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Analysis of Reservoir Partitioning and Determining Timing and Depth of Diagenetic Pore Occlusion within a Fluvial Outcrop Analog: Late Triassic Sonsela Member, Petrified Forest National Park, Arizona

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Summary

The Late Triassic Sonsela Member in the Petrified Forest National Park (PFNP) was evaluated using sedimentologic, stratigraphic and petrographic criteria along a continuous 0.5 km outcrop. The study interval consists of interbedded sandstones and mudstones and is composed of a two-tiered hierarchy of cyclic alluvial deposits with bounding paleosols. The succession is composed of 15 fluvial aggradation cycles (FACs) that comprise two fluvial aggradational cycle sets (FAC-Sets). FAC-Sets are composed of architectural elements suggestive of a mixed-load fluvial system that is alternately dominated by bedload and suspended load deposits. A thinning and fining succession of FACs within FAC-Sets is accompanied by an upward decrease in sandstone continuity and grain size. Point-counts of intergranular volume (as a proxy for primary porosity) within channel facies and subsequent transform to syndepositional permeability provide a 2D depiction of the lateral variability in reservoir quality. Outcrop reservoir attributes are partitioned within a hierarchy of FACs and FAC-Sets, resulting in both vertical and lateral reservoir heterogeneity. Sandstones are volcanogenic-rich, and have undergone an almost complete diagenetic loss of porosity due to the precipitation of authigenic clays. Paragenetic reconstruction suggests that porosity loss occurred contemporaneous with the silicification of fossil logs in channel deposits. Log compaction at the time of silicification averaged 9.1% suggesting that log silicification and porosity loss occurred soon after deposition.

Introduction

The characterization of fluvial reservoirs oftentimes utilizes modern and ancient analogs to calibrate numerical models (Miall, 2006). Outcrop analogs are invaluable because they constrain fluvial facies and architectural element geometries, and may provide corollary distributions of porosity and permeability (Aigner et al., 1996; Bridge et al., 2000; Dalrymple, 2001; Yu et al., 2002; Miall, 2006; Pranter et al., 2007; Donselaar and Overeem, 2008). Outcrops of the Late Triassic Sonsela Member of the Chinle Formation at Petrified Forest National Park (PEFO) are ideal as subsurface fluvial analogs because they are reservoir-scale (0.5 km long by 25 m thick), have lateral facies relationships that are exceptionally well-exposed, and have undergone little structural deformation. In addition, sandstones of the Sonsela Member are mineralogically immature and have undergone several diagenetic episodes. Analysis of these episodes offer insight into the relationship between burial diagenesis and sandstone alteration.

The primary stratigraphic factor that influences recovery efficiency is reservoir continuity and quality (Van de Graaff and Ealey, 1989; Larue and Friedmann, 2005). The outcrop dimensions of the study interval (20-30 m thick by 0.5 km long) are approximately equivalent to a subsurface, production-scale well spacing of

80 acres. Considering the attributes of the Sonsela Member, the objectives of this study are to: 1) evaluate the spatial variability of fluvial facies, architectural elements and paleosols and relate them to their pre-cementation porosity and permeability; 2) determine the controls on reservoir partitioning within the 2-D outcrop; 3) constrain the amount and timing of diagenetic products; and 4) determine the relationship between immature sandstones and the timing and depth of diagenetic porosity reduction.

Methods and Results

Stratal relationships were traced on photopanoramas of each subarea and walked-out on outcrop to establish lateral relationships. Outcrop sections were measured and include documentation of grain size, stratal thickness, sedimentary and biological structures, lithostratigraphic contacts and the stratigraphic location of paleosols. Within each measured section, fresh samples of sandstone were collected for petrographic analysis. Depositional facies observed within the outcrop were classified based on grain size and mechanical and biological structures (classification after Miall, 1978; 1985). Strata consist of interbedded sandstones and mudstones. Facies are grouped into downstream- and lateral-accretion, overbank, thin sandy bedform and massive channel architectural elements that are interpreted as channel fill and overbank deposits (Miall, 1985). The succession of architectural elements within the study interval gradually transitions from downstream accretion and lateral accretion with minimal overbank at the base to thin sandy bedform and overbank at the top. This suggests that fluvial style evolved from a bedload system at the section base to a suspended load system at the section top. Channel deposits are uncommon in the upper portion of the section. This pattern is disrupted in the uppermost portion of the section by a truncation surface overlain by bedload downstream accretion deposits.

Meter-scale fluvial aggradational cycles (FACs) and decameter-scale FAC-sets were identified based on the methodology of Atchley et al. (2004) and Cleveland (2007). The succession consists of fining-upward FACs that stack into longer-period fining-upward FAC-Sets. FACs exhibit an overall decrease in thickness, channel facies proportions and grain size, and increase in the proportion of fine-grained overbank deposits upwards within FAC-Sets. The basal portions of FAC-Sets have high proportions of sand, i.e., 90% sand and 10% mud, and consist of fine to very coarse-grained downstream accretion and lateral accretion sandstones. Paleosols are discontinuous and truncated by adjacent channel facies. Upwards, there is a notable change in architectural element proportions and decrease in inter- and intra-cycle erosion. FACs are dominated by lateral accretion, thin sandy bedform, proximal overbank and distal overbank deposits. FACs have a lower proportion of sand (40% sand and 60% mud), and sandstones are finer-grained and more thinly bedded. Paleosols atop these FACs are laterally continuous.

Sandstone petrography was utilized to determine pre-cementation sandstone porosities and reconstruct the timing of diagenetic events. Twenty-two sandstone specimens were point-count analyzed (300 to 500 counts) under plane-polarized and cross-polarized light to determine both composition and intergranular volume. Quartz-Feldspar-Lithic (QFL) modal percentages were used to determine sandstone composition and to evaluate provenance (Dickinson and Suczek, 1979). Sandstones have high proportions of quartz and lithic grains (altered volcanogenic sediments and hydrated volcanic glass, metamorphic and plutonic igneous lithic grains), and include abundant authigenic clay within the intergranular volume. Sandstone porosity is completely occluded by diagenetic products. The dominant pore-occluding diagenetic phase is authigenic clay.

Authigenic clays can be distinguished from devitrified volcanic rocks by their petrographic characteristics. Authigenic clay mineralogy and volume suggests that devitrification of volcanogenic sediments in Sonsela sandstones resulted in the precipitation of authigenic clays and provided the silica responsible for wood silicification (Sigleo, 1979). If so, then the precipitation of authigenic clay and silicification of wood were concurrent events. To estimate the approximate depth and timing of silicification, burial compaction is calculated using the methodology of Stout and Spackman (1988) from aspect ratios measured from 200 silicified logs. A transform from modern peat compaction (Bloom, 1964) is used to estimate depth of silicification. Results indicate log silicification and pore occlusion by diagenetic products occurred soon after deposition within a burial depth of less than 1 m. To our knowledge, this is the first study to document complete primary porosity destruction at such a shallow burial depth.

Sandstone porosity is completely occluded in Sonsela sandstones. As such, depositional porosity is estimated by using intergranular volume as a proxy. Pre-cementation permeability is estimated using the porosity-permeability transform function of Pape et al. (1999, 2000). A scatterplot of primary porosity versus permeability indicates that sandstones cluster into discrete reservoir classes. Downstream and lateral accretion deposits of reservoir class A have the highest values with porosity ranging from 37 - 41% and permeability from 90 - 250 darcies. Reservoir class B ranges in porosity from 26 - 33% and permeability from 3 – 33 darcies, and also consists of downstream and lateral accretion deposits. Reservoir class C ranges from 16 - 21% porosity and 0.02 – 0.35 darcies of permeability and consists predominately of thin sandy bedform and massive channel fill. The reservoir classes are partitioned stratigraphically. Sandstones of reservoir class A occur at the base of FAC-Sets. Sandstones of reservoir class B occur within the middle portions of FAC-Sets and sandstones of reservoir class C in upper FACs of FAC-Sets.

From an analog reservoir continuity perspective, reservoir flow units are partitioned within a hierarchy of meter-scale FACs that in turn stack into decameter-scale FAC-Sets. This two-tier stratal hierarchy accounts for vertical “reservoir” heterogeneity produced by the cyclic interbedding of relatively coarser-grained sandstones and finer-grained paleosols. Within similar subsurface reservoirs, waterflood or enhanced recovery initiatives should anticipate that injected fluid will likely sweep the lowermost, bedload portion of FAC-Sets, and bypass less permeable, finer grained sand bodies located upsection.

Conclusions

1. The Late Triassic Sonsela Member at Petrified Forest National Park accumulated as a bedload and suspended-load fluvial system, and includes interbedded overbank mudrock and channel sandstone.
2. The study interval consists of a two-tier hierarchy of meter-scale fluvial aggradational cycles (FACs) and decameter-scale fluvial aggradational cycle sets (FAC-Sets). Within a FAC-Set, FACs thin, fine and have increasing mineralogic maturity upsection.
3. Devitrification of volcanogenic sediments resulted in the silicification of wood as well as the precipitation of interparticle authigenic clays. The limited compaction of petrified logs (range from 0-26%, average 9%) suggests replacement cementation within 1 m of burial. To our knowledge, this is the first study to document the complete destruction of primary porosity in immature sandstones prior to burial. This demonstrates the risk associated with the exploration of mineralogically immature sandstones.
4. Primary porosity within sandstones ranges from 16% to 41% and permeability from 90 to 250 darcies. The most continuous, and highest porosity and permeability sandstones coincide with bedload channel complexes concentrated in the lower portion of FAC-Sets, whereas relatively lower quality, more discontinuous sandstones are associated with suspension-load channel complexes (within the upper portion of FAC-Sets).

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