Reservoir Geology of the Morrow Formation, Eastern Colorado and Western Kansas: Implications for CO2 Sequestration and EOR

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ABSTRACT

One of the initial CO_2 sequestration options is geologic storage of CO_2 in depleted and partially depleted oil and gas fields for enhanced recovery. This option, already being established, will continue and expand in the near and mid term because of value-added benefits and a well-established infrastructure. To implement this technology at a much larger scale, however, much research is needed to understand reservoir geology at a higher level of detail than has often been attained for onshore oil and gas fields in the US.

Incised valley-fill systems are one reservoir type that has produced large volumes of oil and gas onshore in the US. These reservoirs will become important as candidates for future EOR/CO_2 sequestration projects. This paper presents the results of a reservoir geology study utilizing a data set of 3500 wireline well logs and 65 cores to research lower Pennsylvanian Morrow Formation incised valley-fill reservoirs in eastern Colorado and western Kansas. These reservoirs have produced greater than 100 million barrels of oil and 500 billion cubic feet of gas, and may be future candidates for CO_2 EOR/sequestration operations. They are also excellent analogs for potential CO_2 EOR/sequestration applications in other incised valley-fills.

Depositionally updip to downdip facies changes in these valley-fill units impact trapping styles, reservoir complexity, and thus, reservoir performance. Also, cross-cutting valley systems are important to consider as escape pathways. The reservoir models constructed in this study coupled with production history matching, reservoir pressure data, and reservoir fluid relationships demonstrate high potential for CO_2 injection but also suggest potential pitfalls to be avoided.

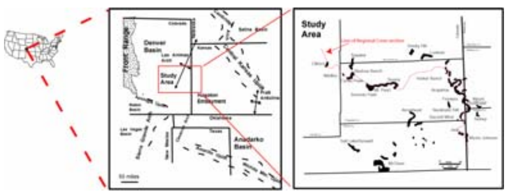
INTRODUCTION

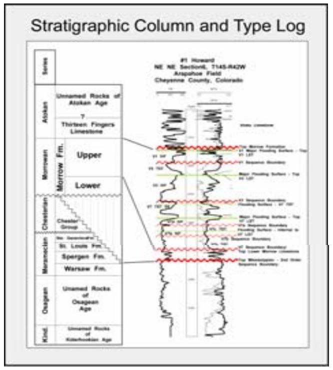
Incised valley-fill sandstones of the Lower Pennsylvanian Morrow Formation in eastern Colorado and western Kansas have produced more than 100 million barrels of oil and 500 billion cubic feet of gas. The 3,500 exploration and development wells that targeted these reservoirs provide a unique data set to study incised valley-fill sandstones. These sandstones are important to understand as potential CO_2 EOR/sequestration opportunities because they are one of the most significant oil and gas reservoir types in the world. Brown (1993) estimated globally that approximately 25% of all off-structure clastic reservoirs containing conventionally trapped hydrocarbons are incised valley-fill deposits.

This poster documents three valley-fill reservoir systems that are a part of the Morrow Formation responsible for oil and gas production in eastern Colorado and western Kansas. The internal stratigraphy of one of these incised valley-fill systems is documented in detail. Within this valley-fill system three facies tracts with unique reservoir characteristics comprise the incised valley-fill: (1) the updip facies tract is dominated by amalgamated fluvial channel sandstones, (2) the transition facies tract consists of fluvial channel sandstones interbedded with finer grained estuarine sandstones, and (3) the downdip facies tract consists of ribbon-like fluvial channel sandstones isolated within estuarine shale. These facies tracts reflect the response of valley-fill sedimentary processes to high-frequency relative sea level changes resulting from glacio-eustacy. This stratigraphy is shown by a longitudinal cross-section through one trunk incised valley-fill drainage with continuous control for 150 miles (241 km) down depositional dip. Along this traverse, internal valley-fill strata change significantly as a function of the interplay of varying depositional systems down gradient in the valley. Key contrasts in reservoir performance are documented as a function of changes in reservoir characteristics, trap controls, and trap configurations from updip to downdip within this valley.

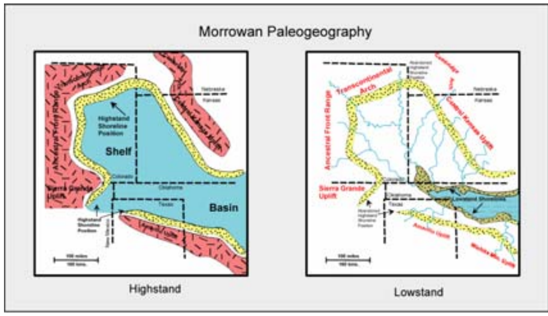
The nature of this incised-valley system requires regional analysis to discern the significance of the internal valley-fill stratigraphy and its relationship to the productive Morrow reservoirs. Accordingly, the purposes of this paper are to: (1) document the regional sequence stratigraphic framework of the Morrow Formation in eastern Colorado and western Kansas, focusing on the complexity of facies associations and key surfaces (2) demonstrate depositional down dip changes in reservoir characteristics and trapping style within one single valley-fill system along 150 miles (241 km) of its course, (3) relate these changes in reservoir characteristics and trapping styles to the potential for CO_2 EOR/sequestration operations, and (4) to suggest the next step in future research of these systems to further their usefulness as analogs for CO_2 sequestration operations.

Location map of the study area

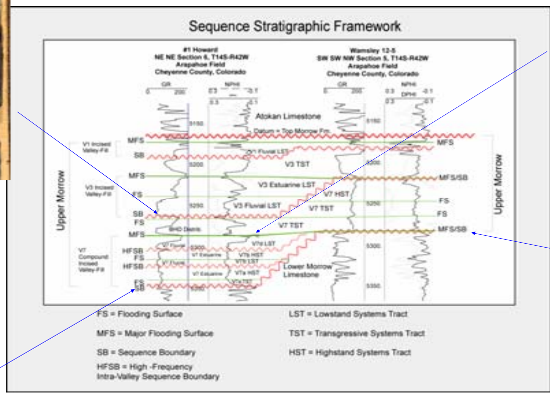




Stratigraphic column and type log of the Morrow Formation in eastern Colorado and western Kansas. Key surfaces are shown and internal stratigraphic nomenclature is annotated.

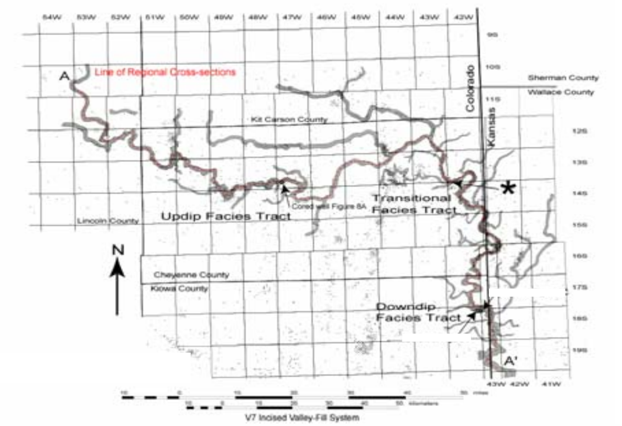


Schematic diagram showing the distribution of depositional systems during deposition of the Morrow Formation. (A) During relative highstands of sea level shorelines rimmed the basin and black muds were deposited on a shallow widespread shelf. (B) During relative lowstands, an extensive series of drainages were developed in eastern Colorado and western Kansas that flowed into the Anadarko Basin. Modified from Swanson (1979) and Sonnenberg (1985).



Two well cross-section through the Morrow Formation illustrating the sequence stratigraphic framework of Morrow depositional sequences in eastern Colorado and western Kansas. The upper Morrow siliciclastic interval lies unconformably on lower Morrow limestone. The V7 compound valley-fill comprises four high-frequency sequences, three of which are represented by strata in the well bore used for this cross-section. The V7 compound valley-fill is capped by a major flooding surface across which the V7 interfluve regions are flooded. Above this surface, a series of backstepping parasequences reflect an overall relative rise in sea level associated with the TST of the V7 sequence, and, where not removed by truncation below the V3 sequence boundary, are followed by fine-grained strata of the prograding HST. The V7 composite sequence is overlain by the V3 sequence. Within the V3 valley, coarse-grained fluvial deposits rest unconformably over black marine shales. A vertical change in lithofacies from fluvial to estuarine is separated by a high-frequency flooding surface within the valley-fill, and a vertical change from estuarine lithofacies to black marine shale is separated by a major flooding surface that transgresses both the valley and the interfluve. The V3 TST is truncated below the V1 sequence boundary. The V1 sequence is very similar to the V3 sequence but has less local relief on the sequence boundary. The V1 sequence is truncated below the sequence boundary at the base of the Atoka Limestone.

A



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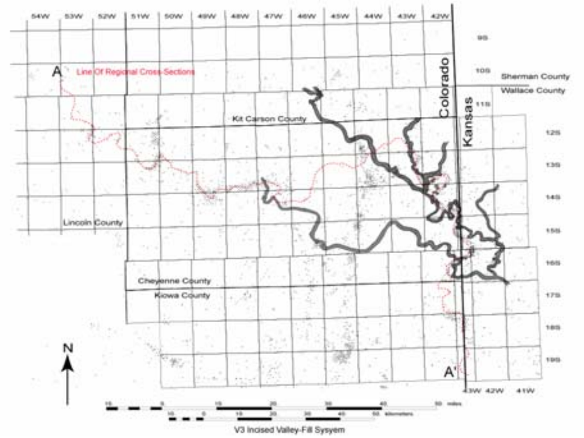

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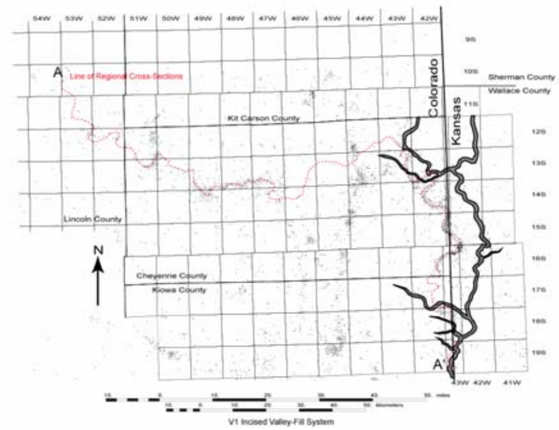
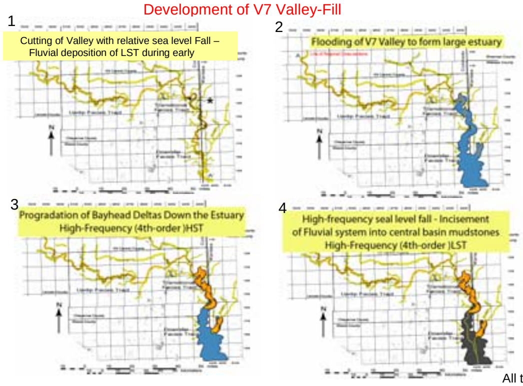
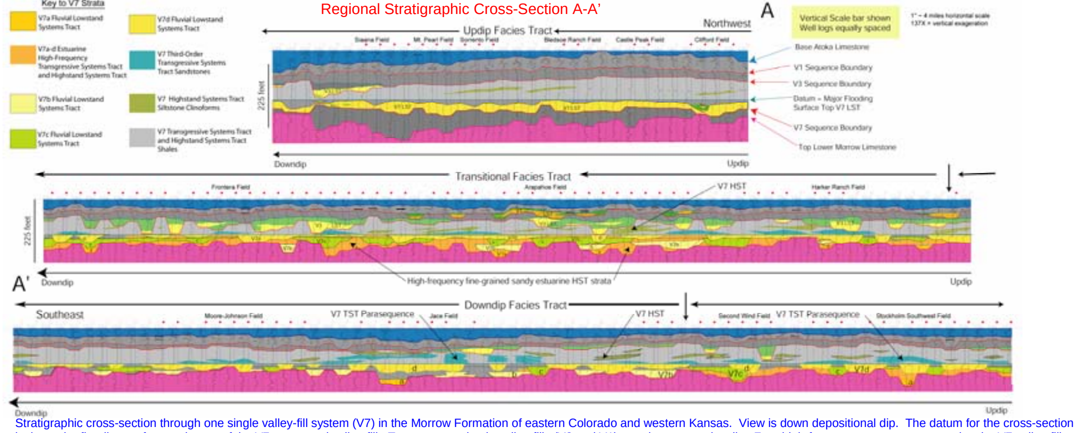


Maps showing the distribution of the Morrow Formation incised valley-fills that are the focus of this study: (A) the V7 compound valley-fill system, (B) the V3 valley-fill system, and (C) the V1 valley-fill system. The line of regional cross-sections (A-A') is shown by the dashed red line.

Development of V7 Valley-Fill



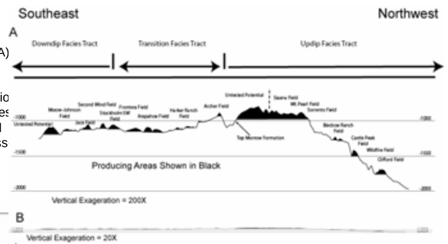
Regional Stratigraphic Cross-Section A-A'



Stratigraphic cross-section through one single valley-fill system (V7) in the Morrow Formation of eastern Colorado and western Kansas. View is down depositional dip. The datum for the cross-section is the major flooding surface at the top of the V7 compound valley-fill. Two younger simple valley-fills (V3 and V1) are also present locally. Four high-frequency sequences comprise the V7 valley-fill system, a compound valley-fill. The high-frequency sequences are confined within the LST (compound valley-fill) of the composite V7 sequence. Each high-frequency sequence (V7a, V7b, V7c, and V7d) has a fluvial dominated lowstand systems tract (LST), a transgressive systems tract (TST) that is often only represented as a transgressive lag within the sequence, and a highstand systems tract (HST) that is represented by prograding bayhead delta strata deposited in a recurring estuary that expanded during periods of valley flooding. The updip facies tract of the V7 compound valley-fill is characterized by amalgamation of fluvial deposits of each of these high-frequency sequences. The individual high-frequency sequences are undistinguishable in this facies tract. The transitional facies tract is marked by the updip limit of the high-frequency sandy estuarine facies, turn-around of the high frequency sequences. At this point, HST fine-grained sandy estuarine fill progrades down the bay formed by flooding during the development of each high-frequency TST. The transitional facies tract is characterized by a complex interfingering of coarse-grained fluvial sandstones and fine-grained estuarine sandstones. The down dip limit of the transitional facies tract is marked by the furthest down-valley extent of these sandy highstand strata. The downdip facies tract is characterized by high-frequency, tidally influenced, fluvial LST incised valley-fill units (a, b, c, and d) separated by predominantly estuarine, central basin mudrock facies. The V7 compound valley-fill is capped by a major marine flooding surface that transgresses interfluve regions. Above the major flooding surface the V7 TST is represented by a series of backstepping parasequences that are sandiest and best developed where side inputs of sediment from tributaries that entered during early development of the TST. These parasequences give the false impression of being time equivalent because of the flattening of the cross-section on the major flooding surface of the V7 composite sequence. In reality, this surface gently slopes in a down depositional dip direction, and, thus, progressively updip parasequences are younger. Above the V7 TST, weakly developed clinoform geometries are observed in the V7 HST. The V7 HST is truncated below the sequence boundary of the V3 sequence.

Trapping Configurations

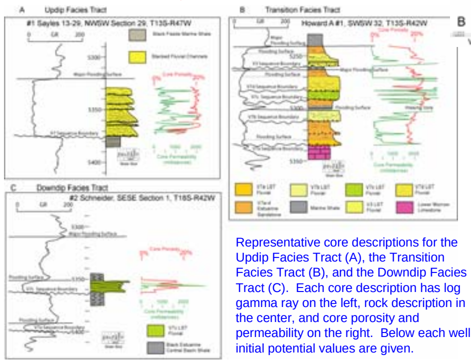
All traps in study area result from a combination of structure and stratigraphy. High-frequency sequences and down-valley facies changes impact reservoir compartmentalization, and reservoir performance.



FACIES TRACTS-V7 Incised Valley-Fill

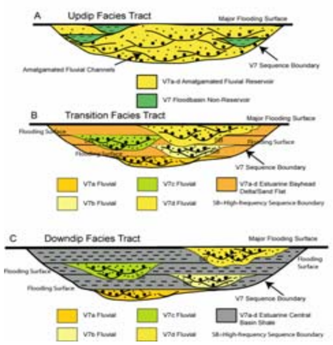
Three informal facies tracts are present along the valley, based on the nature of the lithofacies. The V7 strata up-valley are informally designated the updip facies tract. This region is labeled the updip facies tract on Map A. This facies tract comprises amalgamated fluvial deposits (see core description A and schematic cross-section A). Down-valley of the updip facies tract, high-frequency sequences are recognizable within the V7 compound valley-fill. The upper region of this down-valley segment contains complexly interbedded fluvial and estuarine sandstones (see core descriptio B and schematic cross-section B) and is designated informally as the transition facies tract on Map A. The lower region of this down-valley segment contains interbedded fluvial sandstones and estuarine shales (see core description C and schematic cross section C) and is designated informally on Map A as the downdip facies tract.

Core Descriptions for each Facies Tract



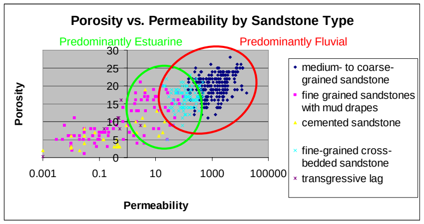
Representative core descriptions for the Updip Facies Tract (A), the Transition Facies Tract (B), and the Downdip Facies Tract (C). Each core description has log gamma ray on the left, rock description in the center, and core porosity and permeability on the right. Below each well initial potential values are given.

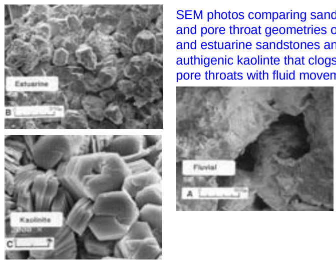
Schematic Cross-sections for each Facies Tract



Schematic cross-sections perpendicular to the axis of the V7 compound valley-fill. These cross-sections show facies variations and the key surfaces in each of the three informal facies tracts: (A) updip facies tract, (B) transition facies tract, and (C) downdip facies tract.

Reservoir Characteristics





SEM photos comparing sand grains and pore throat geometries of fluvial and estuarine sandstones and authigenic kaolinte that clogs smaller pore throats with fluid movement

The reservoir characteristics of different sandstone types is dramatically different. The coarse-grained fluvial sandstones have the best reservoir characteristics, the fine-grained estuarine sandstones have much poorer reservoir quality.

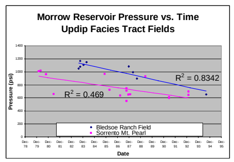
Fluvial Sandstone Facies

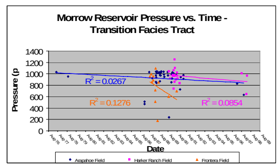
Estuarine Facies

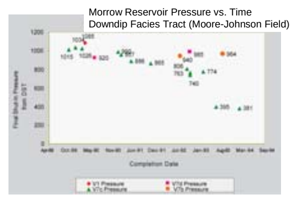
Marine Facies

Production Characteristics and the Potential for CO2 EOR/Sequestration

Production characteristics and the potential for CO2 EOR/sequestration in each of the facies tracts are primarily a function of the reservoir quality, internal reservoir heterogeneity, and the volume of reservoir versus non-reservoir rock comprising the valley-fill of these facies tracts. The best overall reservoir quality, the fewest internal barriers and baffles, and the highest proportion of reservoir versus non-reservoir rock in the valley-fill is in the updip facies tract. The transitional facies tract has lesser reservoir quality than the updip facies tract because of interbedded fine-grained estuarine sandstones, is heterogeneous with many baffles and barriers causing reservoir compartmentalization, and has a lower proportion of reservoir to non-reservoir facies comprising the valley-fill. The downdip facies tract has very good reservoir quality but has vertically segregated reservoirs and a much lower volume of reservoir versus non-reservoir rock comprising the valley-fill. Reservoir pressure versus time diagrams drawn from data collected from progressive field development wells demonstrate the degree of compartmentalization in the three facies tracts (see charts below).







Future Work

➢Create a digital 3-d reservoir model of each facies tract
➢Challenge core plugs of each reservoir lithofacies with supercritical CO2 at reservoir temperature and pressure to document potential geochemical alterations
➢Simulate CO2 injection into each of these facies tracts to compare results

Facies Tract	Cumulative Oil (Bbls.)	Number of Wells	Ave. per Well Production	CO2 Sequestration Potential Based on Reservoir Volumetrics
Updip	26,425,000	95	278,000	8,277,667 metric tonnes
Transition	33,720,000	299	112,776	9,106,151 metric tonnes
Downdip	1,980,000	28	70,714	846,236 metric tonnes

Conclusions

Extensive valley-fill systems can be mapped in the Morrow Formation (Lower Pennsylvanian) of eastern Colorado and western Kansas because of the high density of wells drilled to explore and develop Morrow sandstone reservoirs. One system in particular, the V7 compound valley-fill system, can be mapped for 150 miles (241 km) with great detail. The valley-fill system is subdivided into three facies tracts, each having significant differences in reservoir quality, reservoir compartmentalization, and trapping characteristics.

(1) Amalgamated fluvial deposits characterize the “updip facies tract.” The reservoirs in this segment of the valley-fill system have excellent lateral and vertical continuity, high porosity, and high permeability. Oil and gas fields result from combination structural/stratigraphic traps with the ribbon-like sandstones draped across structures and bending updip against structural strike. The reservoirs within this facies tract have demonstrated the best production performance, the most efficient response to pressure maintenance , and are the best candidates for CO2 EOR/sequestration operations.

(2) High-frequency sequences are discernible in the “transition facies tract,” which is characterized by high-frequency, lowstand fluvial sandstones within a matrix of estuarine sandstones and volumetrically less significant, estuarine shales. Oil and gas fields again result from combination structural/stratigraphic trapping. However, baffles are common within the reservoirs due to differences in permeability between fluvial sandstones and less permeable estuarine sandstones, and occasional barriers result from estuarine mudstones. Less oil, gas, and potentially CO2 can be stored in an equivalent volume of reservoir in the transition facies tract than the updip facies tract because of lower porosity in the estuarine sandstones. Drainage of these reservoirs is also less efficient because of baffles and barriers within the reservoirs. They are more complex reservoirs and CO2 EOR/sequestration operations would be more complicated.

(3) High-frequency lowstand fluvial sandstone units that are encased within estuarine central basin mudstone facies characterize the “downdip facies tract.” Trapping relationships in the downdip facies tract are also structural/stratigraphic. Because the central basin mudstone units act as seals for individual lowstand fluvial sandstones within the valley in the downdip facies tract, several distinct reservoir containers with different fluid contacts and separate pressure regimes are commonly present in the same field as the compound valley drapes a structural high. Fields in this downdip facies tract tend to be smaller with lower per well reserves than the updip and transition facies tract fields. The downdip reservoirs are the narrowest in cross-section of the three facies tracts and are smallest volumetrically per equivalent valley-fill volume because the estuarine mudstones, a significant component of the downdip valley-fill, have no storage capacity. CO2 EOR/sequestration operations in this facies tract would be most limited by storage capacity.

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