0.8259	1.5	0.1011	0.6	0.42	620.8	3.7	611.4	6.8	576.6	29.3	620.8	3.7
Spot 186	2.4917	0.8	0.2149	0.7	0.85	1255.1	8.2	1269.6	6.1	1294.4	8.7	1294.4	8.7
Spot 187	1.9656	1.0	0.1879	0.9	0.92	1110.0	9.1	1103.8	6.6	1091.7	7.9	1091.7	7.9
Spot 188	1.7356	0.8	0.1731	0.5	0.69	1029.3	5.0	1021.8	4.9	1005.8	11.1	1005.8	11.1
Spot 189	0.6958	0.9	0.0868	0.6	0.70	536.4	3.2	536.3	3.7	535.7	13.9	536.4	3.2
Spot 190	3.3080	0.8	0.2565	0.7	0.85	1472.0	8.9	1482.9	6.2	1498.6	8.0	1498.6	8.0
Spot 191	4.0156	0.9	0.2852	0.7	0.84	1617.4	10.5	1637.4	7.0	1663.1	8.6	1663.1	8.6
Spot 192	10.6693	1.0	0.4700	0.9	0.83	2483.4	17.7	2494.8	9.6	2504.0	9.6	2504.0	9.6
Spot 193	3.3286	0.8	0.2601	0.7	0.87	1490.4	9.7	1487.8	6.5	1484.0	7.8	1484.0	7.8
Spot 194	0.5861	2.7	0.0689	1.3	0.49	429.6	5.5	468.4	10.1	663.4	50.6	429.6	5.5
Spot 195	0.7978	1.1	0.0986	0.9	0.85	606.0	5.5	595.6	5.1	556.1	13.1	606.0	5.5

Spot 196	9.9791	1.9	0.4419	1.8	0.97	2359.0	36.0	2432.9	17.3	2495.2	7.8	2495.2	7.8
Spot 197	2.0624	0.8	0.1948	0.5	0.58	1147.2	5.2	1136.4	5.8	1115.9	13.8	1115.9	13.8
Spot 198	13.0831	0.7	0.5000	0.6	0.82	2614.0	12.9	2685.7	6.8	2740.1	6.7	2740.1	6.7
Spot 199	1.7422	1.0	0.1725	0.8	0.76	1026.0	7.4	1024.3	6.6	1020.6	13.3	1020.6	13.3
Spot 200	2.4897	1.1	0.2198	0.7	0.69	1280.6	8.6	1269.0	7.8	1249.5	15.4	1249.5	15.4
Spot 201	15.5839	0.8	0.5527	0.7	0.85	2836.5	16.6	2851.6	8.1	2862.3	7.2	2862.3	7.2
Spot 202	2.5134	0.9	0.2183	0.7	0.80	1272.9	8.7	1275.9	6.8	1280.9	11.0	1280.9	11.0
Spot 203	1.7013	0.7	0.1687	0.5	0.82	1004.9	5.1	1009.0	4.3	1018.0	7.7	1018.0	7.7
Spot 204	1.7479	0.7	0.1701	0.6	0.84	1012.7	5.8	1026.4	4.8	1055.7	8.1	1055.7	8.1
Spot 205	2.4917	0.9	0.2158	0.8	0.84	1259.6	9.0	1269.6	6.8	1286.5	9.7	1286.5	9.7
Spot 206	1.7357	1.0	0.1712	0.9	0.89	1018.7	8.4	1021.9	6.4	1028.7	9.3	1028.7	9.3
Spot 207	1.8366	0.9	0.1752	0.8	0.83	1040.7	7.3	1058.7	6.1	1095.9	10.4	1095.9	10.4
Spot 208	3.2395	0.9	0.2532	0.9	0.95	1454.9	11.6	1466.7	7.3	1483.7	5.5	1483.7	5.5
Spot 209	1.9594	0.9	0.1869	0.6	0.65	1104.3	6.1	1101.7	6.2	1096.4	14.1	1096.4	14.1
Spot 210	5.5527	2.0	0.3321	1.9	0.97	1848.5	30.7	1908.8	16.9	1975.0	8.1	1975.0	8.1
Spot 211	1.7123	0.8	0.1700	0.7	0.80	1012.1	6.2	1013.1	5.3	1015.4	10.0	1015.4	10.0
Spot 212	1.6101	1.0	0.1641	0.7	0.69	979.6	6.2	974.2	6.2	961.9	14.7	961.9	14.7
Spot 213	6.7246	2.1	0.3849	2.0	0.97	2099.1	36.1	2075.9	18.4	2052.9	9.4	2052.9	9.4
Spot 214	1.7657	1.0	0.1743	0.9	0.92	1035.9	8.7	1033.0	6.4	1026.8	7.9	1026.8	7.9
Spot 215	5.1353	1.0	0.3231	0.9	0.89	1805.0	14.3	1842.0	8.7	1884.0	8.5	1884.0	8.5
Spot 216	1.9383	1.0	0.1847	0.9	0.85	1092.8	8.9	1094.4	7.0	1097.7	11.1	1097.7	11.1
Spot 217	1.7984	0.9	0.1771	0.6	0.69	1051.3	5.8	1044.9	5.6	1031.4	12.7	1031.4	12.7
Spot 218	3.3980	1.3	0.2628	1.2	0.92	1504.1	15.6	1503.9	9.9	1503.6	9.4	1503.6	9.4
Spot 219	0.7354	1.2	0.0864	0.5	0.45	534.5	2.7	559.7	5.1	663.8	22.8	534.5	2.7
Spot 220	1.7943	1.0	0.1768	0.8	0.77	1049.5	7.3	1043.4	6.3	1030.5	12.5	1030.5	12.5
Spot 221	13.5204	2.2	0.5298	2.2	0.98	2740.5	49.1	2716.7	21.2	2699.0	6.9	2699.0	6.9
Spot 222	0.5530	1.6	0.0702	0.6	0.40	437.1	2.6	446.9	5.6	497.9	31.4	437.1	2.6
Spot 223	0.8377	2.8	0.0826	0.7	0.24	511.4	3.3	617.9	12.8	1030.1	54.0	511.4	3.3
Spot 224	3.2935	0.9	0.2554	0.8	0.87	1466.4	10.4	1479.5	7.1	1498.3	8.4	1498.3	8.4
Spot 225	1.8269	0.8	0.1752	0.7	0.85	1040.5	6.8	1055.2	5.4	1085.7	8.7	1085.7	8.7
Spot 226	3.3644	1.0	0.2530	0.9	0.82	1453.9	11.2	1496.1	8.2	1556.4	11.1	1556.4	11.1
Spot 227	0.6313	1.9	0.0736	1.4	0.72	457.6	6.0	496.9	7.4	682.4	27.8	457.6	6.0
Spot 228	1.6472	1.2	0.1670	0.9	0.76	995.7	8.3	988.5	7.5	972.4	15.7	972.4	15.7
Spot 229	1.1939	1.2	0.1238	1.1	0.89	752.5	7.9	797.8	6.9	926.3	11.5	752.5	7.9
Spot 230	1.1361	1.1	0.1268	0.9	0.78	769.8	6.3	770.6	6.0	773.0	14.7	769.8	6.3

Spot 231	1.7665	0.8	0.1731	0.7	0.81	1029.0	6.6	1033.2	5.5	1042.3	10.0	1042.3	10.0
Spot 232	0.4786	0.8	0.0627	0.7	0.79	392.3	2.5	397.1	2.8	425.3	11.5	392.3	2.5
Spot 233	1.5911	1.7	0.1572	0.7	0.42	941.1	6.2	966.7	10.4	1025.4	30.7	1025.4	30.7
Spot 234	0.5074	0.7	0.0668	0.6	0.81	416.9	2.4	416.7	2.5	415.7	9.7	416.9	2.4
Spot 235	1.7150	1.0	0.1692	0.8	0.85	1007.8	7.8	1014.1	6.3	1027.9	10.5	1027.9	10.5
Spot 236	4.5634	0.7	0.3088	0.6	0.81	1734.6	8.5	1742.6	5.7	1752.2	7.3	1752.2	7.3
Spot 237	2.0490	1.0	0.1924	0.7	0.77	1134.6	7.7	1132.0	6.6	1126.9	12.4	1126.9	12.4
Spot 238	2.8989	1.0	0.2335	0.9	0.89	1352.9	11.3	1381.6	7.9	1426.2	9.3	1426.2	9.3
Spot 239	1.9095	1.5	0.1813	0.8	0.53	1073.8	8.0	1084.4	10.2	1105.7	26.0	1105.7	26.0
Spot 240	3.0881	1.0	0.2467	0.9	0.89	1421.6	11.4	1429.7	7.7	1441.9	8.9	1441.9	8.9
Spot 241	12.4056	1.0	0.4882	0.9	0.92	2562.7	19.9	2635.6	9.7	2692.0	6.7	2692.0	6.7
Spot 242	1.8825	0.9	0.1778	0.7	0.72	1055.0	6.6	1075.0	6.2	1115.7	12.9	1115.7	12.9
Spot 243	1.8518	1.0	0.1791	0.8	0.78	1061.8	7.5	1064.1	6.5	1068.7	12.3	1068.7	12.3
Spot 244	3.1257	0.8	0.2509	0.6	0.76	1443.4	7.9	1439.0	6.2	1432.6	10.0	1432.6	10.0
Spot 245	4.9517	0.8	0.3280	0.6	0.74	1828.7	9.8	1811.1	7.0	1790.9	10.2	1790.9	10.2
Spot 246	2.0799	0.8	0.1923	0.7	0.82	1133.8	7.1	1142.2	5.8	1158.2	9.6	1158.2	9.6
Spot 247	3.9305	0.9	0.2869	0.8	0.88	1626.1	10.9	1620.0	7.0	1612.0	7.7	1612.0	7.7
Spot 248	1.7534	0.9	0.1723	0.8	0.86	1024.8	7.5	1028.4	5.9	1036.0	9.5	1036.0	9.5
Spot 249	2.2359	0.8	0.2039	0.6	0.74	1196.2	6.3	1192.4	5.5	1185.4	10.4	1185.4	10.4
Spot 250	2.9522	1.5	0.2367	1.4	0.91	1369.3	17.3	1395.4	11.7	1435.5	11.9	1435.5	11.9
Spot 251	2.2994	0.9	0.2074	0.5	0.58	1214.8	5.7	1212.1	6.3	1207.3	14.4	1207.3	14.4
Spot 252	0.7877	1.4	0.0953	1.2	0.82	586.8	6.5	589.9	6.3	601.6	17.1	586.8	6.5
Spot 253	2.1736	1.3	0.1952	1.1	0.87	1149.7	11.6	1172.6	8.7	1215.2	12.1	1215.2	12.1
Spot 254	2.2151	1.2	0.1958	1.0	0.85	1152.7	10.4	1185.8	8.1	1246.7	12.0	1246.7	12.0
Spot 255	1.6998	0.8	0.1695	0.4	0.56	1009.3	4.1	1008.4	5.1	1006.6	13.4	1006.6	13.4
Spot 256	0.7694	1.3	0.0919	1.0	0.73	566.5	5.3	579.4	5.8	630.3	19.3	566.5	5.3
Spot 257	3.1460	0.7	0.2527	0.6	0.80	1452.5	7.2	1444.0	5.3	1431.5	7.9	1431.5	7.9
Spot 258	3.2138	0.7	0.2586	0.6	0.83	1482.5	7.3	1460.5	5.2	1428.7	7.2	1428.7	7.2
Spot 259	0.4698	2.6	0.0630	2.5	0.97	394.1	9.6	391.0	8.4	373.0	13.8	394.1	9.6
Spot 260	3.1203	1.3	0.2495	1.0	0.79	1436.0	12.8	1437.7	9.6	1440.2	14.5	1440.2	14.5
Spot 261	2.0025	1.5	0.1812	1.3	0.88	1073.6	13.0	1116.4	10.1	1200.5	13.9	1200.5	13.9
Spot 262	0.4696	1.1	0.0629	0.8	0.77	393.2	3.1	390.9	3.4	377.3	15.2	393.2	3.1
Spot 263	2.1702	1.0	0.2009	0.6	0.66	1180.0	6.9	1171.6	6.7	1156.0	14.5	1156.0	14.5
Spot 264	2.0337	0.9	0.1920	0.6	0.69	1132.4	6.7	1126.8	6.4	1116.1	13.7	1116.1	13.7
Spot 265	1.7343	0.9	0.1745	0.6	0.65	1036.8	5.5	1021.4	5.7	988.4	13.7	988.4	13.7

Spot 266	1.8439	1.5	0.1786	0.9	0.61	1059.3	8.8	1061.2	9.8	1065.3	23.7	1065.3	23.7
Spot 267	2.7503	0.9	0.2321	0.8	0.84	1345.5	9.3	1342.2	6.8	1336.8	9.7	1336.8	9.7
Spot 268	0.6019	2.1	0.0736	1.3	0.61	457.8	5.6	478.5	8.0	578.7	36.4	457.8	5.6
Spot 269	2.4168	1.3	0.1954	1.2	0.93	1150.7	12.4	1247.6	9.1	1418.9	9.2	1418.9	9.2
Spot 270	0.8884	1.2	0.1042	1.1	0.87	639.1	6.5	645.5	5.9	667.9	12.9	639.1	6.5
Spot 271	1.9558	0.8	0.1886	0.7	0.78	1113.9	6.8	1100.4	5.7	1074.0	10.6	1074.0	10.6
Spot 272	1.8570	2.3	0.1725	0.8	0.37	1025.9	7.9	1065.9	14.9	1148.7	41.7	1148.7	41.7
Spot 273	1.5876	1.1	0.1596	1.0	0.92	954.3	8.9	965.4	6.8	990.6	8.4	990.6	8.4
Spot 274	1.7879	1.0	0.1740	0.8	0.88	1033.9	8.1	1041.0	6.3	1056.2	9.1	1056.2	9.1
Spot 275	1.9356	1.5	0.1830	0.7	0.51	1083.2	7.4	1093.5	9.8	1114.1	25.2	1114.1	25.2
Spot 276	2.7206	0.8	0.2305	0.7	0.82	1337.1	8.2	1334.1	6.1	1329.2	9.0	1329.2	9.0
Spot 277	0.6197	1.3	0.0816	0.6	0.46	505.5	2.9	489.6	5.0	416.0	25.5	505.5	2.9
Spot 278	13.6120	0.8	0.5155	0.7	0.87	2680.2	15.1	2723.1	7.5	2755.1	6.3	2755.1	6.3
Spot 279	3.3666	0.8	0.2634	0.6	0.79	1507.0	8.0	1496.7	5.9	1482.1	8.9	1482.1	8.9
Spot 280	2.0464	0.9	0.1899	0.8	0.83	1120.8	7.8	1131.1	6.3	1150.8	10.4	1150.8	10.4
Spot 281	2.2190	0.9	0.2033	0.6	0.67	1193.0	6.5	1187.1	6.2	1176.3	13.0	1176.3	13.0
Spot 282	2.8212	1.0	0.2344	0.7	0.74	1357.4	9.0	1361.2	7.4	1367.1	12.9	1367.1	12.9
Spot 283	1.6730	2.1	0.1650	0.8	0.40	984.3	7.6	998.3	13.2	1029.2	38.3	1029.2	38.3
Spot 284	1.9895	1.0	0.1876	1.0	0.92	1108.3	9.7	1112.0	7.1	1119.2	8.4	1119.2	8.4
Spot 285	0.7419	0.9	0.0898	0.7	0.84	554.1	3.9	563.5	3.8	601.6	10.3	554.1	3.9
Spot 286	1.5155	1.6	0.1578	0.9	0.57	944.5	7.9	936.6	9.6	918.2	26.4	918.2	26.4
Spot 287	2.5697	0.9	0.2162	0.8	0.89	1261.9	9.4	1292.0	6.8	1342.4	8.1	1342.4	8.1
Spot 288	1.9325	0.9	0.1786	0.7	0.80	1059.2	6.9	1092.4	5.9	1159.2	10.5	1159.2	10.5

APPENDIX B: Detrital Zircon Hf Data

Table 2. Detrital zircon Hf data for the Cottage Grove Sandstone.

Analysis	$(^{176}Yb+^{176}Lu)/^{176}Hf$ (%)	Volts Hf	$^{176}Hf/^{177}Hf$	± (2σ)	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf(T)$	E-Hf(0)	E-Hf(0)±(2σ)	E-Hf(T)	Age (Ma)
CG										
Spot 104	16.8	8.01	0.28167	3.0E-05	0.00113	0.28163	-39.3	1.1	-0.6	1776.9
Spot 245	41.8	5.93	0.28249	3.0E-05	0.00277	0.28247	-10.4	1.1	-1.5	437.1
Spot 188	14.4	10.05	0.28223	3.2E-05	0.00099	0.28222	-19.6	1.1	-9.8	453.8
Spot 106	7.2	5.92	0.28196	3.4E-05	0.00045	0.28195	-29.0	1.2	2.9	1440.4
Spot 277	7.5	6.29	0.28263	3.8E-05	0.00062	0.28262	-5.6	1.3	7.3	586.8
Spot 155	13.6	5.88	0.28260	3.9E-05	0.00098	0.28259	-6.4	1.4	5.9	567.4
Spot 102	14.3	8.74	0.28238	4.0E-05	0.00076	0.28237	-14.4	1.4	-0.8	624.5
Spot 44	24.8	6.07	0.28213	4.3E-05	0.00201	0.28207	-23.0	1.5	11.4	1626.7
Spot 26	28.0	5.52	0.28188	4.3E-05	0.00170	0.28183	-32.0	1.5	3.4	1654.6
Spot 17	42.8	7.86	0.28245	4.3E-05	0.00248	0.28243	-11.8	1.5	-3.7	395.7
Spot 29	14.8	8.56	0.28232	4.3E-05	0.00094	0.28230	-16.4	1.5	7.6	1099.8
Spot 293	34.4	8.03	0.28246	4.5E-05	0.00226	0.28244	-11.6	1.6	-2.1	457.8
Spot 59	21.0	6.25	0.28241	4.5E-05	0.00141	0.28238	-13.3	1.6	8.9	1033.7
Spot 228	15.9	6.55	0.28189	4.7E-05	0.00100	0.28186	-31.6	1.7	0.8	1483.7
Spot 190	25.5	6.56	0.28218	4.8E-05	0.00147	0.28215	-21.3	1.7	1.4	1057.3
Spot 215	24.1	7.00	0.28234	5.0E-05	0.00143	0.28232	-15.9	1.8	-2.9	606.0
Spot 256	30.2	7.73	0.28257	5.0E-05	0.00175	0.28255	-7.7	1.8	0.6	392.3
Spot 162	23.2	5.20	0.28227	5.1E-05	0.00119	0.28226	-18.2	1.8	-5.7	582.3
Spot 82	4.9	6.34	0.28199	5.3E-05	0.00027	0.28199	-28.1	1.9	-15.8	556.3
Spot 178	14.0	6.18	0.28245	5.5E-05	0.00092	0.28244	-11.9	1.9	-3.0	411.4
Spot 120	27.4	7.13	0.28235	5.5E-05	0.00155	0.28232	-15.4	1.9	7.6	1077.0
Spot 18	15.4	9.28	0.28225	6.4E-05	0.00110	0.28222	-19.1	2.3	10.7	1367.1
Spot 142	13.2	6.57	0.28192	6.7E-05	0.00081	0.28190	-30.6	2.4	2.1	1492.8
Spot 46	17.2	5.77	0.28281	6.7E-05	0.00106	0.28280	0.8	2.4	12.8	553.2
Spot 157	18.3	8.20	0.28221	7.0E-05	0.00150	0.28217	-20.3	2.5	8.5	1343.0
Spot 214	57.6	5.47	0.28268	7.8E-05	0.00348	0.28266	-3.5	2.7	5.0	429.6

APPENDIX C: Avant "Hot" Shale Marker Structure Map

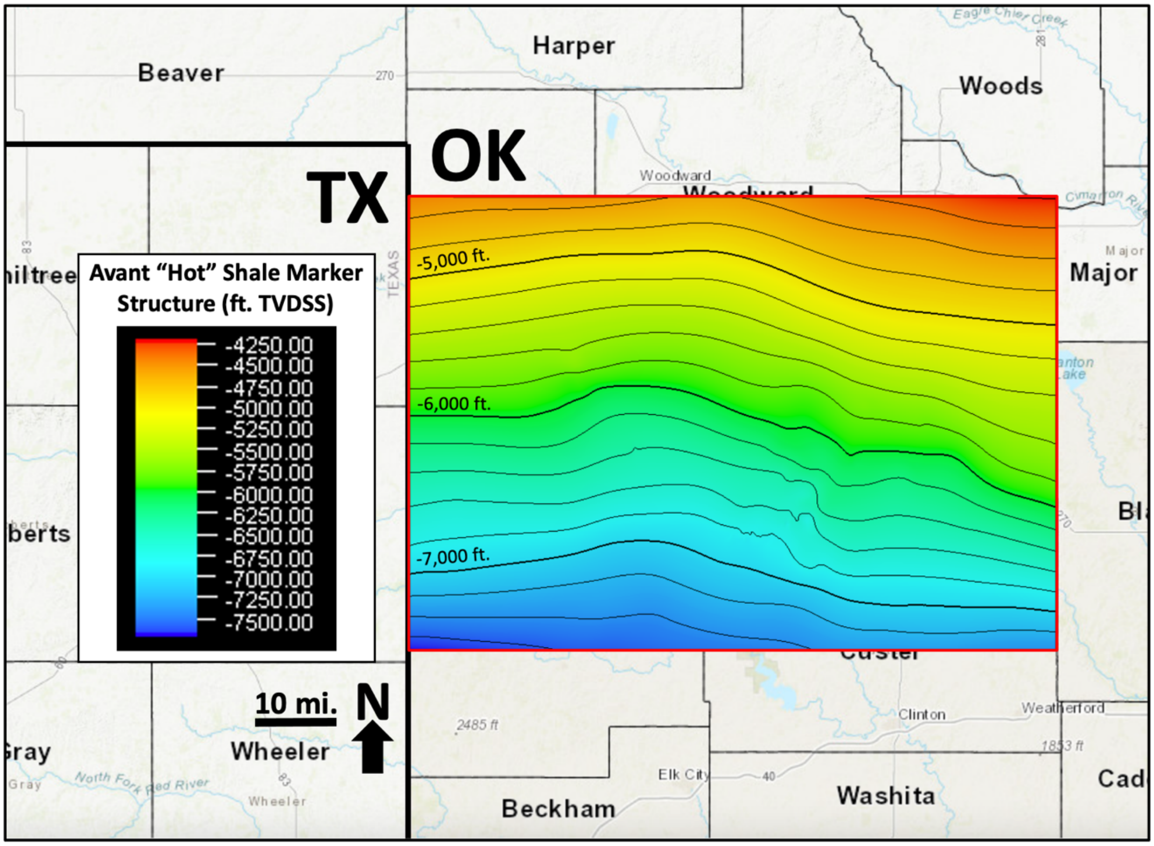

Figure 29. Avant "hot" shale marker structure map in feet total vertical depth subsea (TVDSS) (C.I. = 200 feet) for the general study area in the northern Anadarko Basin, northwest Oklahoma. The red rectangle denotes the general study area. This map was constructed using 160 formation tops.

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