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Sequence Stratigraphic and Tectono-Stratigraphic Successions, Ozark Shelf, Tri-State Region, Southern Midcontinent

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Running Title: Tectono-Stratigraphy of Ozark Shelf, Southern Midcontinent

Abstract

The southern Ozark region, Arkansas, Missouri, and Oklahoma occupies the southern border of the North American craton. Its sedimentary succession preserves a complete Wilson Cycle reflecting the Late Precambrian-Cambrian rifting of Rodinia into the Laurussian and Gondwanan landmasses that opened the Iapetus Ocean Basin during the Late Cambrian-Middle Mississippian. The basin was closed during the Late Mississippian-Middle Pennsylvanian by the collision of Laurussia with Gondwana. During the Late Cambrian through the Middle Pennsylvanian, the Ozark Shelf, including its gently sloping, Northern Arkansas Structural Platform (NASP) and adjacent ramp, records both transgression and regression by epeiric seas as well as regional tectonism that can be recognized as five Tectono-Stratigraphic Successions (TS) and correlated readily with the Sloss Cratonic Sequences. The TS record comprises at least 33 named formations with a potential thickness >2926m (9600ft). However, both eustatic and tectonic sea-level rise and fall also produced regional surfaces of erosion that punctuated deposition, and the preserved thickness on the NASP is significantly less. The five distinct, but related, Tectono-stratigraphic Successions in the Paleozoic record are (TS1) Late Precambrian-Middle Cambrian, (TS2) Upper Cambrian-lowest Ordovician, (TS3) Lower Ordovician-Lower Devonian, (TS4) Middle Devonian-Upper Mississippian, and (TS5) Lower-Middle Pennsylvanian. TS1, a pre-Late Sauk Sequence, is the least well-known succession, consisting of emplaced igneous and low-ranked metasedimentary bodies and pre-Lamotte sedimentary rocks. TS2, Late Sauk Sequence, is potentially >937m (3075ft) of dolomites and sandstones. TS3, Tippecanoe Sequence, is the penultimate thickest interval, possibly >1257m (4125ft) of dolomites, limestones, shales, and supermature sandstones. TS4, Kaskaskia Sequence, measures at least 736m (2416ft). The final TS5, Lower Absaroka Sequence of first cycle sandstones with variable amounts of mrfs, and shales is the thickest interval, >1267m (4160ft) and may exceed 7620m (25,000ft) in the adjacent Arkoma Basin.

Relationship of Sequence Stratigraphy and Tectonostratigraphy

Depending on their setting, lithostratigraphic successions may reflect two independent, but potentially simultaneous processes: 1) *eustasy* – change in the total volume of global seawater, producing a stratigraphic sequence record, and 2) *tectonism* – change in elevation of earth's crust; uplift or subsidence, providing or reducing accommodation space. Recognition of the effects of these two processes on the geologic record provides the basis for its tectono-stratigraphic divisions.

Sequence Stratigraphy – Although thought to be a relatively new concept, the basic concepts and foundation of sequence stratigraphy were already laid in the 19th century, and developed further through the first-half of the 20th century. Most of the modern understanding of sequence stratigraphy has evolved from the concepts of cratonic sequences published by L. L. Sloss (1963). He recognized that the stratigraphic record of the North American craton (late Precambrian to the present) was punctuated by six, essentially cratonwide, unconformities that defined six successive groupings of strata, or sequences. A complete sequence can be divided into lowstand, transgression, maximum flooding, highstand and regression, although location on the craton influences development of individual stages and some sequences may not be complete (see Sloss 1963, Van Wagoner *et al.* 1988, and Gradstein *et al.* 1998, for further discussion of the development of sequence stratigraphic concepts).

Tectono-stratigraphy – Lithostratigraphic sequences may also record tectonic influences on the depositional succession. This subdiscipline of stratigraphy has been applied since at least 1875, originally describing sequences in large-scale, stacked, thrust sheets (nappes), in tectonically influenced areas, such as thrust belts (Medlicott 1875). More recently, it has been broaden to include the study of any area that exhibits a tectonic imprint on its lithostratigraphy, including the cratonic interiors (e.g., Houseknecht 1986). Change in cratonic elevation is accomplished by seafloor spreading either by underplating continental crustal masses forming domes and mountains or by crustal subsidence from mantle flow away from the craton interior forming basins and rifts. Not all cratonic areas experience active tectonism, and their lithostratigraphic record may only reflect eustatic change. The gently sloping southern Ozark cratonic platform and its adjacent ramp preserve a Paleozoic record of five distinct but related tectono-stratigraphic successions.

Sequence and Tectono-stratigraphic Record, Southern Ozark Region

The Paleozoic sequence record of the southern Ozark region, northern Arkansas, can be divided into 25 cycles comprising the interval from the Late Cambrian through Middle Pennsylvanian (Atokan) periods. This succession is preserved, all or in part, four first-order, seven second-order, and fifteen third-order cycles (Waite 2002; Figure 1). At least three condensed sections and seventeen unconformities punctuate the record (McFarland 2004). The first-order and second-order cycles recognized by Waite (2002) are preserved, but three third-order cycles – between the Middle and Upper Ordovician, the lowermost cycle of the Upper Silurian, and the lowermost cycle of the Middle Devonian strata are missing (Figure 1).

Type - 1 unconformities at the Eminence-Gunter, Roubidoux-Jefferson City, Everton-St Peter, Lafferty-Penters, Penters-Clifty, Clifty-Sylamore, Chattanooga-St. Joe (Bachelor), Boone-Batesville, Pitkin-Hale and Morrowan-Atoka contacts (McFarland 2004) in northern Arkansas correspond to Waite’s third-order unconformity surfaces. In contrast, predicted third-order unconformities at the Upper Ordovician-Lower Silurian and Lower-Middle Silurian contacts (Waite 2002) fall within continuously deposited successions.

Composite Thicknesses for the Paleozoic Record, Southern Ozark Region

Thickness data for this study were compiled from published water and geophysical well logs (Huffman 1951; Sheldon 1954; Howe and Koenig 1961; McKnight and Fischer 1970; Johnson *et al*. 1989; Simms *et al*. 1995; Boyd, 2008; Pasteris 2014). The thinnest and thickest preserved stratigraphic intervals of the southern Ozark region vary from 566-2954m (1860-9692ft) and 452-2052m (1483-6733ft) in the northwest and north-central Arkansas, to 880-2729m (2888-8936 ft) and 998-2371m (3276-7781ft) in the southeast and southwest Missouri, and 42-669m (140-2196ft) and 355-729m (1165-2393ft) northeast and Cherokee Platform, Oklahoma, respectively (Figure 2). The sedimentary succession is thickest in northwest Arkansas, where it peaked at 2954m (9692ft), and thinnest in the northeasternmost Oklahoma area, where only a minimum thickness of 42m (140ft) is documented. The tristate area is carbonate-dominated, representing a maximum of 64% of the total Paleozoic sedimentary record in northeast Oklahoma, 59% in southern Missouri, and 46% in northern Arkansas. The remaining section comprises terrigenous clastic sediment with sandstone contributing approximately 18% and shale about 19% of the interval in Arkansas, where they make their greatest contribution.

Paleozoic Tectono-stratigraphic Divisions and Rates of Sedimentation, Southern Ozark Region

TS1 is poorly known, but the TS2 and TS3 divisions show a general Missouri-Arkansas-Oklahoma thinning trend, the TS4 division thins progressively from Missouri into Arkansas and Oklahoma, while the TS5 division thins into Oklahoma and Missouri from Arkansas. The average rates of deposition in Arkansas for TS3 and TS4 are 0.01 mm/year, and 0.03 mm/year and 0.04 mm/year for TS2 and TS5, respectively. In Missouri, the TS3 and TS4 averaged 0.021 mm/year whereas the average rate of the TS2 and TS5 are 0.04 mm/year and 0.001 mm/year, respectively. In Oklahoma, the rate is 0.002 mm/year for TS3 and TS5, while TS2 and TS4 are 0.01 mm/year and 0.004 mm/year, respectively.

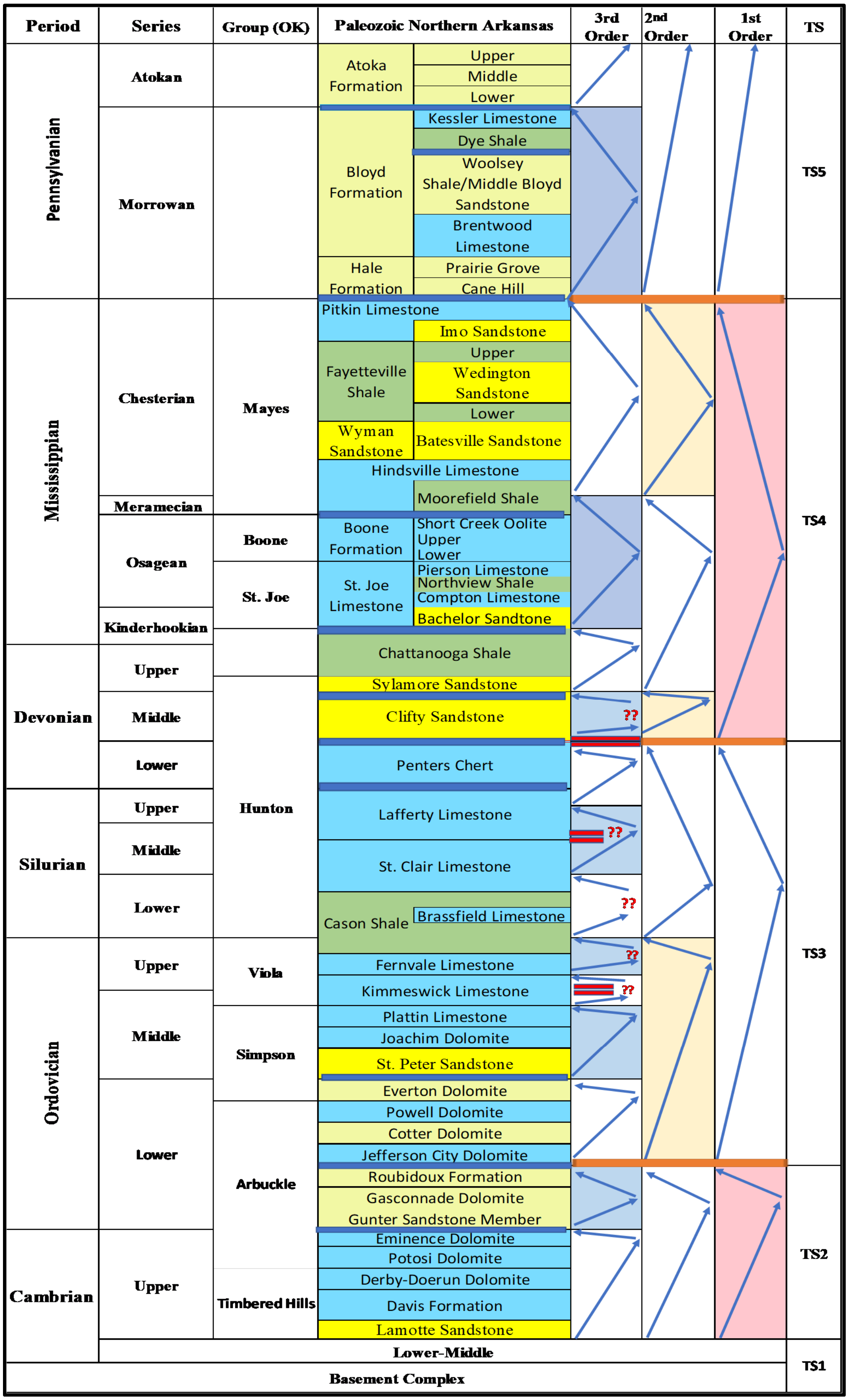

Figure 1 – Chronostratigraphy, Lithostratigraphy, Sequence Stratigraphy, and Tectono-Stratigraphic Assignments, southern Ozark Dome, northern Arkansas, modified from McFarland, 2004 (eustatic cycles from white, 2002) (Colors: Yellow – Sandstone; Green – shale; Blue – Limestone; Tan – mixed lithologies including sandstones).

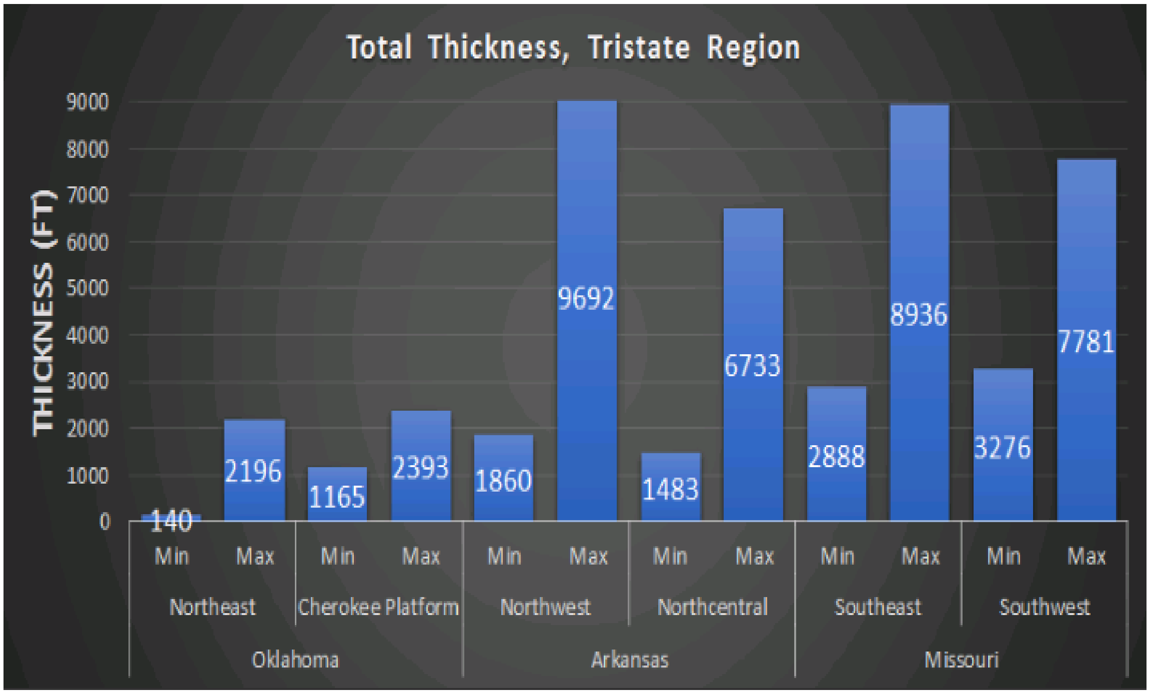

Figure 2 - The composite thicknesses (maximum and minimum) of the Upper Cambrian-Middle Pennsylvanian interval for the Upper Cambrian-Middle Pennsylvanian interval of the southern Ozark Region, Arkansas, Missouri, and Oklahoma. Sources of most thickness data: Arkansas – McFarland 2004; Missouri – Howe and Koenig 1961; Thompson 2001; Oklahoma – Huffman 1958; Johnson *et al*. 1989; see text for full list of sources.

Tectono-stratigraphic Interval 1 (TS1) – Late Precambrian to Middle Cambrian, > 1 Ga.

The poorly known TS1 Interval comprises the basement of igneous, metamorphic, and pre-Lamotte sedimentary rocks, locally present beneath the basal Lamotte-Reagan sandstones. These basement rocks formed between 1.4 billion and 600 million years ago and are exposed in the St. Francois Mountains of southeastern Missouri and the Wichita and Arbuckle Mountains of southern Oklahoma (Johnson *et al*. 1989). In northern Arkansas, the Mowery 1 gas well drilled by Gulf Oil Company in 1968 is situated in Section 14, Township 10N, and Range 32W, Crawford County, and penetrated about 54m (150 ft) of these rocks in northern Arkansas. Houseknecht and Weaverling (1983) documented more than 499m (1640 ft) of a pre-Lamotte section of carbonates and shales in the Reelfoot Rift Basin in northeastern Arkansas. These pre-Lamotte units are the correlative equivalents of the Conasauga (Middle Cambrian) and Rome (Lower Cambrian) Formations of the southern Appalachian Mountains (Houseknecht and Weaverling 1983).

Tectono-stratigraphic Interval 2 (TS2) – Upper Cambrian to earliest Ordovician, ~ 19+ Ma.

The TS2 Interval is a dolomite-dominated interval with a secondary contribution by terrigenous clastic sediment. The component TS2 lithostratigraphic divisions include (ascending order): Lamotte, Bonnetterre-Davis, Derby-Doerun, Potosi, Eminence, Gasconade, Roubidoux, and Jefferson City Formations. TS2 is thickest in the southeast Missouri, where it is approximately 937m (3075ft), and thinnest in the northeastern Oklahoma area, with only a recorded thickness of 73m (240 ft). The minimum and maximum thicknesses across the tristate area range from 215-398m (704-1306ft) and 155-722m (510-2370ft) in the northwest and north-central Arkansas, to 126-709m (416-2327ft) and 423-937m (1390-3075ft) in the southeast and southwest Missouri, and 196-287m (642-940ft) in northeastern Oklahoma. The TS2 interval comprises 35% of the section in northcentral Arkansas, 40% in southwest Missouri, and 39% in the northeastern Oklahoma. Carbonates represent the most abundant lithotype, contributing a maximum of 83% of the total TS2 interval in Arkansas, 78% in southwestern Missouri, and 87% in northeasternmost

Oklahoma. This interval is absent in the northeastern Oklahoma.

Tectono-stratigraphic Interval 3 (TS3) – late Lower Ordovician-Lower Devonian, ~ 85 Ma.

The TS3 Interval is the most well-developed tectono-stratigraphic unit across the tristate region. Its lithostratigraphic divisions include the, ascending order: Jefferson City, Cotter, Powell, Everton, St. Peter, Joachim, Plattin, Kimmeswick, Fernvale, Cason, St. Clair, Lafferty, and Penters Formations. Carbonates dominate the interval, constituting 95% across southern Missouri, 84% in northwest Arkansas, and 97% in northeastern-most Oklahoma, although minor sandstones and shales occur sporadically, and numerous unconformities punctuate TS3. The sandstones of the Cotter, Everton, and St. Peter, Clifty Formations are entirely supermature, orthoquartzite sandstones. The maximum TS3 interval thickness is 722m (2370ft) in north-central Arkansas, 1143m (3751ft) in southeast Missouri, and 233m (764ft) in northeast Oklahoma. The interval contributed up as much as 35% to the northern Arkansas record, 48% in southeast Missouri, and 35% in northeast Oklahoma of the total Paleozoic sediment. Sandstone abundance is greatest in the northcentral Arkansas area, reaching 152m (500ft) thick, 61m (200ft) in southeast Missouri, and 32m (106ft) in northeast Oklahoma. These values correspond to 14% of the maximum TS3 interval in southeast Missouri, 21% in northcentral Arkansas, and 5% in northeast Oklahoma, respectively. Shale is significantly low abundance in the region, except in northeastern Oklahoma, where it reaches only 121m (37ft), yet constitute 16% of the TS3 section in that area. Its greatest thickness is approximately 21m (68ft) in northcentral Arkansas, and the least is 6m (15ft) across southern Missouri.

Tectono-stratigraphic Interval 4 (TS4) – Middle Devonian-middle Upper Mississippian, ~ 70 Ma.

The Clifty, Sylamore, Chattanooga, St. Joe, Boone, Moorefield, Hindsville-Batesville, Wyman, Fayetteville, and Pitkin Formations (ascending order), and their component subdivisions comprise Tectono-stratigraphic Interval 4 (TS4). The section is thickest in the southeast Missouri region, and it thins progressively into northern Arkansas and northeastern Oklahoma. The greatest TS4 thicknesses are 644m (2112ft) in northwest Arkansas, 736m (2416ft) in southeast Missouri, and 312m (1025ft) in northeast Oklahoma. TS4 contributed about 23% of the total lithostratigraphic thickness in the tri-state region. Local irregularities in the TS4 possibly reflect Devonian and Mississippian post-depositional erosion and truncation.

The Clifty Sandstone, Sylamore Sandstone, and Chattanooga Shale make up the Middle-Upper Devonian component of the TS4 section. Their composite thickness is 464m (1522ft) in southeast Missouri, where it is thickest, 41m (134ft) in northwest Arkansas, and 27m (90ft) in Oklahoma. The TS4 Devonian rock is thinnest and missing in most of the northcentral region of Arkansas and the northeastern-most Oklahoma region.

The Mississippian TS4 component is a third-order transgressive-regressive cycle bounded by type 1 unconformities and divided into the St. Joe, Boone, Batesville, Hindsville, Fayetteville, and Pitkin Formations, ascending order. The Mississippian interval is thickest in the northwest Arkansas region, while it progressively thins into Missouri and Oklahoma. Thicknesses vary from 100-603m to 132-470m (329-1978ft to 432-1542ft) in northwestern and northcentral Arkansas, to 114-273m to 103-276m (473-894ft to 339-905ft) in southeastern and southwestern Missouri, and 5-256m to 34-255m (15-845ft to 110-837ft) in northeastern and northeasternmost Oklahoma, respectively. The interval contributes a maximum of 23% in northern Arkansas, 27% in southern Missouri, and 47% in northeast Oklahoma to the entire Paleozoic section in those areas.

The TS4 sandstones account for a maximum of 38% of the total TS4 section in southeast Missouri, 20% in northcentral Arkansas, and 8% in the northeasternmost Oklahoma. The sandstones of the Clifty, Sylamore, and St. Joe Formations (Bachelor Sandstone Member) are supermature quartzarenites. The appearance of first cycle sandstones with a minimum of metamorphic rock fragments (mrfs) in the Upper Mississippian Batesville, Wyman, Wedington, and Imo sandstones distinguish the upper TS4 interval. Shale comprises 40% of the entire TS4 section in northwestern Arkansas, but only 12% in southwest Missouri, and 11% in northeasternmost Oklahoma area.

Tectono-stratigraphic Interval 5 (TS5) - Lower-Middle Pennsylvanian, ~ 16+ Ma.

The TS5 interval constitutes a cyclic succession of sandstone and shale likely derived from the Appalachian and Ouachita regions with minor local carbonate. The Hale Formation (Cane Hill and Prairie

Grove Members), Bloyd Formation (Brentwood Limestone, Woolsey Shale-middle Bloyd Sandstone, Dye Shale-Kessler Limestone), and Atoka Formation (Lower, Middle, and Upper Members) comprise the TS5 group. The TS5 division is the thickest of TS intervals. But component divisions may not be laterally persistent across the region. The greatest thickness is 1268m (4160ft) in northwest Arkansas, 21m (68ft) southeast Missouri, and 124m (407ft) in northeast Oklahoma. The interval contributed a maximum of 43% of the total sedimentary record in northern Arkansas, less than one percent in southern Missouri, and only 19% in northeastern Oklahoma.

As can be seen already in the Upper Mississippian, TS4 first cycle sandstones, metamorphic rock fragments (mrfs) ranging from common to abundant appear in the TS5 sandstone succession. The interval is not present in southwest Missouri, probably because of later erosion, and sporadic to absent across northeastern Oklahoma and southeastern Missouri for the same reason. Local anomalies in the TS5 thickness are the result of both Morrowan and Atokan erosion, which removed some of the pre-Pennsylvanian intervals in the Ozark region and produced the Woolsey/middle Bloyd Sandstone-Dye Shale, and Morrowan-Atokan regional unconformities. Consequently, TS5 strata onlap older rocks toward the Ozark core and progressively thicken to the south. Before TS5 deposition, a Middle-Upper Mississippian uplift exposed the area to erosion and significant karst development before subsequent Pennsylvanian submergence and deposition of the Pennsylvanian TS5 Hale, Bloyd, and Atoka strata. TS5 can be subdivided into three divisions based on an increase in the contribution by metamorphic rock fragments. The terrigenous clastic contribution in the region is highly variable and may be absent in most of the southern Missouri and northeastern Oklahoma areas, while it is thicker and more persistent across northern Arkansas.

Conclusions

The Paleozoic record of the southern Ozark region, northern Arkansas, southern Missouri, and northeastern Oklahoma, accumulated on the gently sloping, cratonic Arkansas Structural Platform (NASP) and its adjacent ramp that experienced transgressive-regressive sequences deposited by epeiric seas, including both first-cycle and reworked terrigenous clastic sediments, as well as blanket shallow-water carbonates. In addition, the region experienced modest and sporadic uplift that affected the component lithologies and their regional distribution. That combination provides the basis for organization of the Paleozoic record into five separate, but related, tectonostratigraphic units (TS1-TS5): (TS1) Late Precambrian-Middle Cambrian, (TS2) Upper Cambrian-lowest Ordovician, (TS3) Lower Ordovician-Lower Devonian, (TS4) Middle Devonian-Upper Mississippian, and (TS5) Lower-Middle Pennsylvanian.

TS1, a pre-Late Sauk Sequence, is the least well-known succession, consisting of emplaced igneous and low-ranked metasedimentary bodies, and pre-Lamotte sedimentary rocks. TS2, Late Sauk Sequence, is potential >937m (3075ft) of dolomites and sandstones. TS3, Tippecanoe Sequence, is the penultimate thickest interval, possibly >1257m (4125ft) of dolomites, limestones, shales, and supermature sandstones. TS4, Kaskaskia Sequence, measures at least 736m (2416ft) of mixed lithologies. The final TS5, Lower Absaroka Sequence, is the thickest interval, >1267m (4160ft) of first-cycle sandstone, and shale, that may exceed 7620m (25,000ft) in the adjacent Arkoma Basin.

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