PS Use of Sequence Boundaries to Map Siliciclastic Depositional Patterns across North America*

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Abstract

Sequences are discrete packages of sedimentary rock bounded by interregional erosional surfaces that are traceable on a continental scale. They are the ideal stratal units for regional stratigraphic study, but few continent-wide studies of the Sloss-defined sequences have been published. We present a new, comprehensive and continental-scale study of the six sequences across North America, with special emphasis on siliciclastic architecture. Details of the siliciclastic rocks across North America, including offshore shelf regions, were compiled using the AAPG COSUNA stratigraphic columns and supplemented with the Geological Atlas of Western Canada Sedimentary Basin and numerous other published sources and wells. Rockworks 16 software was used to track individual sequence boundaries, lithologic data and stratigraphic column locations. The raw data were processed into 16 subset areas, which were sampled using a 10-km spacing grid to create comprehensive, three-dimensional models of the lithology on a sequence-by-sequence basis. Isopach maps and basal sequence lithology maps were also created for each of the six sequences. Results show siliciclastics in the first three sequences (Sauk, Tippecanoe and Kaskaskia) comprise a significantly lower volume compared to the latter three sequences (Absaroka, Zuni and Tejas). Siliciclastics total 13.2 million km^3 in the first three sequences combined, whereas siliciclastics within the individual Absaroka, Zuni and Tejas sequences total 9.4 million km^3, 19.9 million km^3 and 12.0 million km^3, respectively. In addition to the highest volume, the overall percentage of siliciclastics reaches a maximum in the Zuni sequence, with 36% of all sandstone and 36% of all shale deposited as part of the Middle Jurassic to Late Cretaceous systems across North America. Isopach maps show most of the siliciclastics in these later sequences were deposited across the western portion of North America and offshore in the East and Gulf of Mexico. Three-dimensional diagrams of lithology within each sequence allow visualization of shale architecture across the continent through time. These data provide insight into potential exploration targets for shale oil and gas. Identification of areas of thickest shale in the individual Absaroka, Zuni and Tejas sequences, in combination with geochemical data, can focus renewed exploration efforts into previously overlooked regions.

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USE OF SEQUENCE BOUNDARIES TO MAP SILICICLASTIC DEPOSITIONAL PATTERNS ACROSS NORTH AMERICA

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ABSTRACT

Sequences are discrete packages of sedimentary rock bounded by interregional erosional surfaces that are traceable on a continental scale. They are the ideal stratal units for regional stratigraphic study, but few continent-wide studies of the Sloss-defined sequences have been published. We present a new, comprehensive and continental-scale study of the six sequences across North America, with special emphasis on siliciclastic architecture.

Details of the siliciclastic rocks across North America, including offshore shelf regions, were compiled using the AAPG COSUNA stratigraphic columns and supplemented with the Geological Atlas of Western Canada Sedimentary Basin and numerous other published sources and wells. Rockworks 16 software was used to track individual sequence boundaries, lithologic data and stratigraphic column locations. The raw data were processed into 16 subset areas which were sampled using a 10-km spacing grid to create comprehensive, three-dimensional models of the lithology on a sequence-by-sequence basis. Isopach maps and basal sequence lithology maps were also created for each of the six sequences.

Results show siliciclastics in the first three sequences (Sauk, Tippecanoe and Kaskaskia) comprise a significantly lower volume compared to the latter three sequences (Absaroka, Zuni and Tejas). Siliciclastics total 13.2 million km^3 in the first three sequences combined, whereas siliciclastics within the individual Absaroka, Zuni and Tejas sequences total 9.4 million km^3, 19.9 million km^3 and 12.0 million km^3, respectively. In addition to the highest volume, the overall percentage of siliciclastics reaches a maximum in the Zuni sequence, with 36% of all sandstone and 36% of all shale deposited as part of the Middle Jurassic to Late Cretaceous systems across North America. Isopach maps show most of the siliciclastics in these later sequences were deposited across the western portion of North America and offshore in the East and GOM.

Three-dimensional diagrams of lithology within each sequence allow visualization of shale architecture across the continent through time. These data provide insight into potential exploration targets for shale oil and gas. Identification of areas of thickest shale in the individual Absaroka, Zuni and Tejas sequences, in combination with geochemical data, can focus renewed exploration efforts into previously overlooked regions.

INTRODUCTION

Sequences are defined as discrete packages of sedimentary rock bounded top and bottom by erosional surfaces, often with coarse sandstone layers commonly at the base (Sloss, 1963). A transgressive surface of marine erosion (TSE) marks the base of most Sloss-type sequences, representing the base of a rapid transgressive tract. Whereas, a maximum flooding surface (MFS) marks the top of each Sloss sequence, representing the maximum sea level highstand.

Subsequent sequences formed as sea level repetitively rose and fell, resulting in flooding of the North American continent up to six times in the Phanerozoic (Sloss, 1963; Haq et al, 1988). Upper erosional boundaries were created as each new sequence eroded the top of the earlier sequence as it advanced. The sequences stack one on top of each other as shown in Fig.1.

Well log, seismic data and biostratigraphic data allow correlation of the upper (MFS) and lower (TSE) unconformity bounding surfaces for each sequence across the North American continent.

We created a three-dimensional, sequence-by-sequence, stratigraphic model using vertical stratigraphic columns across North America. Available well logs, outcrop and seismic data were utilized in the construction of the columns.

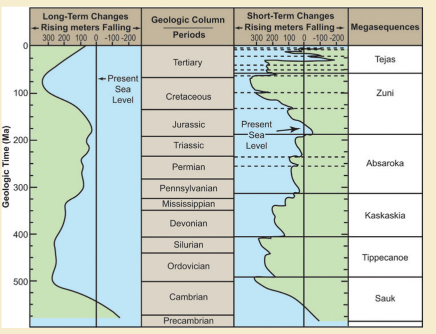


Figure 1

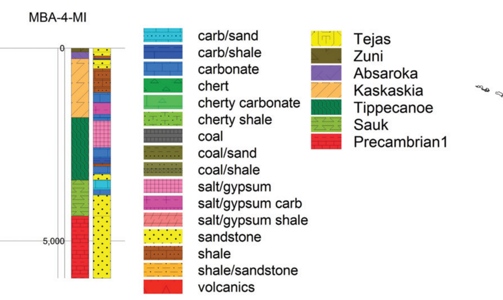


Figure 2

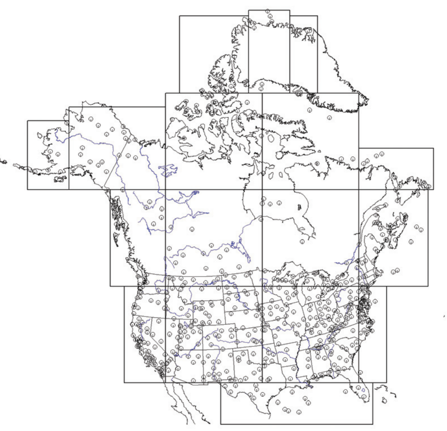


Figure 3

METHODS

Our primary database consisted of the AAPG-supported CUSUNA stratigraphic columns across the United States, stratigraphic data from the Atlas of Western Canada Sedimentary Basin, numerous well logs and hundreds of other available online sources. We constructed 569 stratigraphic columns across North America from the pre-Pleistocene down to local basement, recording detailed lithologic data, sequence boundary picks and latitude and longitude coordinates into RockWorks 16, a commercial software program for geologic data, available from RockWare, Inc. Golden, CO, USA. Figure 2 is an example stratigraphic column from the Michigan Basin, showing the 16 types of lithology that were used for classification and the sequences. Depths shown are in meters.

A graphics program in RockWorks 16 allowed us to record the basal lithology in each sequence. We assumed the basal lithologic unit was the best preserved in the transgressive/regressive depositional/erosional cycle. We then trimmed the computer-generated isopach maps to match the extent of each sequence shown by the basal lithology maps.

To generate a more detailed look at the lithologic data across the continent, we divided the North American continent into sections (Figure 3), the size of which was a compromise between computer processing time per section and the total number of sections. RockWorks 16 was used to calculate models of the thickness of each stratigraphic unit, and the maximum extent maps were used to constrain the thickness models. The adjusted thickness models were then used along with column data to create 3-dimensional models and volume estimations of the lithology for each stratigraphic sequence. The total volumes are shown in Figure 4, sequence by sequence. All volume data are recoded in cubic kilometers.

TOTAL SEDIMENT BY SEQUENCE

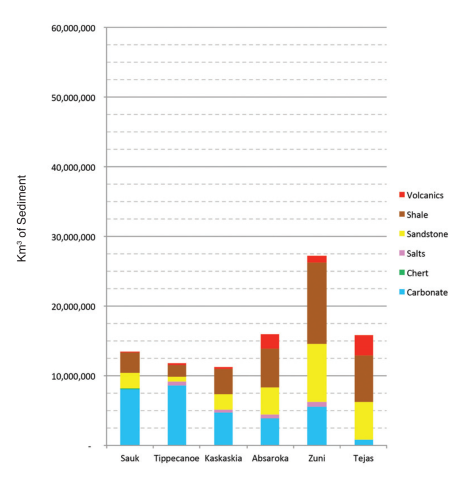
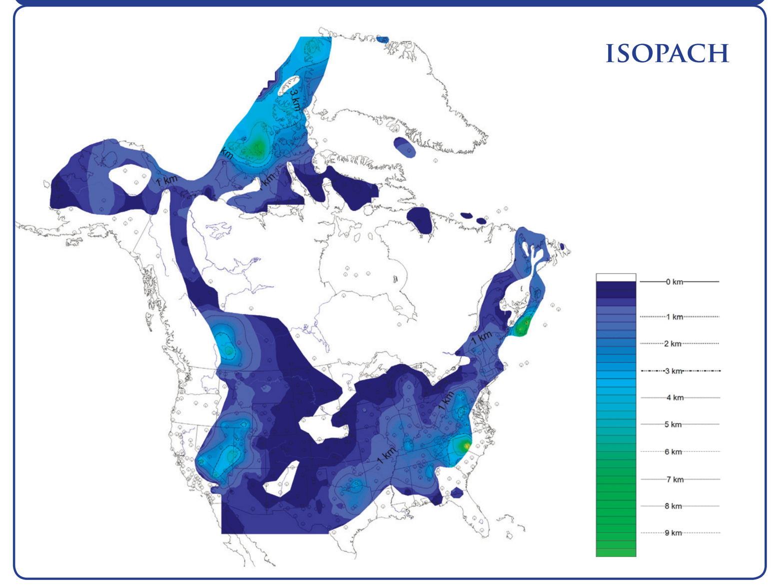
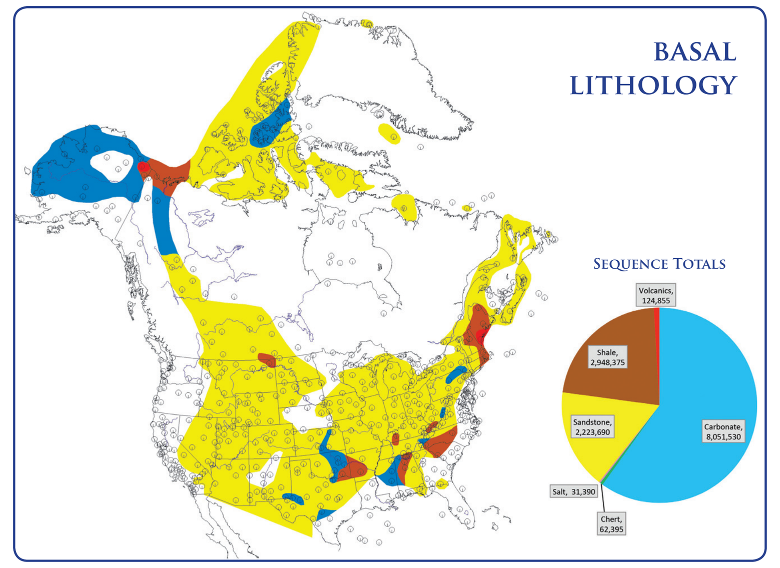
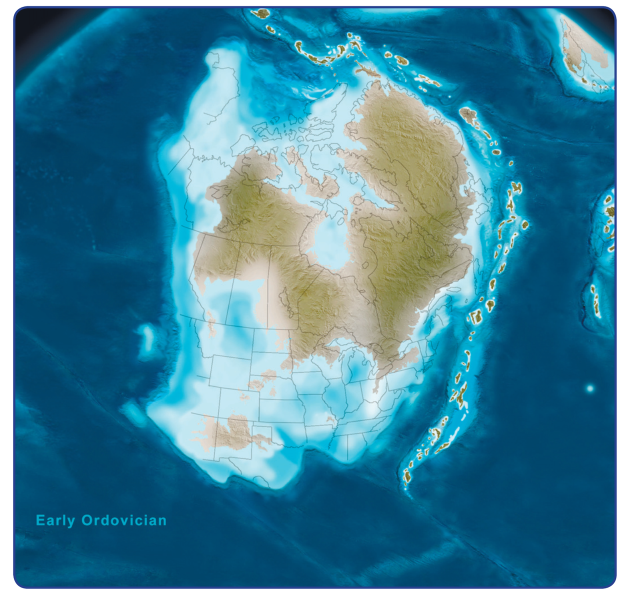


Figure 4

SAUK



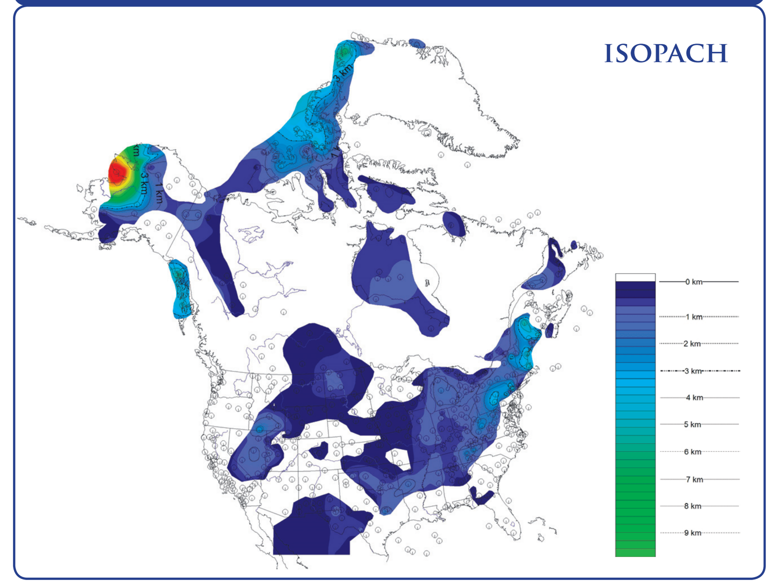


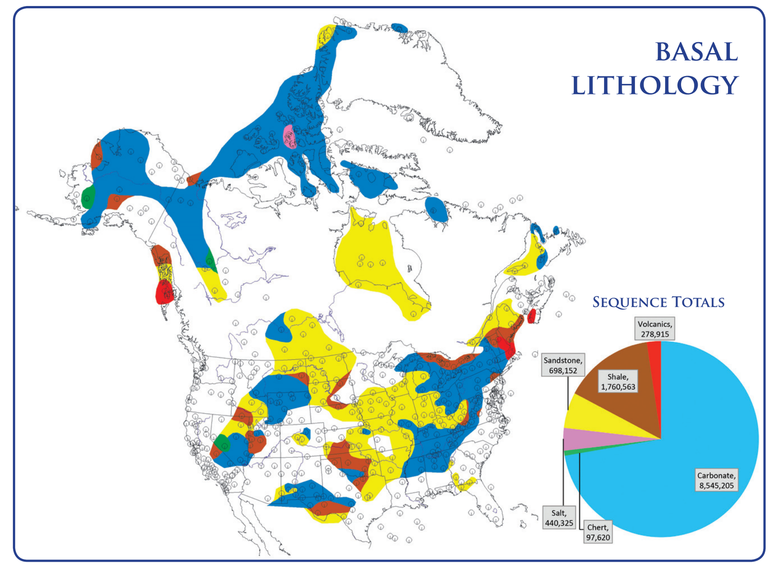


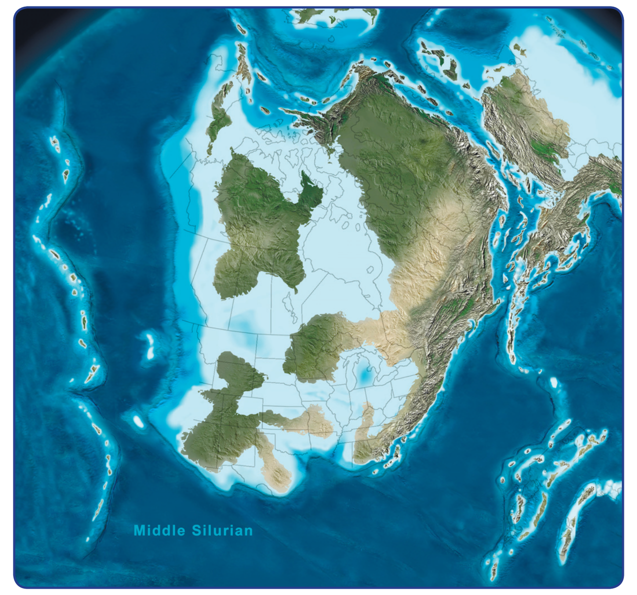
RESULTS 1: SAUK SEQUENCE

The Sauk sequence extends from the Cambrian to the Early Ordovician System. This sequence has the most extensive sandstone layer at its base compared to all subsequent sequences. However, much of this SS layer is very thin, often less than 100 m. This is especially true along the NE-SW-trending Transcontinental Arch that runs from Minnesota to New Mexico. Here, the Sauk sequence thins to just a few 10s of meters in many places or is non-existent altogether. The thickest deposits of the Sauk sequence are found in northernmost Canada and isolated locations along the east coast and some of the western states and Alberta, with thicknesses exceeding 3 km. Sandstones only make up about 17% of the entire Sauk sequence. The shale and limestone layers on top of the basal SS unit are much thicker, making up 22% and 60% of the Sauk, respectively.

TIPPECANOE



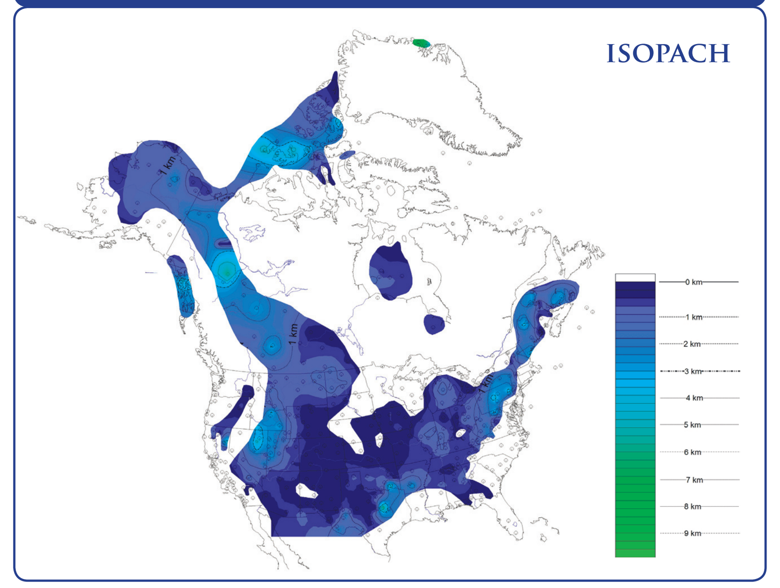


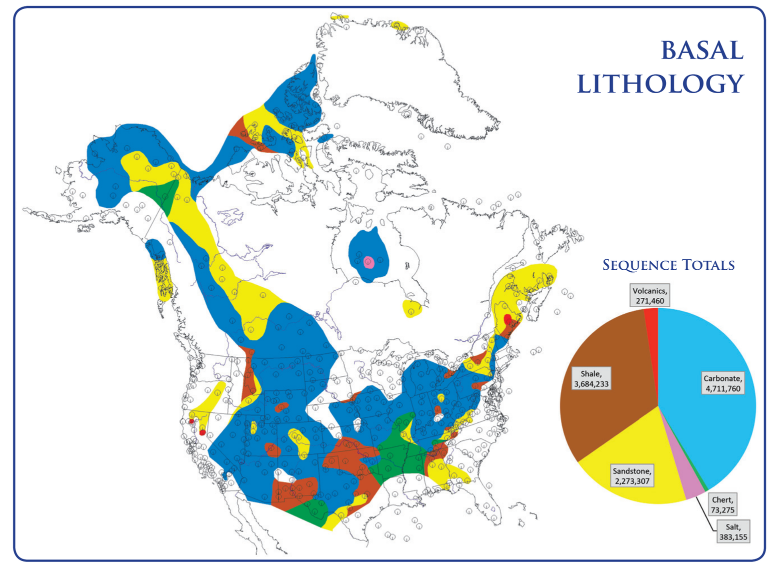


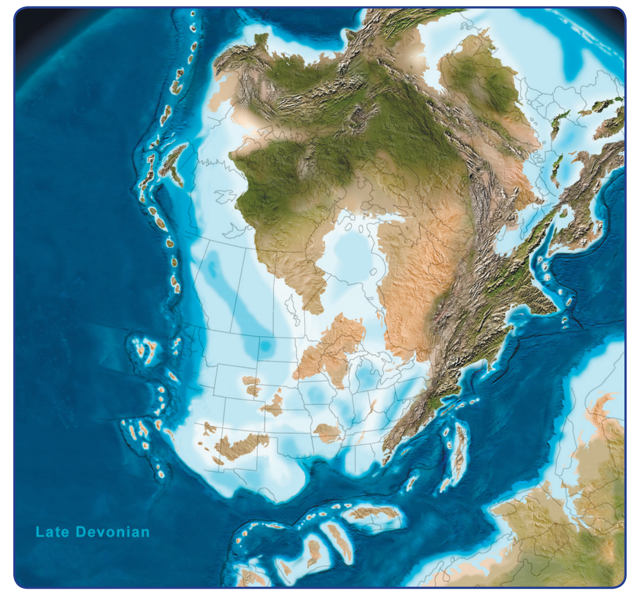
RESULTS 2: TIPPECANOE SEQUENCE

The Tippecanoe sequence extends from the Middle Ordovician to the top of the Silurian System. This sequence contains the highest percentage of carbonate rock. It has a fairly extensive basal SS layer in the Midcontinent region of the USA (St. Peter SS and equivalent), including an incursion into Hudson Bay. This SS layer is also quite thin, often less than 100 m. A large part of the basal Tippecanoe consists of an extensive carbonate layer that was deposited across northern Canada and along the eastern and western margins of the continental USA. The uplifted Transcontinental Arch still caused thinning of this sequence across the center of the USA, and in many places, prevented any Tippecanoe deposition. The thickest Tippecanoe sections are found in northernmost Canada, Alaska and up the East Coast. Sandstone only makes up about 6% of the entire Tippecanoe sequence. Shale makes up an additional 15% of this sequence. Carbonate rock dominates, however, comprising about 72% of the rock volume of this sequence.

KASKASKIA



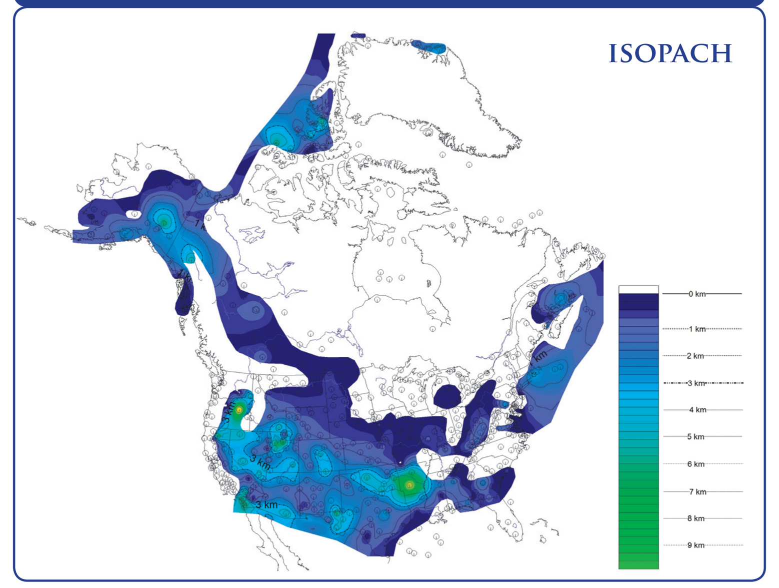


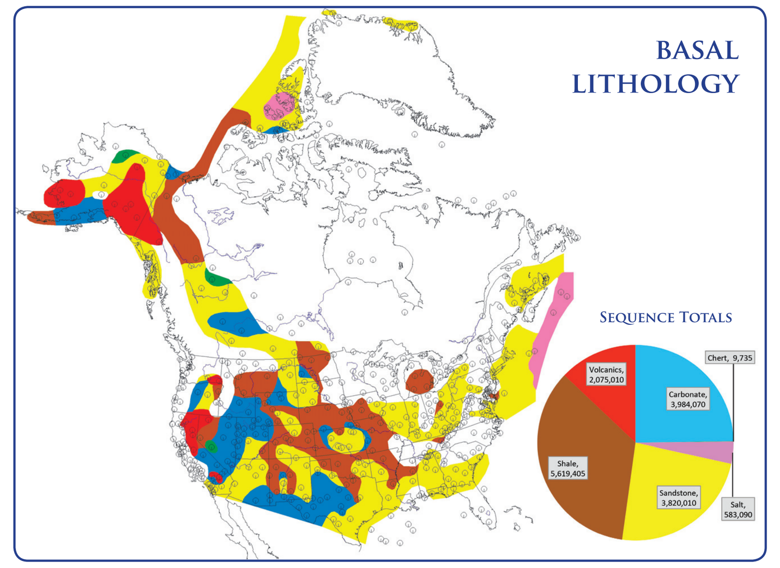


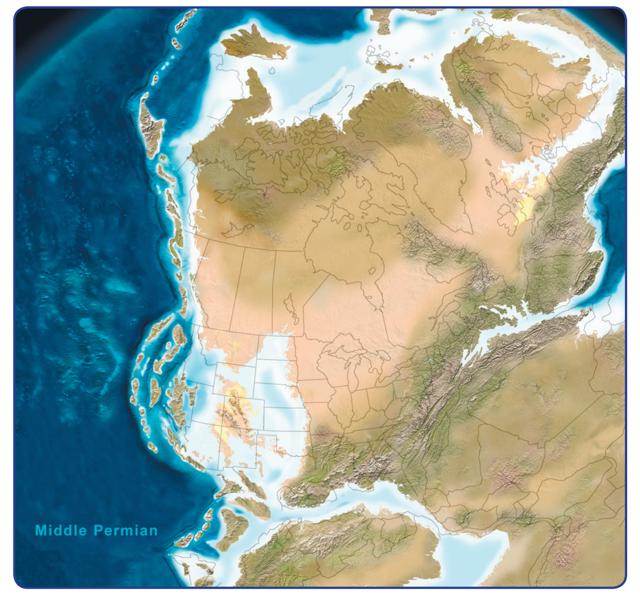
RESULTS 3: KASKASKIA SEQUENCE

The Kaskaskia sequence extends from the Devonian to the top of the Mississippian System. This sequence contains the most extensive basal layer of carbonate rock. However, some basal sandstone was deposited in western Canada and along the East Coast of the USA. The uplifted Transcontinental Arch still caused thinning of this sequence across the center of the USA, and in many places, prevented any Kaskaskia deposition. The thickest Kaskaskia stratigraphic columns are found in the western USA and Canada and along the east coast. Some basal chert-rich layers are also found in Arkansas, Illinois, southwest Texas and Alaska (shown in green). Sandstones make up about 20% of the entire Tippecanoe sequence. Shale makes up 32%, and carbonate rock, although less that previous sequences, still dominates, comprising about 42% of the total rock volume.

ABSAROKA



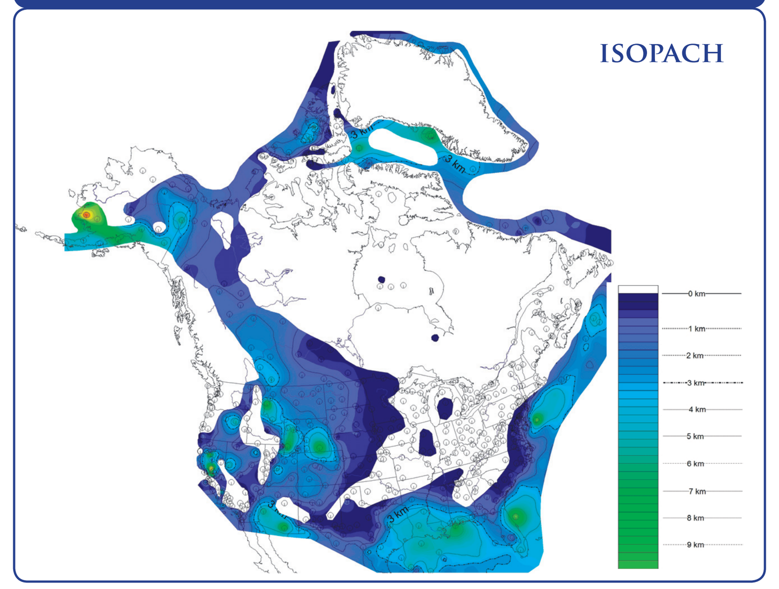


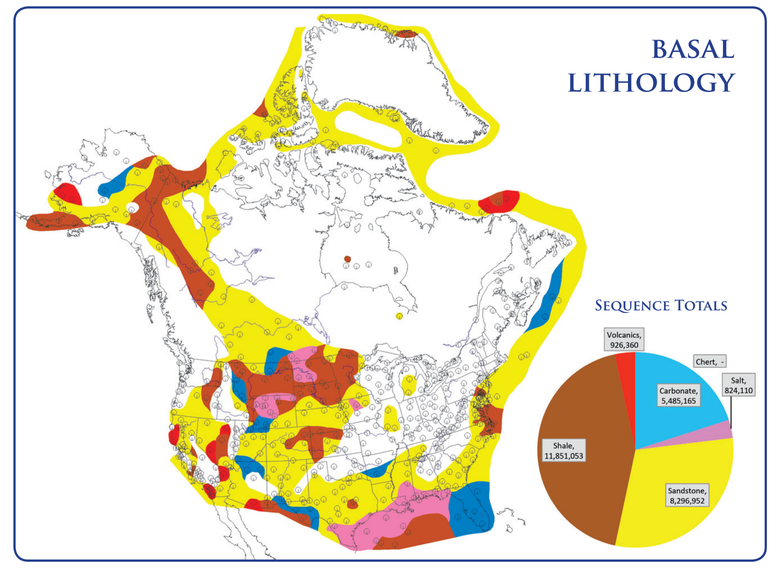


RESULTS 4: ABSAROKA SEQUENCE

The Absaroka sequence extends from the Pennsylvanian to the Lower Jurassic System. This sequence marks a major shift in depositional pattern and initiates the dominance of siliciclastic deposition across North America. The basal layer is predominantly sandstone and shale, but significant deposits of volcanic rocks also mark some locations along the West Coast and Alaska. These volcanic rocks are part of the subduction and accretion process that initiated along the Western Cordillera during the Absaroka sequence. This sequence also recorded the opening of the Atlantic Ocean on the East Coast and the formation of a new passive margin. The thickest sedimentary layers were deposited across the American Southwest, where many areas received over 3 km of Absaroka siliciclastics. Uplift of the Appalachians prevented widespread deposition across much of the eastern USA. Sandstones and carbonate rocks each make up about 24% of the entire Absaroka sequence. Shale is the dominant lithology comprising 35% of the total sequence volume.

ZUNI

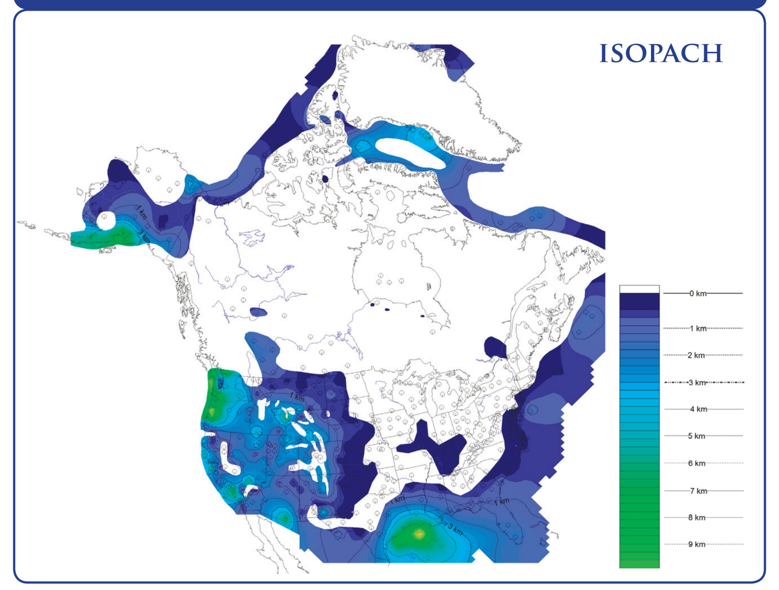


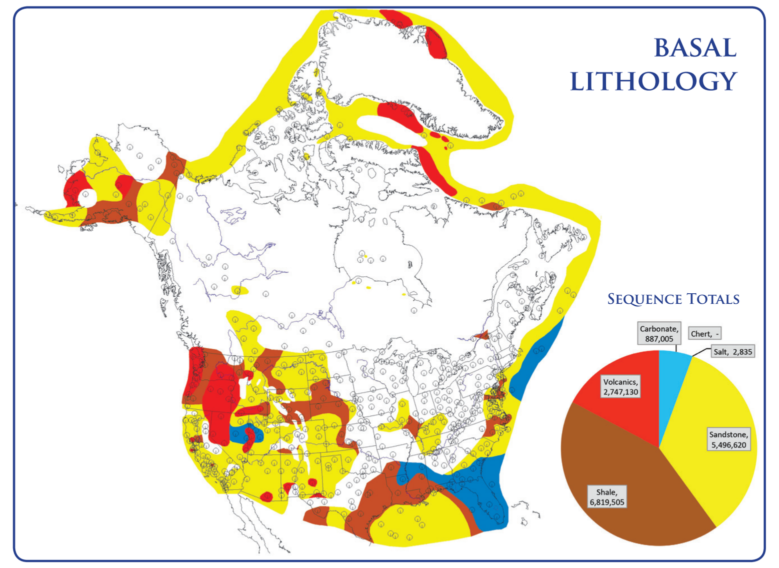


RESULTS 5: ZUNI SEQUENCE

The Zuni sequence extends from the Middle Jurassic to the lowermost Paleogene System (post Cretaceous). This sequence continued the dominance of siliciclastic deposition across western North America, with a slight shift in pattern to the northern Rocky Mountains and Canada. The Zuni deposits also buried the last of the dinosaurs across the West. The basal Zuni layer is predominantly sandstone and shale, but shifted to salt deposition in the northern Gulf of Mexico (Louann salt). Siliciclastic deposition continued to spread across the passive Atlantic margin, recording the split of Greenland and Canada. Although the Appalachian uplift prevented extensive deposition across the eastern states, there are limited Zuni deposits preserved in the Illinois and Michigan Basins and remnants near Hudson Bay. The thickest Zuni deposits are found across the western portion of the continent and in the Gulf of Mexico (GOM), where many areas received sediments in excess of 3 km. Sandstones make up about 30% of the Zuni sequence. Carbonate rocks have diminished to only 20% and shale is again the dominant lithology comprising 43% of the total sequence volume.

TEJAS





RESULTS 6: TEJAS SEQUENCE

The Tejas sequence extends from near the base of the Paleogene System to the top of the Neogene. This sequence documents another shift in depositional pattern, recording the highest percentage of siliciclastic sedimentation of any sequence. The uplift of the Rocky Mountains shed millions of km^3 of shale and sandstone across the western states. A notable shift in drainage to the south during the Tejas also poured tremendous amounts of siliciclastics into the Gulf of Mexico (GOM), including the basal Tejas Whopper Sand (Wilcox). Siliciclastic deposition continued to spread across the continental shelf along much of the Atlantic seaboard, offshore northern Canada and Greenland. Few deposits were preserved in the eastern USA and across Canada, other than offshore. The thickest Tejas deposits are found in the GOM, where the entire area received siliciclastic sediment in excess of 3 km. Sandstones make up about 34% of the Zuni sequence. Carbonate rocks diminished to only 6% and shale is again the dominant lithology comprising 42% of the total sequence volume.

CONCLUSIONS

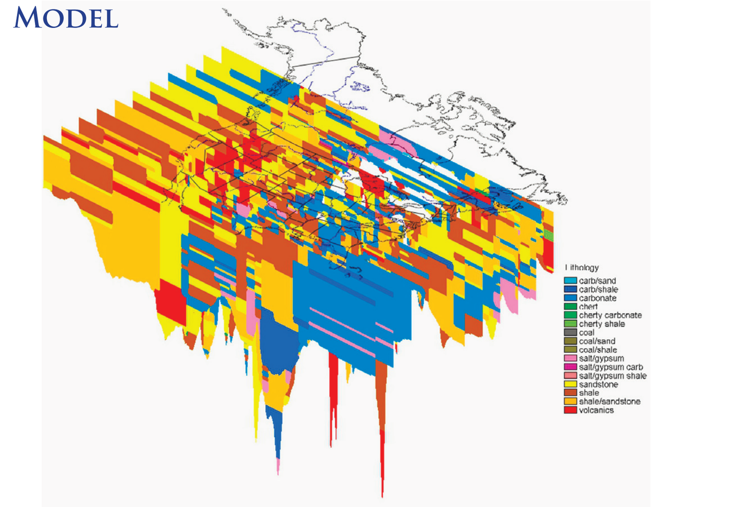
Siliciclastic depositional patterns across North America changed dramatically form the earliest sequences to the later sequences. The Sauk, Tippecanoe and even the Kaskaskia are dominated by carbonate deposition. Whereas, the Absaroka, Zuni and Tejas show increasing amounts of siliciclastic deposition and less and less carbonate rock by percentage. The volume of sedimentation for the earliest three sequences is also fairly constant at 11-13 million km^3 each. Because of increasing siliciclastic deposition, the Absaroka shows a volume increase to about 16 million km^3. The Zuni sequence exhibits the greatest volume of deposition with over 27 million km^3 of sediment, dominantly siliciclastics, and also the maximum areal coverage of the North American continent.

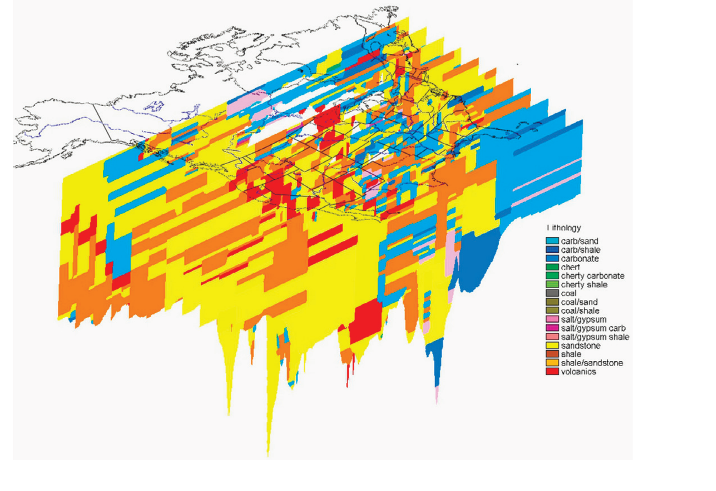
The major shift in depositional pattern, beginning with the Absaroka sequence, coincides with a significant increase in siliciclastic deposition across North America. This is likely related to the changes in tectonic style that occurred at this junction. Prior to the Absaroka, the Transcontinental Arch appears to have dominated deposition across the central USA, and the collisional activity associated with the Appalachian uplift confined much of the siliciclastic deposition to the east coast. Simultaneously, deposition in the Sverdrup Basin, Canada primarily consisted of carbonate rocks.

During the deposition of the Absaroka sequence, subduction along the Western Cordillera began, creating a new source for siliciclastic deposition. The initial sediment pulse was concentrated in the southwestern USA, but soon spread across the northern Rocky Mountain region and Canada by the time of Zuni deposition. A similar shift in depositional pattern also occurred in the Sverdrup Basin, with a shift to dominantly siliciclastic sedimentation during the Absaroka and Zuni.

The Tejas sequence continued the trend in dominantly siliciclastic deposition, but again tectonics seemed to control the locations. The uplift of the Western Cordillera and drainage of the floodwaters associated with the Western Interior Seaway caused a major drainage pattern shift from dominantly northwest to southern across the USA and toward the GOM. In Canada, the drainage appears to have shifted from the northwest to the northeast and out through Hudson Bay (Blum and Pecha, 2014).

3-D LITHOLOGY MODEL





ACKNOWLEDGEMENTS

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EXPLORATION APPLICATIONS

Whopper Sand

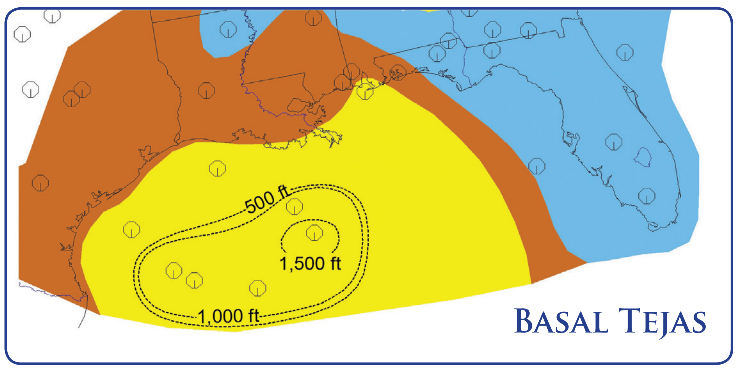
Application of this study may contribute to an explanation for the "Whopper Sand" in the deep Gulf of Mexico. Since 2001 with the drilling of the BAHA-2 well, billions of barrels of oil have been discovered in the Paleocene-Eocene Wilcox-equivalent "Whopper Sand" (Higgs, 2009). This well reportedly encountered 1100 feet of sand in the Lower Wilcox in over 7000 feet of water within the Perdido Fold Belt of Alaminos Canyon. In Keathley Canyon the Sardinia-1 well encountered over 1200 feet of sand and in Walker Ridge, the Jack-2 well and Chinook and Cascade-2 wells reached similarly thick Lower Wilcox sands approaching 1900 feet thick (Trammel, 2006). Average porosity in the whopper sand is 18% and permeabilities range from 10-30 md (Trammel, 2006). Up to 15 billion barrels have been discovered in this trend since 2001.

What makes the Whopper Sand unusual is its location in deep water, nearly 200 miles (300 km) from the Lower Wilcox shelf margin, and far from any conventional sand source (Higgs, 2009). Two competing interpretations have been suggested to explain the presence of the Whopper Sand, one by Higgs (2009) and Sweet and Blum (2011), and a second model supported by Berman and Rosenfeld (2007), Rosenfeld and Pindell (2003), and more recently, Cossey et al (2016).

Berman and Rosenfeld (2007), Rosenfeld and Pindell (2003) and Cossey et al (2016) argue for the "GOM drawdown hypothesis," where the Gulf of Mexico became isolated from the open Atlantic Ocean by the closure of the Florida straits. These authors have suggested a drop in sea level in the center of the GOM of well over 200 m in order to transport the Whopper Sand into its deep-water position.

Higgs and Sweet and Blum have counter-argued that the lack of evaporite-type deposits within the stratigraphic interval precludes this interpretation. Higgs has countered with a more traditional river transport interpretation with drops in sea level of more modest values (100 m) to explain the Whopper Sand and the deep-water canyons. Instead of evaporative drawdown as called on in the first model, Higgs believes sustained river flow into the lowered GOM exceeded evaporation, lowering the salinity and turning the GOM into a brackish lake. Sweet and Blum propose a less extreme model and advocate more traditional long-distance river flow to explain the Whopper Sand.

However, critics argue the "river model" still does not address the high purity (70% sand) and the thickness (>1000 feet) of the Whopper Sand. Rivers today mostly transport clays, with minimal silts and even sands out into deep water.



Whopper Sand Explanation?

Research by Blum and Pecha (2014) may provide an answer to how the Whopper Sand formed in deep-water. These authors used detrital zircons to map out the direction of drainage in the Cretaceous and in the Paleocene across North America. They determined that the drainage patterns shifted dramatically between these two depositional episodes.

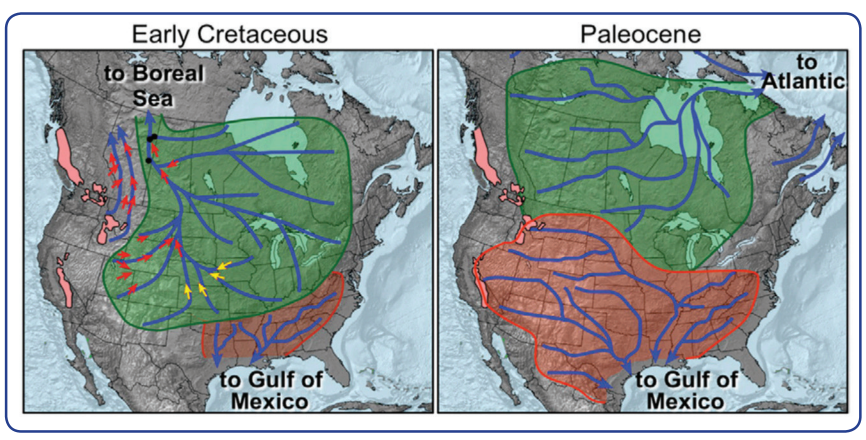
These authors found that during deposition of the Cretaceous (Zuni Sequence), the drainage pattern was dominantly to the north and northwest across much of the USA. Drainage was to the Boreal Sea near present-day Alberta and Saskatchewan. They also determined that very little area was draining to the Gulf of Mexico (GOM) during this time.

In contrast, they determined that the Paleocene drainage shifted dramatically from that of the Cretaceous, resulting in much of the USA draining southward to the GOM. As noted on their map, this was not a single river like the modern Mississippi River, but a series of rivers, effectively behaving more like sheet wash, draining into the GOM all at once. This shift in drainage coincides nicely with the end of the Zuni Sequence and the onset of the Tejas Sequence.

Blum and Pecha (2014) believe this change in drainage occurred because of the high flooding levels of the North American continent during the Upper Cretaceous, known as the Cretaceous Interior Seaway. They claim that the withdrawal of the flood waters during the uppermost Cretaceous and earliest Paleocene caused significant reorganization in the drainage pattern and a reverse in flow toward the GOM.

The Whopper Sand may be a consequence of this rapid drainage shift, when multiple rivers began to suddenly and simultaneously drain off the continent (Interior Seaway) into the GOM, permanently reversing the earlier direction of flow. This shift seems to be marked by the sudden change in deposition at the Zuni-Tejas sequence boundary where the uppermost Zuni layer (the Lower Paleocene Midway Shale) changes to the Paleocene-Eocene Whopper Sand. Initial drainage rates in the Paleocene, coinciding with a sudden drop in sea level at the onset of the Tejas, were likely high volume and highly energetic, providing a possible mechanism to transport the thick Whopper Sand into deep-water. Over time, the drainage volume lessened, lowering the energy available for transport, until the present-day pattern developed. We now observe small flows compared to what was likely happening during the initial draining of the vast Cretaceous Interior Seaway.

Are there more "Whopper Sands" off North America and even other continents?



Blum and Pecha (2014)

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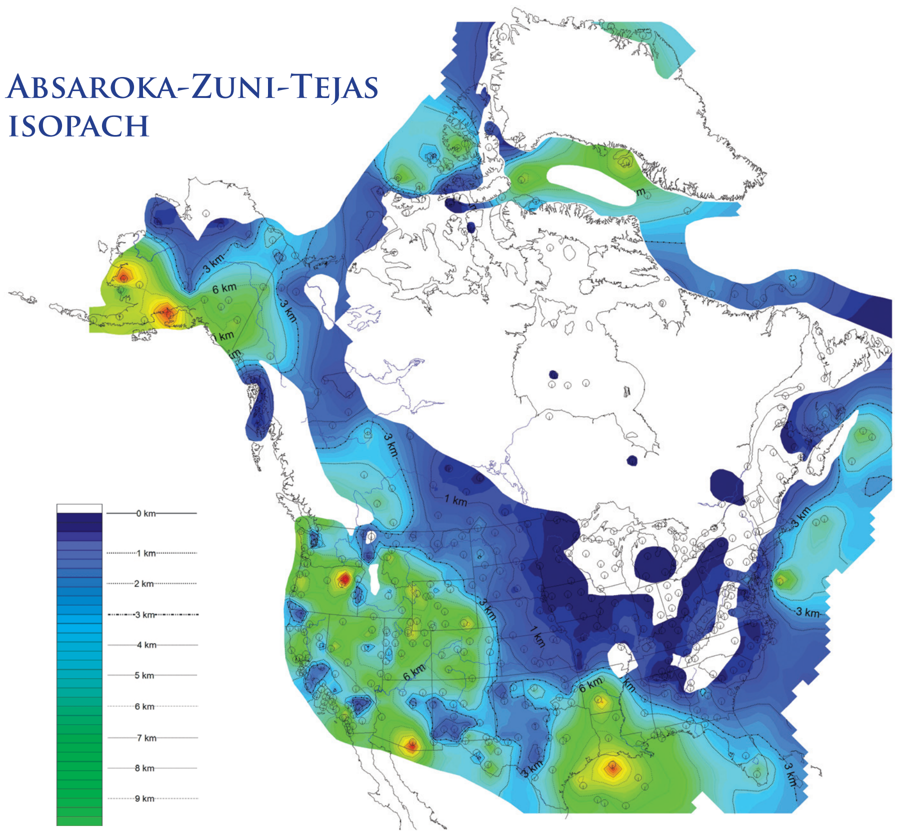
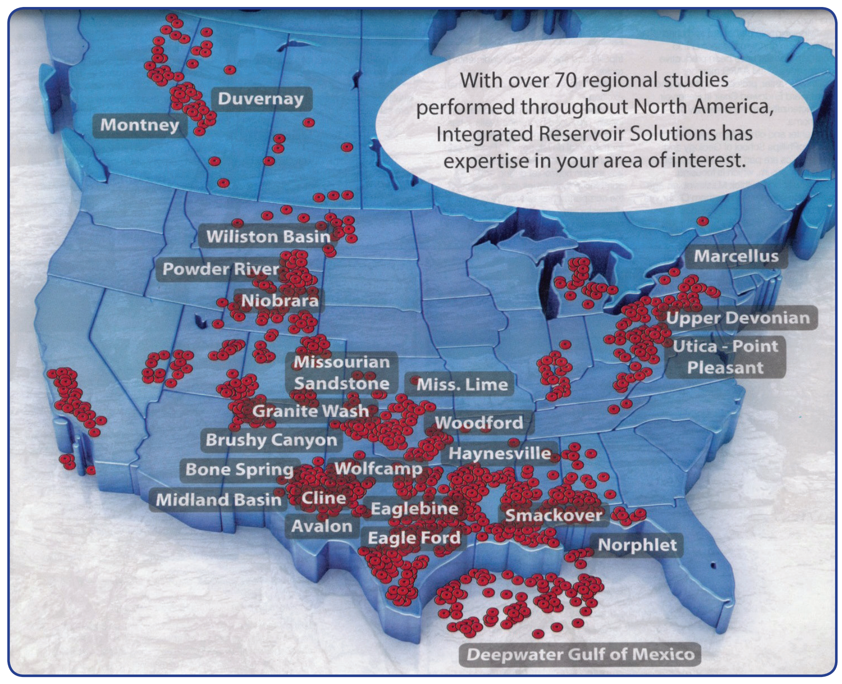
Untapped Potential in Arizona?

Examination of the Absaroka-Zuni-Tejas combined isopach map shows a thick stratigraphic section across Arizona, and southern Arizona in particular. Few wells have penetrated these sections. Thick, untapped sediments, including shale beds, are identified in stratigraphic sections across this area.

Is this an area of unidentified fracking potential?

Absaroka-Zuni-Tejas isopach





Taken from *AAPG Explorer* advertisement

Stratigraphic Sections Across Arizona