Regional sequence stratigraphic setting and reservoir geology of Morrow incised-valley sandstones (lower Pennsylvanian), eastern Colorado and western Kansas

David W. Bowen and Paul Weimer

ABSTRACT

Oil and gas exploration for the lower Pennsylvanian Morrow Formation of eastern Colorado, western Kansas, and northwestern Oklahoma provides a subsurface data set that transects the entire range of lowstand depositional systems from incised-valley-fill systems to deep-water basin-floor systems in one composite depositional sequence. One compound incised-valley fill that is a part of this system contains three facies tracts with unique reservoir characteristics: (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 ribbonlike fluvial channel sandstones isolated in estuarine shale.

A 175-mi-long (283-km-long) longitudinal cross section through one trunk of the incised-valley-fill drainage shows that 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 in this valley-fill drainage.

The strata of the Morrow Formation were deposited in a cratonic basin during a period in the Earth's history when the climate was cooler than today. High-frequency changes of sea level across an extremely low-gradient depositional surface controlled erosion and deposition. These facies tracts reflect the response of valley-fill sedimentary processes to high-frequency relative sea level changes resulting from glacio-eustasy. The resultant valley-fill systems have many characteristics in common with published valley-fill models, but have significant differences as well.

Manuscript received April 18, 2001; provisional acceptance November 26, 2001; revised manuscript received September 12, 2002; final acceptance January 15, 2003.

AUTHORS

David W. Bowen ~ *Department of Earth Sciences, Montana State University, 895 Technology Blvd. South #103, Bozeman, Montana, 59718; dwbowen@theglobal.net*

David Bowen received his B.S. degree from Hobart College in 1978, his M.S. degree from Montana State University in 1980, and his Ph.D. from the University of Colorado in 2001. He is a consulting petroleum geologist with Savant Resources LLC and is an associate research professor at Montana State University. His current work focuses on the application of stratigraphy to exploration and exploitation problems in the western United States. His research interests include sequence stratigraphy, basin analysis, and the study of incised-valley-fill systems. David will be an AAPG Distinguished Lecturer in 2003–2004.

Paul Weimer ~ *Energy and Minerals Applied Research Center, Department of Geological Sciences, University of Colorado, Boulder, Colorado, 80309-0399; paul@emarc.colorado.edu*

Paul Weimer holds the Bruce D. Benson Endowed Chair in the Department of Geological Sciences at the University of Colorado, Boulder and serves as director of the Energy and Minerals Applied Research Center. He is the current treasurer of the AAPG. In 2004, he will give the Society of Exploration Geophysicists Distinguished Instructor Short Course.

ACKNOWLEDGMENTS

We thank AAPG reviewers James Coleman, Jr., William Goff, and James Rogers for their insightful reviews and AAPG Editor John Lorenz for his insight and help. An earlier version of the manuscript benefited from the reviews of Andy Pulham, Mary Kraus, Jack Edwards, and Roy Kligfield. We thank several of our colleagues for many lively discussions concerning the Morrow sandstone: Lee Krystinik, Beverly Blakeney-DeJarnett, Al Scott, Steve Gillis, Paul Dowden, Ross Mathews, Stuart Strife, and Dick Castle are especially noted. We thank Jay Austin and John Roesink for their help in drafting figures.

INTRODUCTION

Incised-valley-fill sandstones of the lower Pennsylvanian Morrow Formation in eastern Colorado and western Kansas have produced more than 100 million bbl of oil and 500 bcf of gas. The 3500 exploration and development wells that targeted these reservoirs provide a unique data set to study incised-valley-fill sandstones. This data set allows for the construction of a detailed stratigraphic framework of the Morrow Formation in an area of 7500 mi^2 (19,425 km^2). Within this framework, one valley system is mappable for greater than 175 mi (283 km) along its axis. Full diameter cores have been cut in many of the fields producing from this valley-fill system and provide additional sedimentologic information for understanding and predicting reservoir stratigraphy. Production data and pressure information from drillstem tests support both compartmentalization and communication of Morrow reservoirs because of the nature of facies changes across key surfaces along the valley.

Internal valley-fill strata change significantly along this valley as a function of the interplay of varying depositional systems. Key contrasts in reservoir performance are documented here as a function of changes in reservoir characteristics, trap controls, and trap configurations from updip to downdip.

Morrow Formation strata were deposited in a cratonic basin during a period of Earth's history in which the climate was cooler than today (Crowell, 1999). In this paper, we refer to such an interval as an ''icehouse phase.'' High-frequency changes of sea level across an extremely low-gradient, depositional surface controlled erosion and deposition of these strata. The resultant valley-fill systems have many characteristics in common with published valley-fill models derived primarily from modern systems representing limited time and ancient systems formed during intervals in which the climate was warmer than today (e.g., Zaitlin et al., 1994). We refer to these intervals as ''greenhouse'' phases. However, this paper shows that Morrow Formation valley-fill strata are also significantly different from published valley-fill models.

The Morrow Formation of eastern Colorado and western Kansas has been studied extensively on a field-by-field basis (Table 1). However, 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 downdip changes in reservoir characteristics and trapping style in one valley-fill system along 175 mi (283 km) of its course, and (3) develop a valley-fill model applicable to strata deposited as a result of glacio-eustasy in cratonic basins.

Table 1. Morrow Formation Fields in the Study Area and Selected References for those Fields*

Field	Publication References
Arapahoe	Blakeney et al., 1990; Nolte, 1990
Bledsoe Ranch	Sonnenberg and Von Drehle, 1990
Castle Peak	Bowen et al., 1993
Clifford	Shannon, 1990
Frontera	Blakeney et al., 1990; Shumard, 1991
Grouse	Wheeler et al., 1990
Harker Ranch	Wheeler et al., 1990
Jace	Adams, 1990; Bowen and Weimer 1997
Lookout	Wheeler et al., 1990
Moore-Johnson	Bowen and Weimer, 1997
Mount Pearl	Bowen et al., 1990
Second Wind	Bowen and Weimer, 1997
Siaana	Bowen et al., 1990
Smoky Hill	Bowen et al., 1993
Sorrento	Sonnenberg et al., 1990
Speaker	Wallace and Heintz, 1992
Stockholm Northwest	Moriarity, 1990
Stockholm Southwest	Brown et al., 1990

*See Figure 1 for the location of the fields and Figure 14 for the fields in a trapping configuration. See Bowen (2001) for a complete list of references for each field.

DATA SET

The subsurface data set used for this study comprises wire-line logs, cores, and production information. Approximately 1000 wire-line logs were used for interpretation. More than 65 cores have been cut in the Morrow along this trend, providing detailed lithologic data; many of these descriptions are published in the field studies presented in Table 1. Pressure data acquired from drillstem tests and production data provide important corroboration of stratigraphic interpretations and are discussed in more detail below.

REGIONAL SETTING

Structure

The study area for this project is located in eastern Colorado and western Kansas along the northern and western margins of the Pennsylvanian Hugoton embayment of the Anadarko basin (Figure 1). The major structural feature in the area is the Las Animas arch (Figure 1A), which is primarily a Laramide tectonic feature (latest Cretaceous through Eocene) having local precursory movement during the late Paleozoic (Rascoe, 1978). West of the arch, strata dip northwest into the Denver basin, a Laramide foreland basin associated with the development of the Rocky Mountains (Tweto, 1975). East of the arch, strata dip east-southeast into the Anadarko basin, a Paleozoic basin with initial development during the Cambrian as an extension of the southern Oklahoma aulacogen. These features were important to the migration and entrapment of petroleum in the study area.

Stratigraphy

The Morrow Formation is early Pennsylvanian in age (Figure 2). An angular unconformity, the result of late Mississippian epeirogeny, separates Mississippian carbonate strata from the Morrow Formation. Thin-bedded Pennsylvanian Atoka Formation limestones and shales disconformably overlie the Morrow Formation (Rascoe and Adler, 1983). Morrowan strata in eastern Colorado and western Kansas are informally divided into a lower Morrow limestone interval and an upper Morrow siliciclastic-dominated interval (Figure 2).

The upper Morrow interval is dominated by shallow-marine shales that were deposited on a low-gradient shelf northwest of the Anadarko basin foredeep during relative highstands in sea level (Figure 3A). Encased in the shale are valley-fill strata consisting of interbedded sandstones, siltstones, and shale. The valley fills developed when extensive river systems incised the subaerially exposed marine shelf during periods of relative lowstand (Figure 3B). Using the classification system for valley-fill systems from Zaitlin et al. (1994), both coastal plain and piedmont valley-fill systems are present in the Morrow Formation, with the best reservoirs occupying the piedmont valley fills. Only the piedmont systems reached far enough into the hinterland to access sediments from the Ancestral Front Range, the Transcontinental arch, and the Central Kansas uplift, the three major sand sources for Morrowan river systems of the eastern Colorado–western Kansas drainage

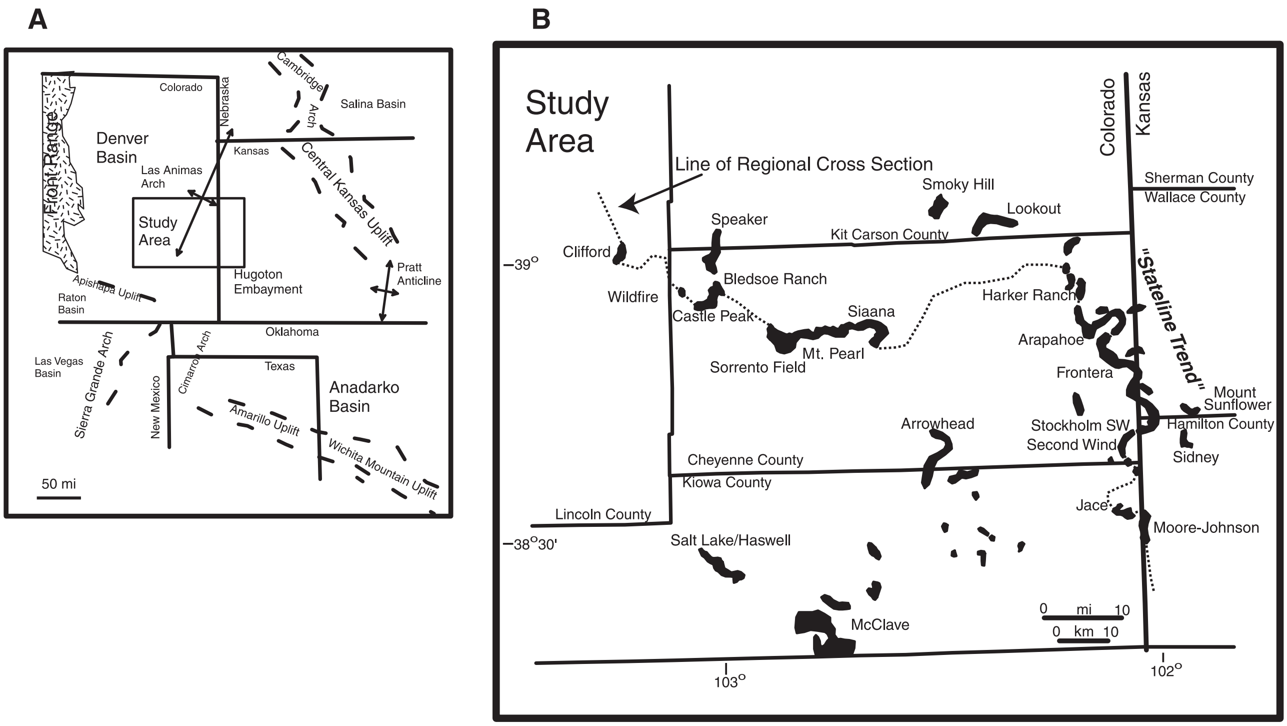
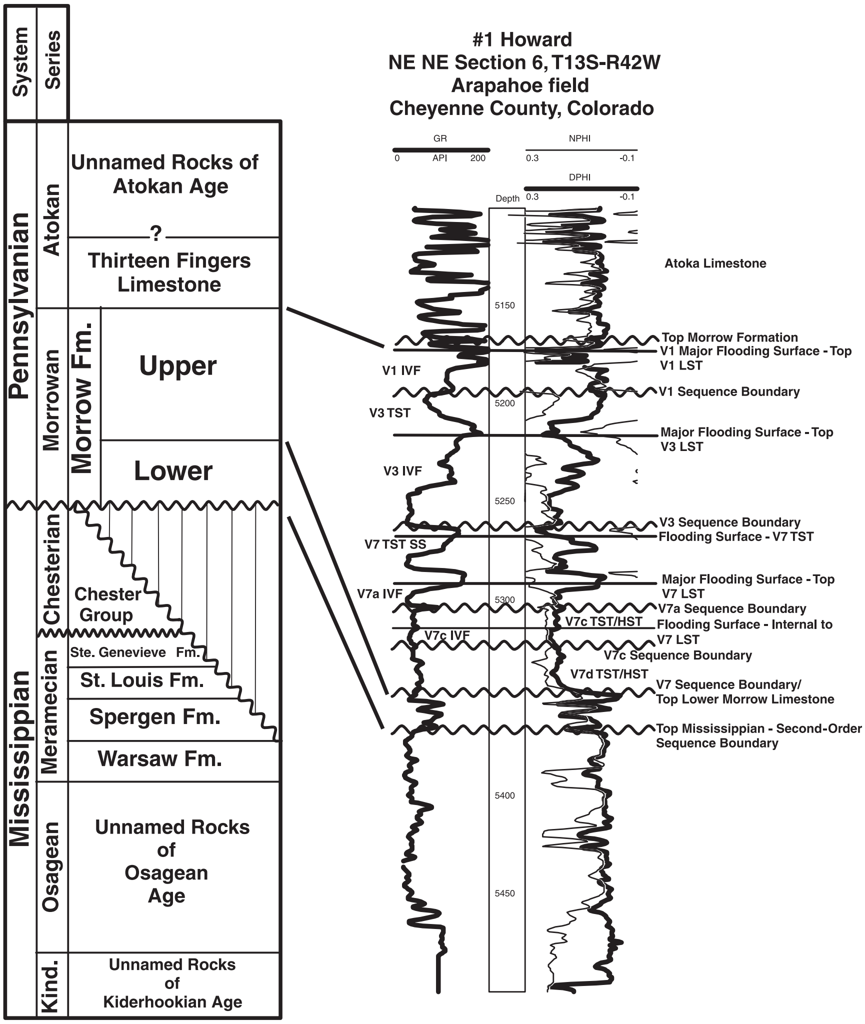


Figure 1. Location map of the study area, eastern Colorado and western Kansas. (A) Major tectonic elements and (B) producing fields are shown. The line of regional cross section (Figures 11, 16) is shown in (B), and location of the Stateline trend.

Figure 2. 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. Location is shown in Figure 10A.



basin (Figure 3). These valleys typically have widths of 0.5–2.0 mi (0.8–3.2 km) in updip depositional positions and 1.0–4.0 mi (1.6–6.4 km) near the shelf edge on the margin of the Anadarko basin in downdip depositional positions. The valleys have incised to depths of as much as 100 ft (30.5 m) (Figure 4). Both simple and compound valley systems are present in the Morrow Formation. Simple valley systems are cut and filled during a single cycle of relative sea level change. Compound valleys are cut and filled during more than one relative sea level cycle and have multiple internal sequence boundaries. Depositional subenvironments in the valley fill vary from fluvial (braided to low-sinuosity to high-sinuosity river systems), estuarine, and marine.

Detailed lithofacies descriptions of petroleum-producing Morrow Formation incised-valley-fill strata are published in Krystinik and Blakeney (1990) and Wheeler et al. (1990). A summary of lithofacies for one depositional sequence is shown in Figure 4. Where a valley is present (Mull Drilling Co. 1 Howard; Figure 4), the sequence boundary is marked by an erosional base cutting into marine shale of the underlying highstand systems tract or directly into lower Morrow limestone. This unconformity is commonly overlain by coarse-grained sandstone or conglomerate lag deposits that grade upward into fluvial, mixed fluvial/estuarine, or estuarine deposits depending on the position along depositional dip in the valley and lateral position in the valley (Figure 5). These valley-fill facies comprise the lowstand systems tract deposits that onlap the valley floor and are the primary reservoir facies.

Medium- to coarse-grained fluvial sandstones are the best reservoirs in terms of production rates and cumulative production. They have porosity values ranging from 18 to 28% and permeability ranging from 0.5 to 2.0 d (Figures 5A, 6). The overlying estuarine reservoirs commonly have lower porosity (8–18%) and lower permeability (10.0–500 md) than the fluvial reservoirs (Figures 5B, 6). The top of the valley fill is marked by a major flooding surface that also floods

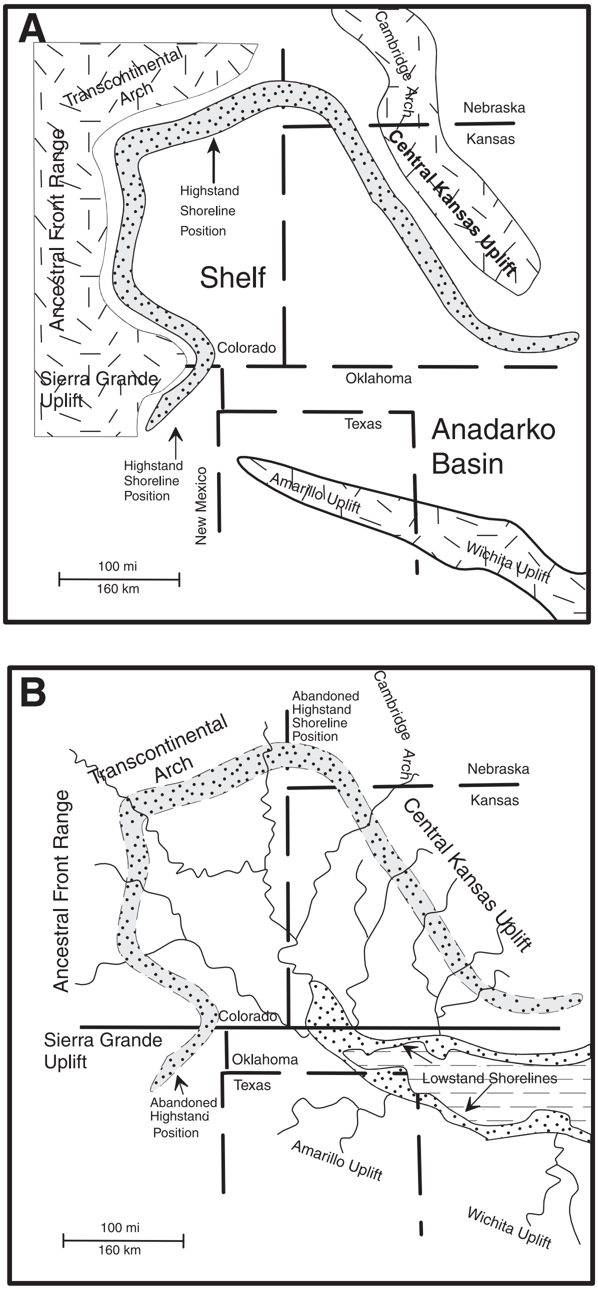


Figure 3. Schematic diagrams showing the distribution of depositional systems during deposition of the Morrow Formation. (A) During relative highstands of sea level, shorelines rimmed the basin, and black muds were deposited on a shallow widespread shelf. (B) During relative lowstands of sea level, an extensive series of drainages developed in eastern Colorado and western Kansas that flowed into the Anadarko basin. Modified from Swanson (1979) and Sonnenberg (1985).

the interfluve regions (Figure 4). Commonly, a transgressive lag deposit, consisting of brachiopod, bryozoan, and crinoid fragments of open-marine origin, occurs at this flooding surface (Wheeler et al., 1990). In places, bayhead delta strata overlie the major flooding surface both above the valley fill and above near-valley interfluve areas. These bayhead delta strata have porosity values ranging from 8 to 18% and permeability ranging from 10.0 to 500 md. The bayhead deltas develop as backstepping parasequences in the transgressive systems tract. These parasequences are lower quality reservoirs than the fluvial units, but can be significant, especially where they are in the gas column. The higher relative permeability of gas overcomes the lower quality of the reservoir. The upper strata of the sequences are marine shales interpreted to represent late transgressive systems tract and highstand systems tract deposition. Outside the valleys in the interfluve areas, no time-equivalent strata exist that correspond to valley-fill strata. Instead, soil horizons and/or exposure surfaces developed. Only transgressive systems tract and highstand systems tract shales are present outside of the incised-valley fills.

In upper Morrow Formation strata of the study area, five valley-fill systems have been identified (Wheeler et al., 1990), each reflecting at least one depositional sequence corresponding to one sea level cycle (sensu Mitchum and Van Wagoner, 1991). Maximum shoreline displacements associated with these sea level fluctuations were at least 175 mi (283 km) across a low-gradient muddy shelf (Figure 3). A portion of the lowstand deposits, specifically the lowstand wedge and lowstand fan strata, is not present in the depositional sequences deposited on the shelf in eastern Colorado and western Kansas. Associated lowstand systems tract strata were deposited to the south in the Anadarko basin (Figure 3B; Andrews et al., 1995; Andrews, 1999). The sequences deposited on the shelf also lack sand-rich highstand systems tract deposits. These highstand deposits probably exist in the subsurface of the Denver basin to the northwest, but control is not adequate to identify the nature of the strata (Figure 1).

During relative lowstands of sea level when the shelf was exposed, paleosols formed at sequence boundaries on the black marine mudstones of the underlying sequence and are preserved on the low-relief interfluves. The significance of these paleosols is twofold. First, soils form during periods of landscape stability, not regional denudation (Birkeland, 1999). Therefore, the absence of earlier highstand systems tract strata is not because of erosion but because of nondeposition on this region of the shelf. Second, preservation of these paleosols demonstrates that little erosion occurred during the subsequent transgression. Sandy highstand systems tract deposits were not eroded by this event. The implication is that sea level rises associated with glacio-eustasy

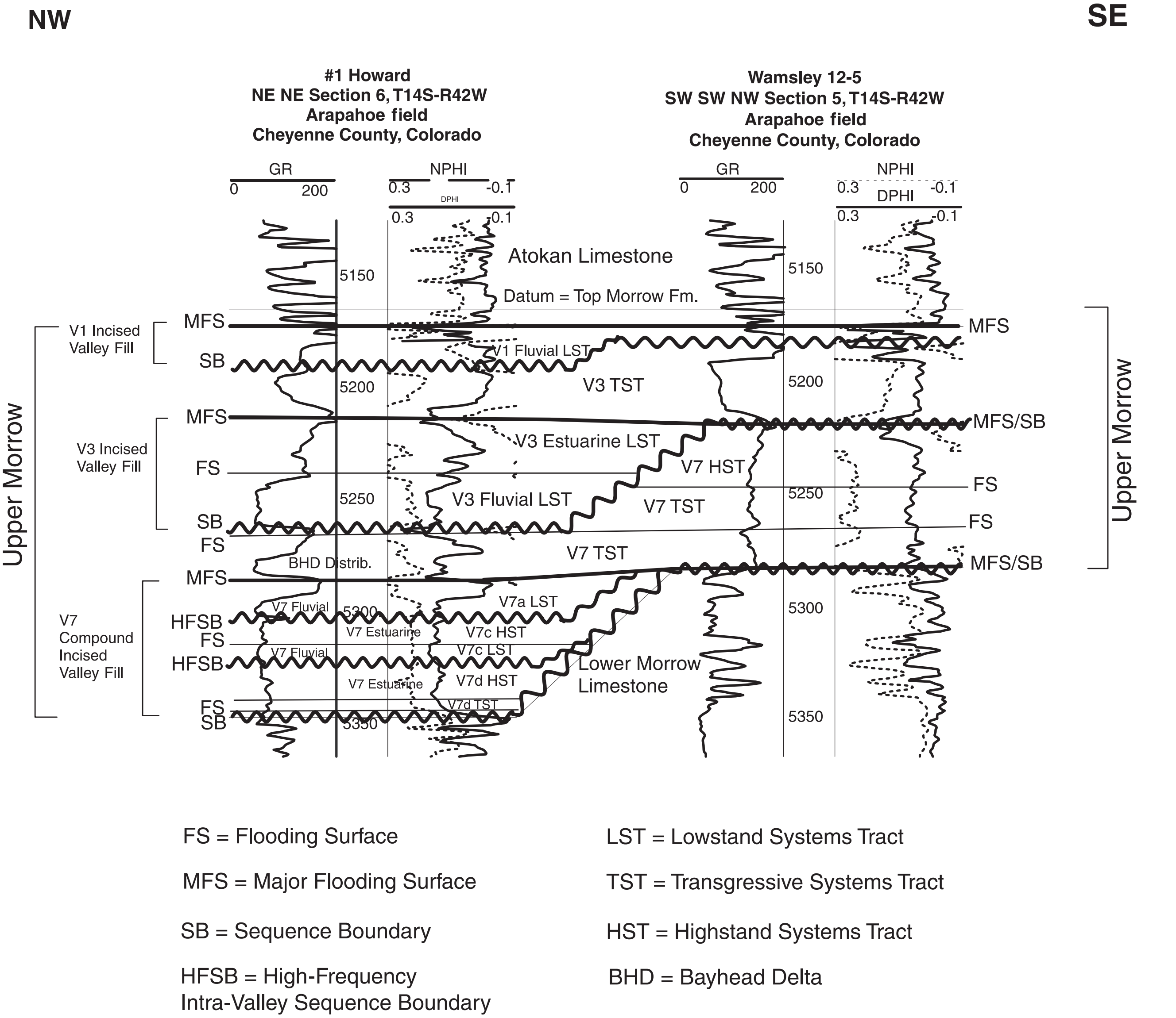


Figure 4. A two-well cross section through the Morrow Formation at Arapahoe field illustrating the sequence-stratigraphic framework of Morrow depositional sequences in eastern Colorado and western Kansas. The upper Morrow siliciclastic interval lies unconformably on lower Morrow limestone. The V7 compound valley fill comprises four high-frequency sequences, three of which are represented by strata in the wellbore used for this cross section. Location of the two wells is shown in Figure 10A.

displaced shoreline facies tracts updip to a significant degree. This displacement did not allow progradation of the shoreline back across the shelf during the subsequent highstand. Another implication is that given the low gradient and the distribution of strata, the glacially controlled fluctuations caused abrupt facies changes.

OIL AND GAS FIELDS

Incised-valley-fill strata are the dominant reservoirs in Morrow Formation oil and gas fields of the study area (Figure 1). Descriptions of many of these fields have been published (Table 1). These fields produce at drilling depths between 4800 and 6800 ft from solution gas/gas-cap expansion reservoirs. The average cumulative production for wells in the study area is 230,000 bbl of oil and 470 mmcf gas. Morrow exploration in the study area began in earnest after 1979, when Mull Drilling drilled the discovery well for Sorrento field and this trend (Figure 1B). Subsequent to that discovery, exploration accounted for numerous additional discoveries along the linear trend of the valley system, resulting in significant oil and gas reserves

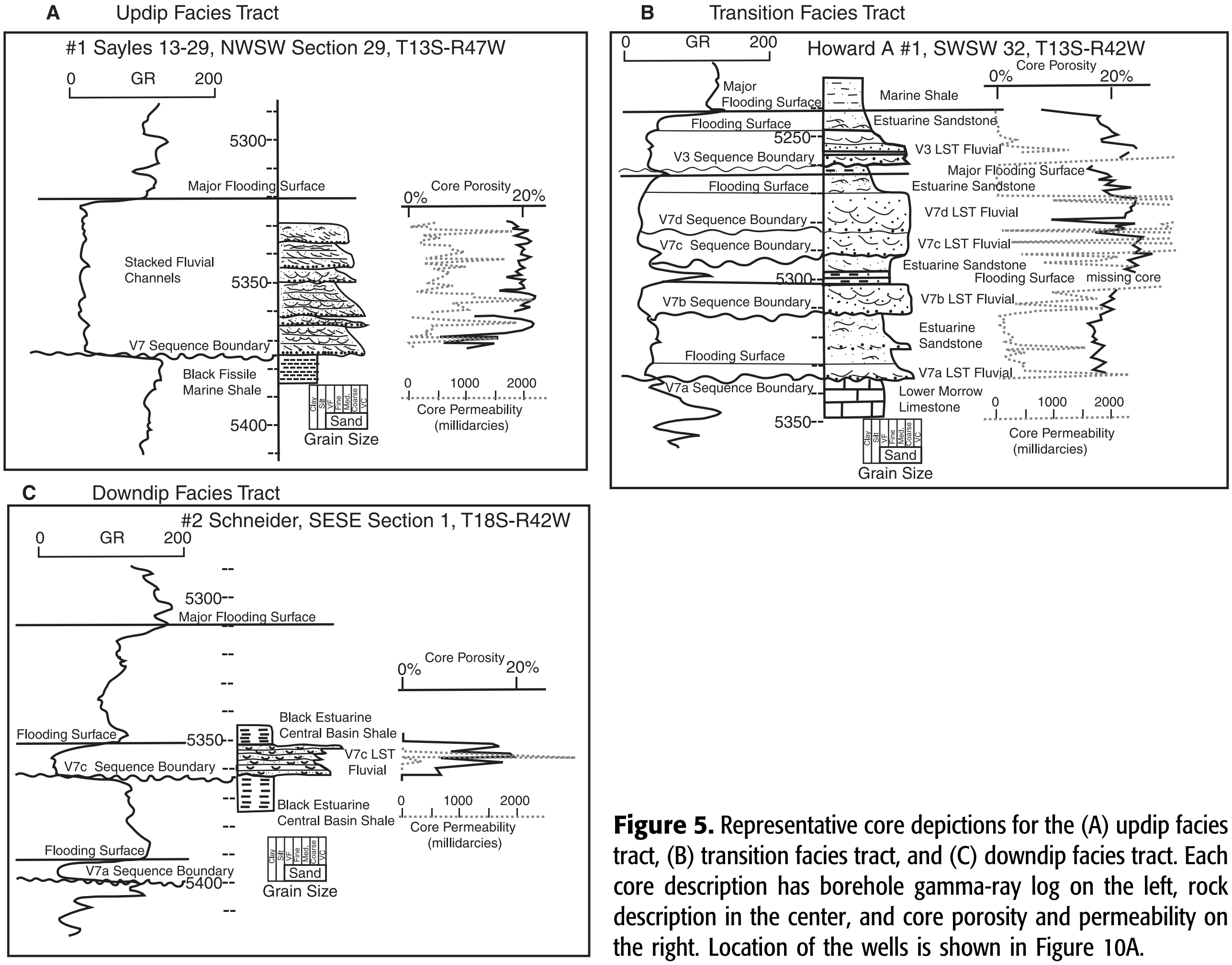


Figure 5. Representative core depictions for the (A) updip facies tract, (B) transition facies tract, and (C) downdip facies tract. Each core description has borehole gamma-ray log on the left, rock description in the center, and core porosity and permeability on the right. Location of the wells is shown in Figure 10A.

(Figure 1; Table 2). The reservoir characteristics, reservoir geometries, and trapping configurations in these fields result from the relationship between valley depositional systems and the structural arrangement of the reservoir and sealing strata. These reservoir factors are defined in a sequence stratigraphic framework and are discussed in greater detail below for each segment of one valley-fill system.

SEQUENCE STRATIGRAPHIC FRAMEWORK

Regional Correlation

A distinct hierarchy of depositional sequences (second to fourth order) are present in the Morrow Formation that are necessary to recognize to correlate accurately the different reservoirs. Specifically, the recognition and correlation of key surfaces (flooding surfaces, sequence boundaries, and their correlative exposure surfaces) provide the stratigraphic framework in which depositional sequences are interpreted (Figure 4). Broad, low-relief shelf physiography, rapid glacio-eustatic sea level fluctuations, low subsidence rates, and low rates of sediment supply influenced the sediment distribution in individual depositional sequences and provided a strong control on reservoir distribution.

In eastern Colorado and western Kansas, the Morrow Formation is bounded at its base by a second-order sequence boundary (base of Absaroka sequence, Sloss, 1963; Ross and Ross, 1988) and at its top by a third-order sequence boundary that separates Morrow siliciclastic strata from Atokan carbonate strata (Figure 2). The upper Morrow siliciclastic interval comprises at least five fourth-order depositional sequences; from oldest to youngest, these are the V11, V9, V7 composite, V3, and V1 depositional sequences (Table 3). This terminology was developed during the mid-1980s at Union Pacific Resources, where workers defined different

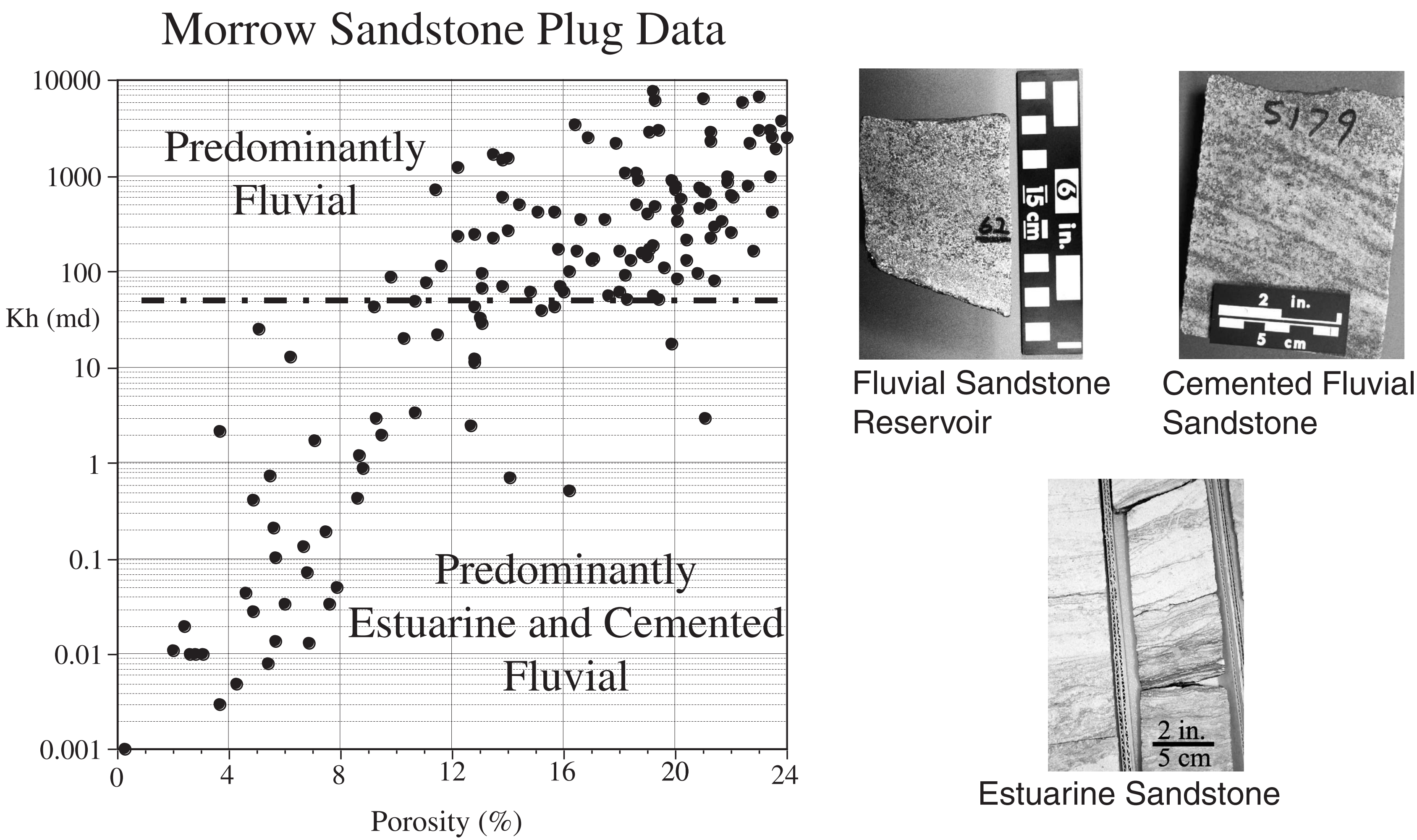


Figure 6. Plot of porosity versus permeability by reservoir lithofacies for core plug data from the Morrow Formation in eastern Colorado. Core photographs of representative lithofacies are shown.

Table 2. Cumulative Oil Production for the Significant Fields in the V-7 Incised-Valley-Fill System Subdivided by Facies Tract*

Field	Facies Tract	Cumulative Oil (bbl)	Number of Wells	Average per Well Production
Clifford	updip	2,000,000	8	250,000
Castle Peak	updip	325,000	6	54,167
Bledsoe Ranch	updip	2,100,000	16	131,250
Sorrento	updip	10,750,000	30	358,333
Mount Pearl/Siaana	updip	11,250,000	35	321,429
	Total updip	26,425,000	95	278,000
Harker Ranch	transition	925,000	23	40,217
Arapahoe	transition	19,920,000	129	154,419
Frontera	transition	3,725,000	35	106,429
Stockholm	transition	6,500,000	93	69,892
Second Wind	transition	2,650,000	19	139,474
	Total transition	33,720,000	299	112,776
Jace	downdip	830,000	13	63,846
Moore-Johnson	downdip	1,150,000	15	76,667
	Total downdip	1,980,000	28	70,714

*Summary values are given for each facies tract. Only oil production numbers are given because cumulative gas production reflects gas reinjection for pressure maintenance operations and because water injection has also occurred in many of the fields.

valley systems (Table 3) based on position in the stratigraphic framework. Although this terminology is widely used by industry (e.g., references cited in Table 1), the results of this study indicate that industry's V5 sequence should be considered part of the V7c and V7d high-frequency sequences contained in the V7 composite sequence. The youngest three of these sequences, V7 composite, V3, and V1, are the focus of this study. The previous V5 occupies space in the third-order sequence boundary that defines the V7 valley.

Regionally mappable unconformities bound each of these fourth-order sequences (Figures 2, 4). Flooding surfaces develop in three places: (1) internal to valley-fill systems, (2) at the top of valley-fill systems and interfluves (major flooding surfaces; Figures 2, 4, 7), and (3) at the top of individual backstepping parasequences in the transgressive systems tract that overlie the valley-fill systems. Diastems at the base of bayhead deltas (Figure 7A, B) develop in bay-fill deposits overlying the lowstand incised-valley-fill strata in the transgressive systems tract. Abrupt vertical changes in lithofacies across these key surfaces produce seals, baffles, or breaches to reservoir compartments, depending on the reservoir characteristics of the deposits juxtaposed across these surfaces.

Table 3. Chart Showing Stratigraphic Nomenclature of Previous Usage Versus Stratigraphic Nomenclature Used in This Study

Previous Stratigraphic Nomenclature	Stratigraphic Nomenclature This Paper
V-1, Johannasberg	V-1
V-3, Johannasberg	V-3
V-4	V-7 TST Sandstone
V-5, Stockholm	V-7c, V-7d
V-6, Stockholm	V-7b
V-7, Stockholm	V-7a
V-9	V-9
V-11	V-11

The geographic distribution of each of these sequences was strongly influenced by both depositional relief created by grainstone shoals in the lower Morrow and erosional relief present on the top of the lower Morrow limestone. An isopach of the Morrow siliciclastic section (top of the Morrow shale to the top of the lower Morrow limestone) is a good proxy for the topography of the lower Morrow limestone surface (Figure 8). Younger sequences progressively onlap onto the lower Morrow limestone (Figure 9). Note that Morrowan strata younger than the V7 major flooding surface (V7 MFS in Figure 9) thicken to the west, the result of basin subsidence after V7 deposition. The narrow topographic low expressed on the lower Morrow surface along the Colorado and Kansas state line is occupied by the V7 compound incised-valley-fill system

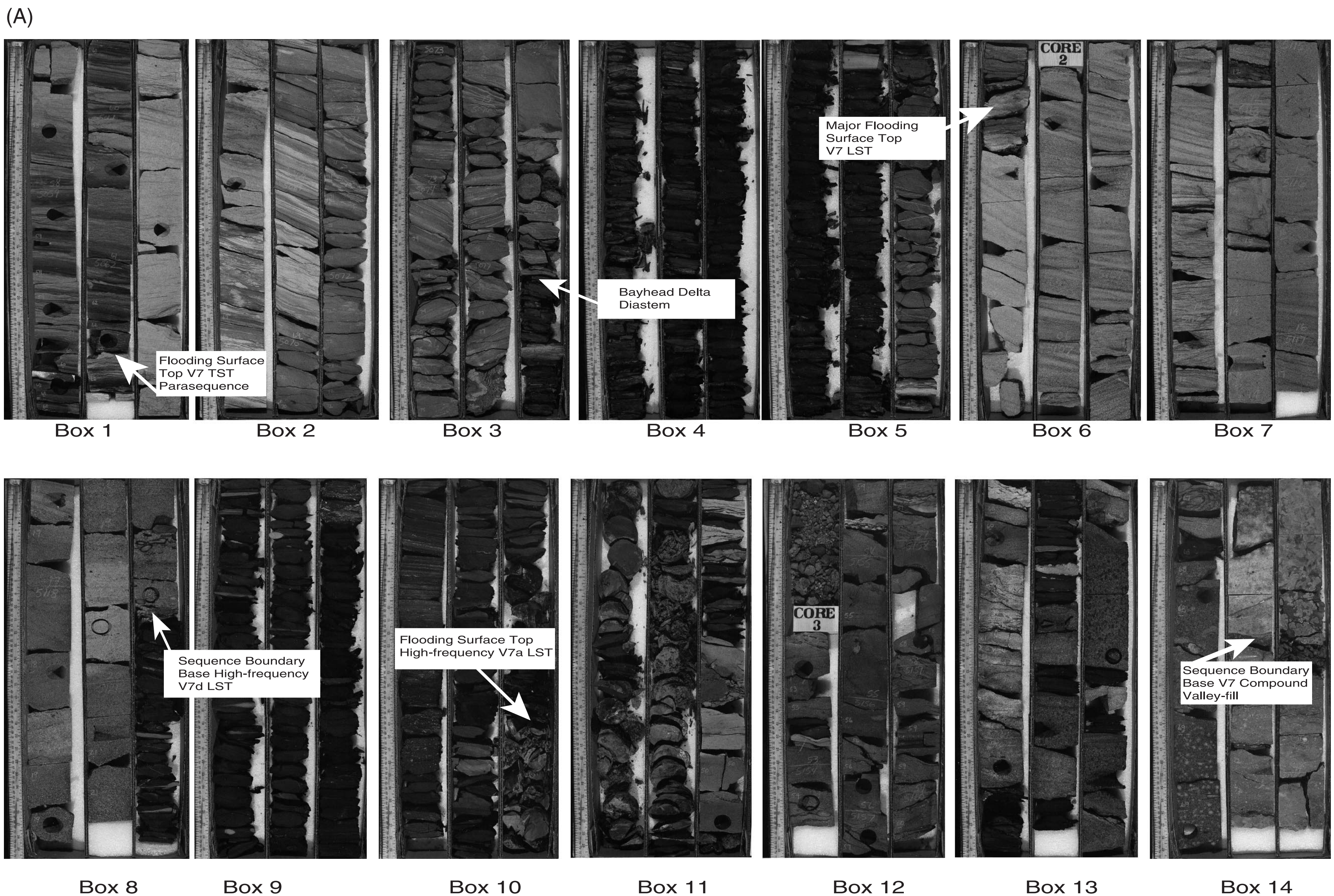


Figure 7. (A) Core photographs of one complete depositional sequence, the V7 composite sequence, 3 Schneider 34-1, SW SE Section 1, T18S-R42W, Jace field. The location of Jace field is shown in Figures 1, 15, and 16. Each core box is 3 ft long. (B) Core description to accompany core photographs of the 3 Schneider 34-1 shown in (A).

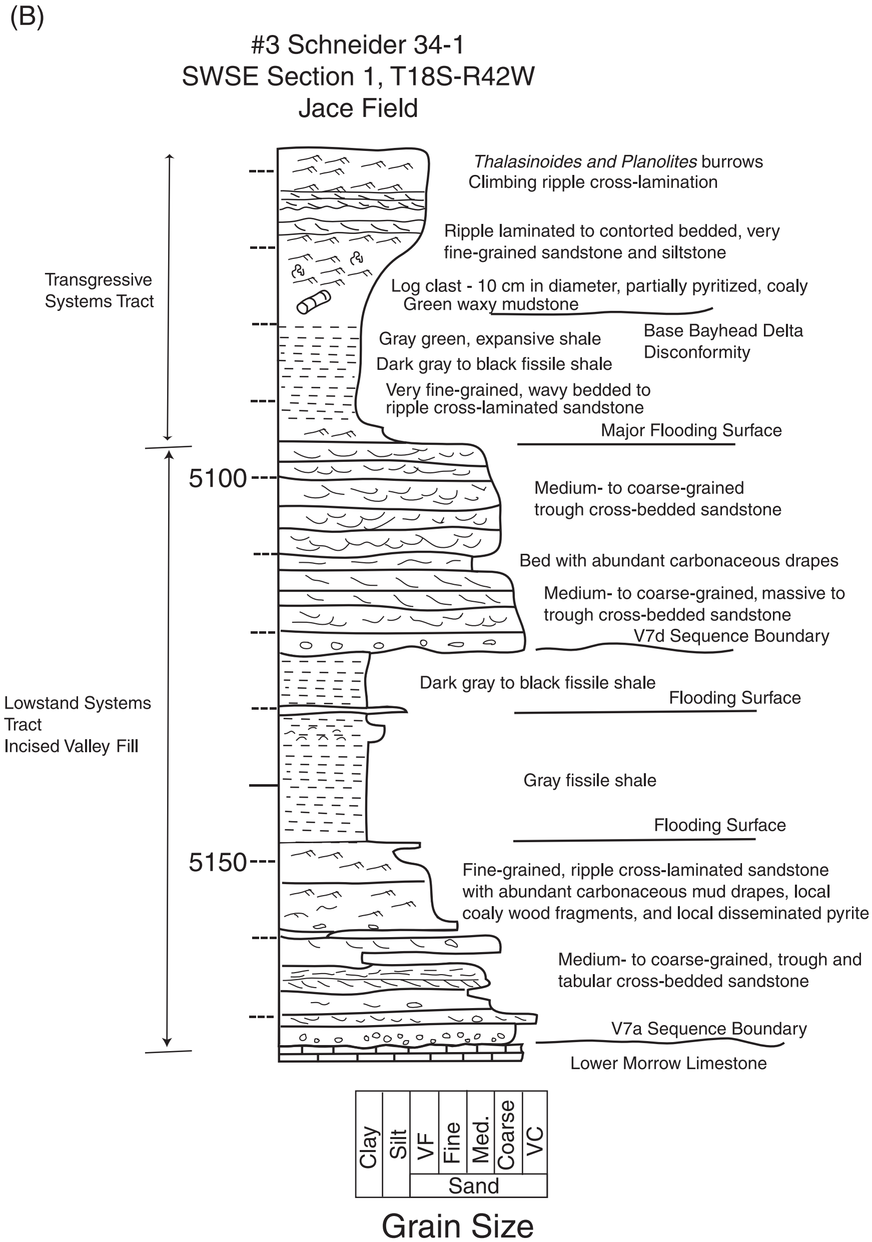


Figure 7. Continued.

(Figures 1, 10A). This low area (Figure 8) facilitated the development of a long, narrow bay during flooding episodes of the V7 composite sequence.

Facies Tracts

Three informal facies tracts are present along the valley, based on the nature of the lithofacies. (1) The V7 strata upvalley from this topographically restricted region (11S, R45W shown by the white asterisk in Figure 8) comprise amalgamated fluvial deposits (see core description Figure 5A) and are designated informally as the updip facies tract (Figure 10A). (2) Within this topographically restricted area, downvalley of the updip facies tract, high-frequency sequences are recognizable in the V7 compound valley fill. The upper region of this downvalley segment contains complexly interbedded fluvial and estuarine sandstones (see core description Figure 5B) and is designated informally as the transition facies tract (Figure 10A). (3) The lower region of this downvalley segment contains interbedded fluvial sandstones and estuarine shales (see core description Figure 5C) and is designated informally here as the downdip facies tract (Figure 10A).

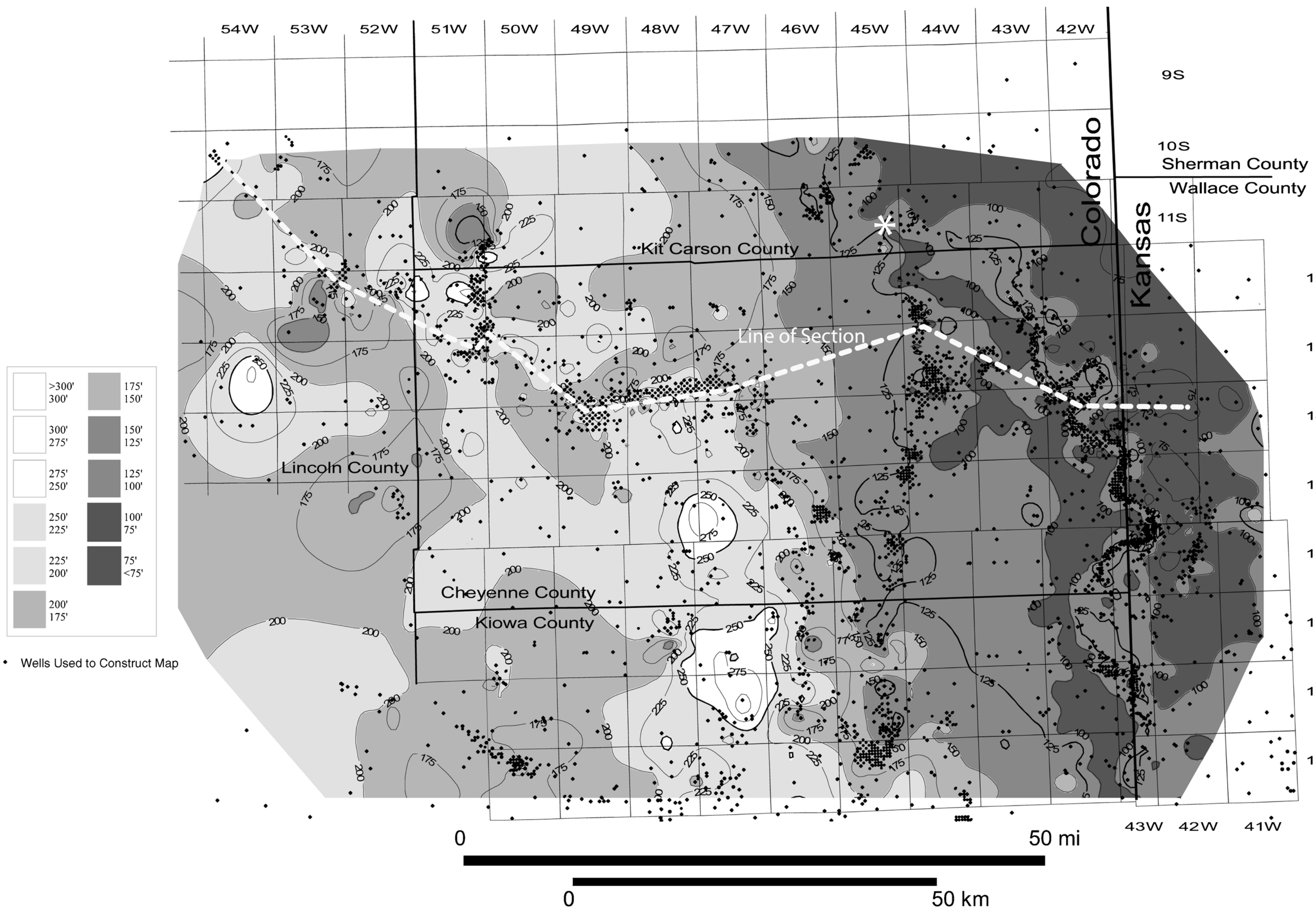


Figure 8. Isopach map of the interval between the top of the Morrow Formation (a relatively flat surface) and the top of the lower Morrow limestone. Note the isopach thick (lighter gray color-fill) along the border between Colorado and Kansas. During the time represented by the V7 compound valley fill, this thick area was alternately occupied by a fluvial system during relative sea-level lowstand and an estuary during relative sea-level highstand. The line of cross section for Figure 9 is shown by white dashed line.

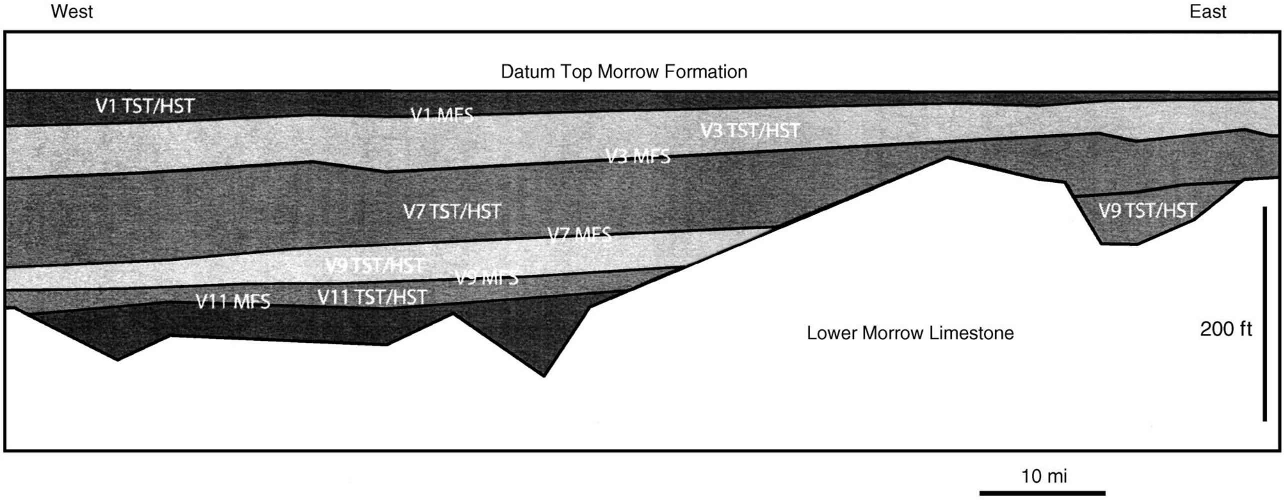


Figure 9. Schematic west-east cross section demonstrating the onlap of progressively younger Morrow sequences onto the lower Morrow limestone. The major flooding surface of each of the sequences in the study area is highlighted and labeled. Location of the cross section is shown in Figure 8.

Local Correlation Concepts: V7 Valley

To illustrate the changing nature of the valley-fill strata, a 175-mi (283-km) cross section was constructed down the axis of the V7 compound valley fill (Figure 11). Logs are spaced about 0.5 mi (0.8 km) apart in producing fields and 2.0–4.0 mi (3.2–6.4 km) apart in nonproductive areas where well control is less dense. This cross section is unique in demonstrating the detailed stratigraphic relationships over such a long distance in one valley system. Correlations on the cross section were derived in and between several continuous loop grid systems, using 1000 digital Morrow logs. Multiple marker horizons (primarily flooding surfaces), both above and below the V7 system, were tied between each loop. This substantially increased correlation confidence in this area of complex stratigraphy. The cross section in Figure 11 provides the foundation for further discussion of the details of the V7 composite sequence and, more specifically, the V7 compound valley fill.

Two important concepts must be recognized to accurately characterize Morrowan valley-fill deposits and reservoirs: (1) reservoir sandstones reflect high-frequency sequences, and (2) both compound and simple valley-fill deposits are present.

High-Frequency Sequences

Mitchum and Van Wagoner (1991) described the differences in stratal stacking patterns between low-frequency (i.e., third-order) and high-frequency (i.e., fourth-order and higher) sequences. These authors derived their findings primarily from Tertiary strata from the northern Gulf of Mexico, reflecting both greenhouse and transitional phases of Earth's history. They used the following parameters for generating their models: high subsidence rate (0.5 ft [0.15 m]/1000 yr) and relative sea level change amplitudes of ±100 ft (30.48 m) for third-order changes, ±40 ft (12.92 m) for fourth-order changes, and ±10 ft (3.04 m) for fifth-order changes. These workers demonstrated the formation of asymmetric, incomplete fourth-order sequences formed only during the falling limb of the third-order sea level cycle (Figure 12A).

Shown in Figure 12B are the resulting stratal patterns for an idealized composite third-order sequence with superposed fourth-order sequences. This composite sequence is bounded at the top and base by third-order sequence boundaries. Between the two boundaries are a series of fourth-order sequences that comprise the lowstand, transgressive, and highstand systems tracts. Each high-frequency sequence is bounded at the top and base by higher frequency sequence boundaries. Each fourth-order sequence is asymmetric in its stacking patterns. Fluvial incision and basinward shift in marginal marine lithofacies occur across the higher frequency sequence boundaries, although the amount of facies dislocation across the boundary and the areal extent of the erosion are considerably less than what is present at the third-order composite sequence boundary. According to this scheme, the greatest amount of fluvial incision occurs early in the lowstand systems tract and late in the highstand systems tract. By comparison, the fluvial incisions in the late lowstand systems tract, transgressive systems tract, and early highstand systems tract are considerably smaller in scale. Fourth-order transgressive systems tract and highstand systems tract strata are deposited across the shelf above both interfluve areas and incised-valley fills of the fourth-order sequences.

To emphasize the differences between the high-frequency incised-valley fills described by Mitchum and Van Wagoner (1991) and Van Wagoner (1995) with those of the icehouse Morrow Formation incised-valley fills, we constructed a similar analysis of eustasy, subsidence, and development of sequences (Figure 12C). The following assumptions were used for generating the curves: (1) 0.06 ft (1.8 cm)/1000 yr subsidence rate (decompacted Morrow shale thickness of 400 ft [122 m] deposited during 7 m.y. of late Morrow deposition; Harland et al., 1990), (2) third-order change of ±100 ft (30.5 m) with a 2.3-m.y. duration (three third-order cycles in 7 m.y.; Ross and Ross, 1988), (3) fourth-order duration of 400 k.y. during the Pennsylvanian (Maynard and Leeder, 1992), and (4) fourth-order amplitude changes of 150 ft (45.7 m) (Crowley and Baum, 1991). This analysis, shown in Figure 12C and D, demonstrates the formation of complete fourth-order sequences, each having a lowstand systems tract, transgressive systems tract, and highstand systems tract, limited areally to the incised region of the third-order sequence boundary. During the falling limb of the third-order sea level cycle, the valleys are deepened and widened by erosion. During the rising limb of the third-order cycle, the valleys are filled with fourth-order sequences. Accommodation for these fourth-order sequences is a function of incisement of older valley-fill

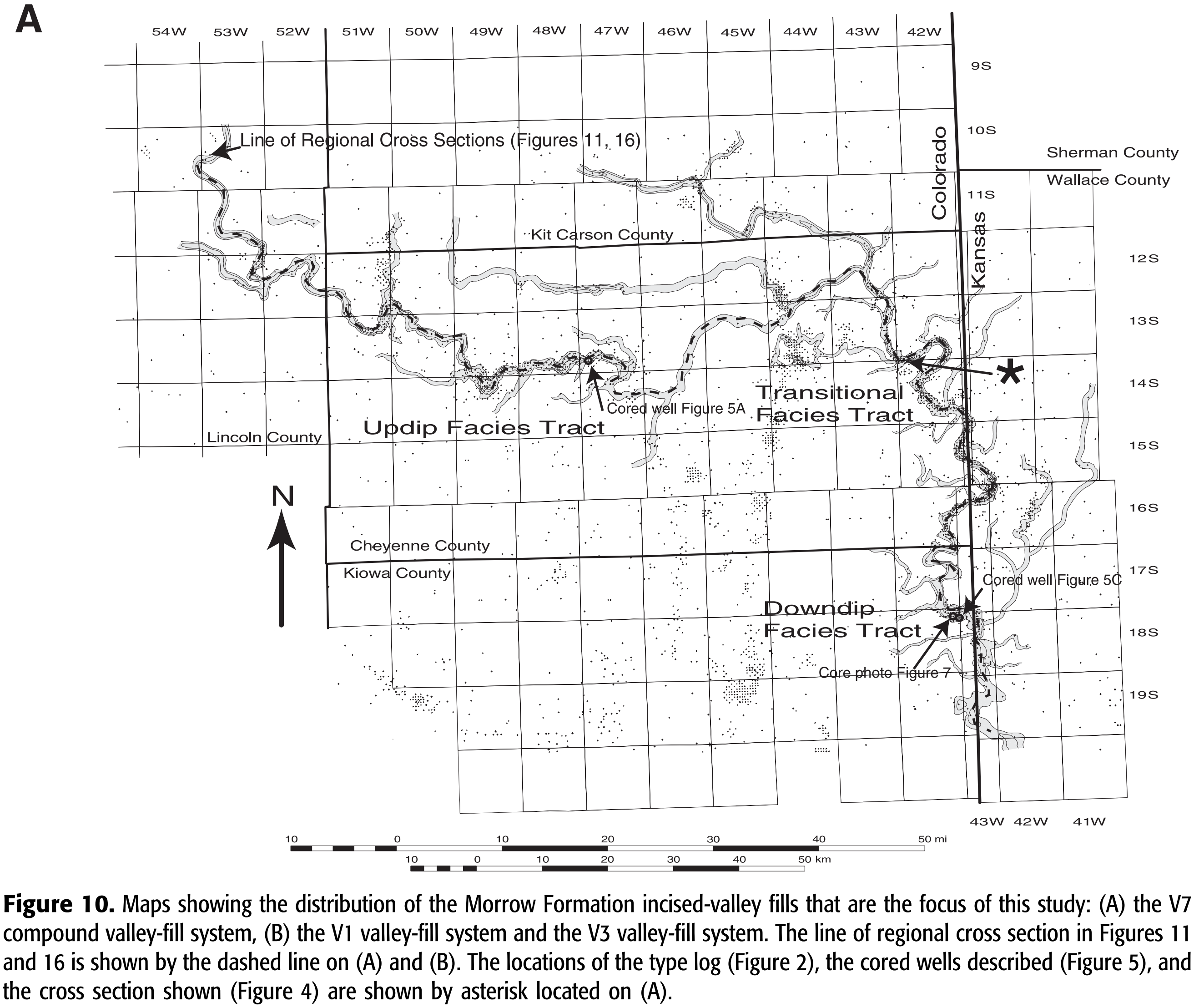


Figure 10. Maps showing the distribution of the Morrow Formation incised-valley fills that are the focus of this study: (A) the V7 compound valley-fill system, (B) the V1 valley-fill system and the V3 valley-fill system. The line of regional cross section in Figures 11 and 16 is shown by the dashed line on (A) and (B). The locations of the type log (Figure 2), the cored wells described (Figure 5), and the cross section shown (Figure 4) are shown by asterisk located on (A).

deposits for lowstand systems tract and subsidence rate combined with the rate of third-order relative rise in sea level for the high-frequency transgressive and highstand systems tracts (Figure 12C). The duration of high-frequency cycles, in conjunction with the subsidence rate and the rate of third-order relative rise in sea level, controls the thickness of transgressive systems tract and highstand systems tract strata between flooding surfaces in the valleys (Figure 12C). The preserved higher frequency sequences in the Morrow Formation are limited to the incised region of the third-order sequence (Figure 12D). Fourth-order transgressive systems tract and highstand systems tract are not present above the interfluve regions of the third-order sequence boundary (Figure 12D).

Simple and Compound Valleys

The second important concept in understanding Morrow Formation incised-valley-fill strata is the recognition of both simple and compound incised valleys. Compound valley fills have multiple internal high-frequency sequence boundaries, whereas simple valley fills do not (Zaitlin et al., 1994). High-frequency sequence boundaries (Figure 12C, D) are recognized in the Morrow Formation.

The relation of compound and simple valleys (Figure 12D) is best illustrated in the transition and downdip facies tracts of the valley fill. In the Morrow Formation (1) one compound valley (e.g., V7) comprises multiple simple valleys; (2) a compound valley has an areally extensive, third-order sequence boundary (in contrast, simple valleys have higher frequency sequence boundaries, and erosion is limited in the compound valley); (3) at the top of each simple valley is a high-frequency flooding surface; (4) across the top of the entire compound valley is a regional flooding surface. This hierarchy of valley systems is recognized by the systematic integration of multiple data sets: first, the detailed examination of lithofacies and key surfaces in cores; second, the correlation of the core

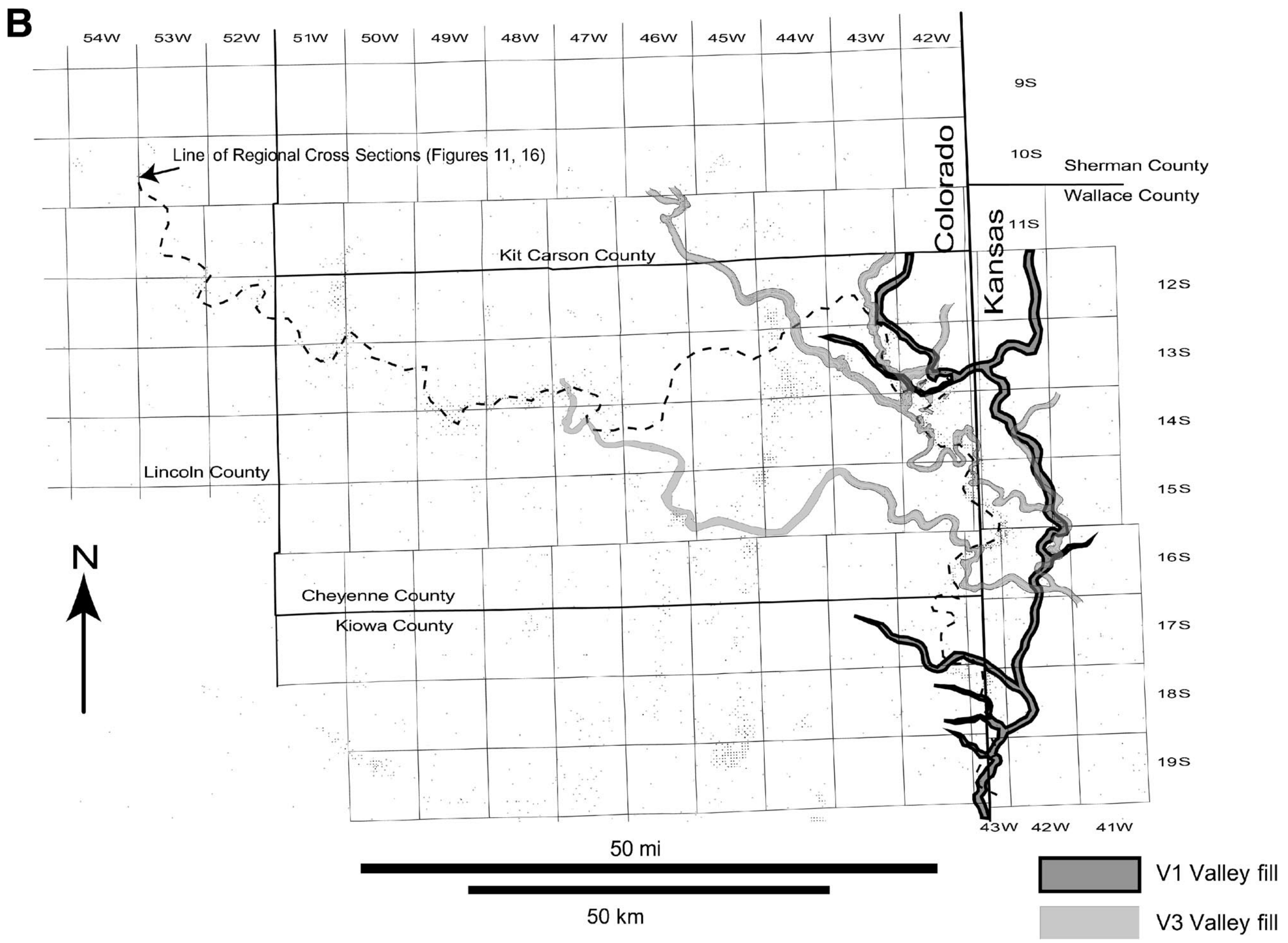


Figure 10. Continued.

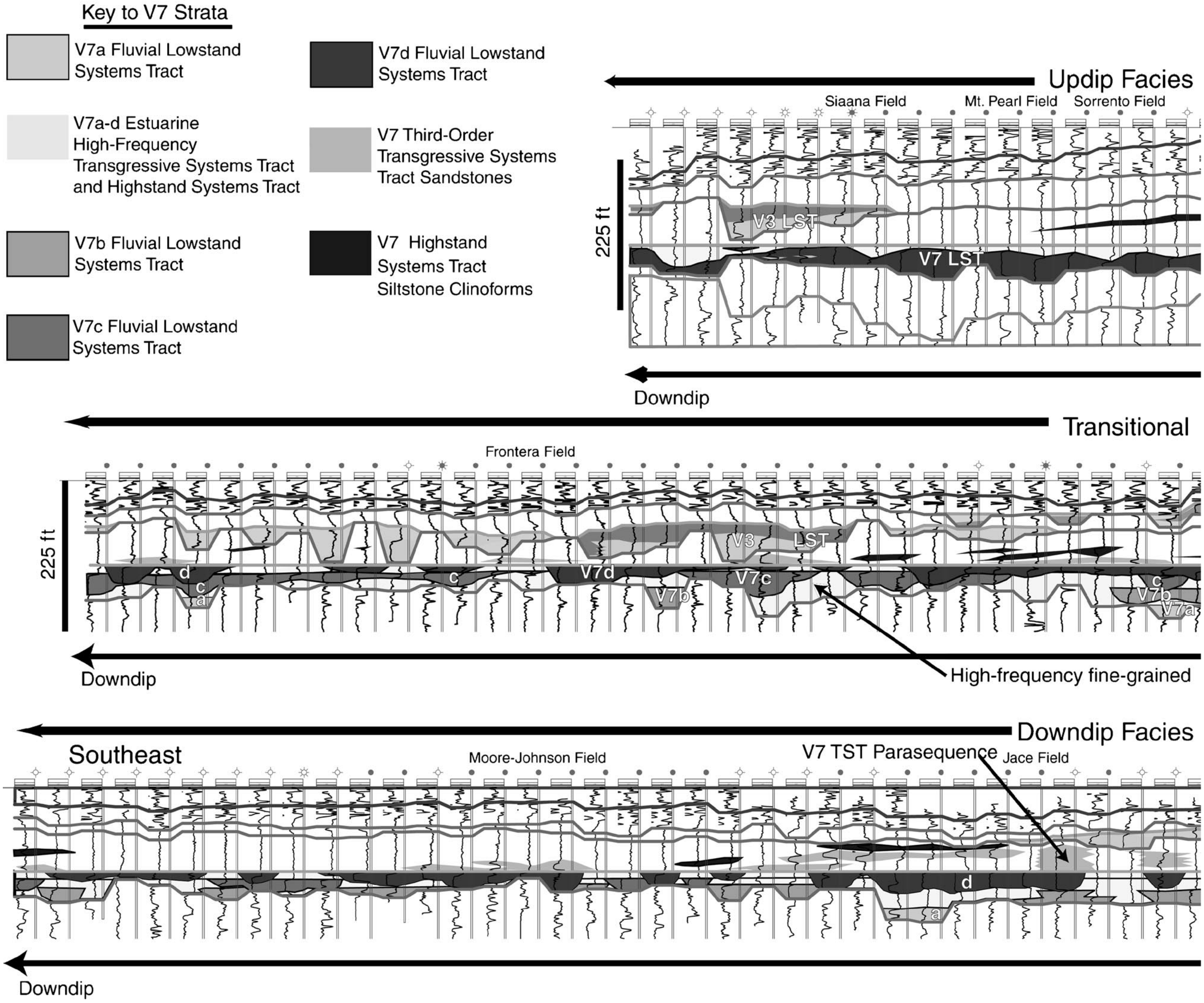


Figure 11. Stratigraphic cross section through one single composite depositional sequence (V7) in the Morrow Formation of eastern Colorado and western Kansas. View is down depositional dip. The datum for the cross section is the major flooding surface at the top of the V7 compound valley fill. See text for detailed interpretation. Note: for a color version of this figure that can be plotted at a larger scale, a pdf file can be downloaded from http://emarc.colorado.edu.

descriptions to the wire-line logs; third, the correlation of these key surfaces and lithofacies on all logs regionally.

In addition, the recognition of high-frequency sequence boundaries in the updip facies tract is difficult because the lithofacies do not change across the sequence boundaries. Within the valley fill, the dominant rock type is medium- to coarse-grained cross-bedded sandstone that fills erosional scours in individual channel deposits. Based on sedimentologic data, it is not possible to differentiate erosional surfaces that represent high-frequency sequence boundaries from the erosional scours in channel units caused by autocyclic processes. In the updip facies tracts of any of the Morrow valley-fill systems studied (V7, V3, and V1), compound valley fills could be mistaken as simple valley fills because of the difficulty in differentiating scour surfaces associated with normal fluvial processes from high-frequency sequence boundaries.

High-Frequency Sequences: V7 Valley

Four high-frequency sequences comprise the V7 valley-fill system. The general stratal and reservoir relationships that characterize these sequences in each of the three facies tracts are shown in Figure 13. The high-frequency sequences are confined in the lowstand systems tract of the compound valley fill. Each high-frequency

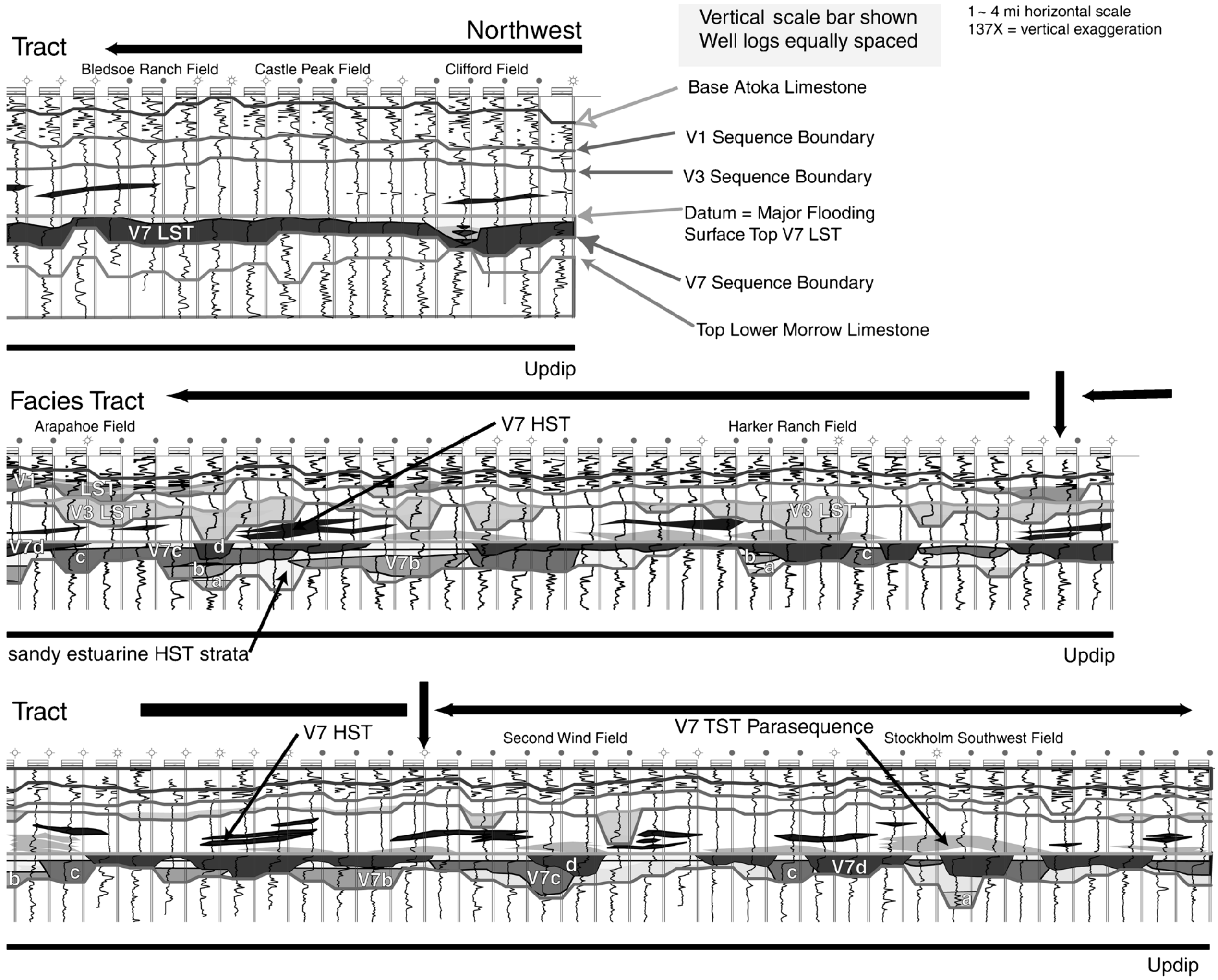
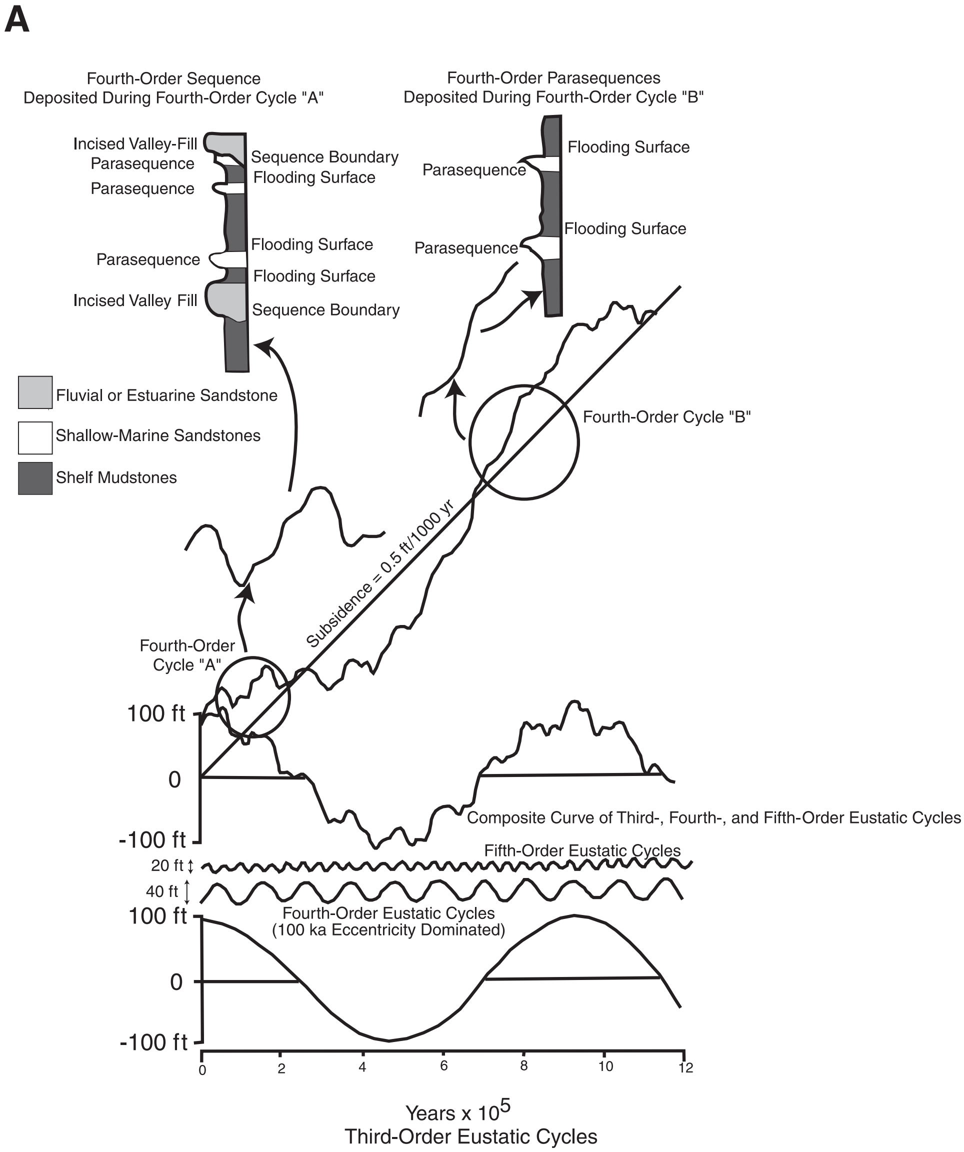


Figure 11. Continued.

sequence (V7a–d) has a (1) fluvial-dominated lowstand systems tract (LST), (2) transgressive systems tract (TST) (commonly only represented as a transgressive lag in the sequence or thin, fine-grained strata deposited during a flooding event), and (3) highstand systems tract (HST) (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 the amalgamation of fluvial deposits of each of these high-frequency sequences. This relationship is documented by (1) core description (Figure 5A), (2) log and stratigraphic relations shown in Figure 11, updip facies tract, and (3) the schematic illustration of the valley in Figure 13A. The individual high-frequency sequences are indistinguishable in this facies tract. The transitional facies tract (Figure 13B) is marked by the updip limit of the high-frequency estuarine sandstone facies (core description in Figure 5B, log and stratigraphic relationships in Figure 11, northwest limit of the transition facies tract, and the schematic diagram in Figure 13B). This northwest limit of the transition facies tract marks the turnaround zone of the high-frequency sequences. At this location, fine-grained estuarine sandstones (high-frequency HST) have prograded in a southerly direction down the flooded valley. These high-frequency HST strata are shown in Figure 11 in the V7 compound valley LST and are labeled "V7 HST." Each high-frequency LST is a simple valley fill and is labeled V7a–d in Figure 11. Each of these LST valley fills is capped by a high-frequency flooding surface (horizontal, correlatable surface) at the top of each simple valley fill, V7 a–d, in the V7 compound valley fill. Each flooding event in the V7 compound valley LST results in thin, high-frequency TST deposits in the valley. The downdip limit of the

Figure 12. Interaction of eustasy and subsidence to produce high-frequency sequences during greenhouse (A and B) versus icehouse (C and D) periods of Earth history. (A) and (B) are modified from Mitchum and Van Wagoner (1991) and illustrate (A) idealized high-frequency sequence formation during a greenhouse period and (B) the resultant stratal stacking patterns of high-order sequences into composite sequences. Note the composite sequence is the third-order cycle, and the high-frequency sequences are the fourth-order cycles.



transitional facies tract is marked by the farthest down-valley extent of these sandy highstand strata (shown as the southeast limit of the transition facies tract in Figure 11).

The downdip facies tract is characterized by high-frequency, fluvial LST incised-valley-fill units (V7a–d of Figure 11, downdip facies tract), with minor tidal influence, separated by predominantly estuarine central basin mudstone (see core description in Figure 5C, log and stratigraphic relationships in Figure 11, and schematic diagram in Figure 13C).

The V7 compound valley fill is capped by a major marine flooding surface that also floods interfluve regions. Above the major flooding surface, the V7 TST is represented by a series of backstepping parasequences (sandstones) best developed where input of sediment from tributaries entered the estuary during early development of the TST (Figure 11). To further support this observation, note the bayhead delta on the cross section in the vicinity of Jace field.

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 (Figures 11, 14B). In reality, this major flooding surface gently dips down the valley, reflecting the original depositional dip prior to flooding (Figure 14A). Consequently, progressively backstepping parasequences (TST) are younger. Above the V7 TST, poorly developed clinoform geometries are observed in the V7 HST (note the dipping strata labeled V7

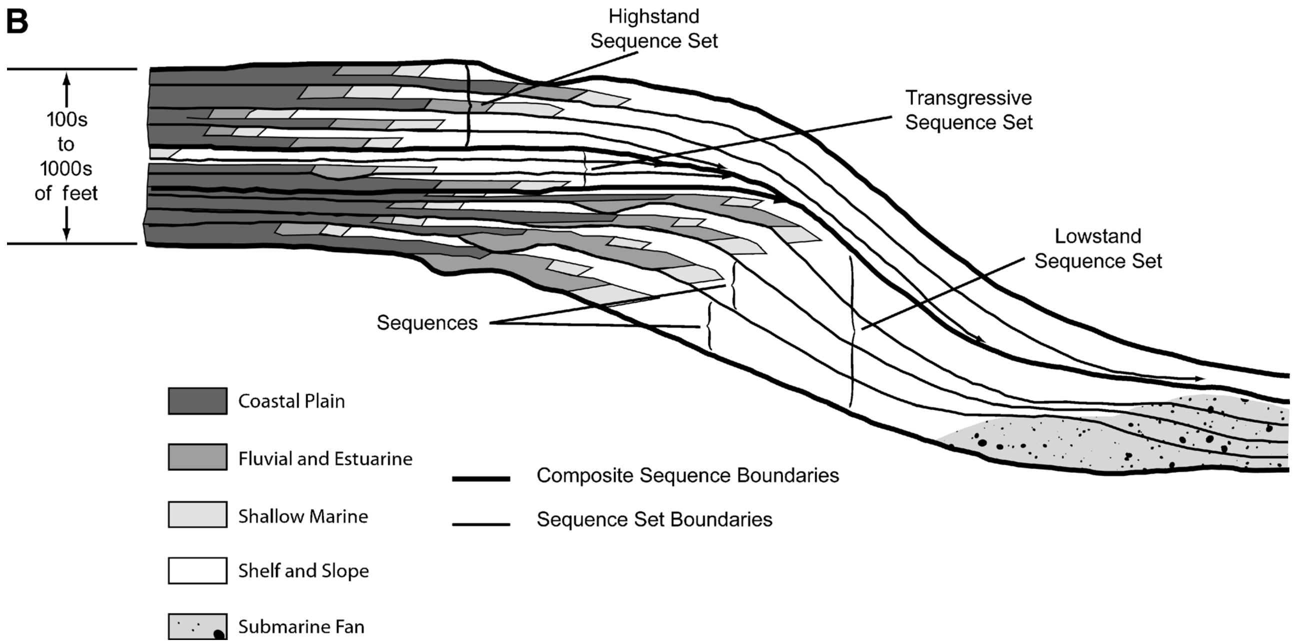


Figure 12. Continued.

HST in Figure 11 in the transition facies tract and the upper part of the downdip facies tract). The V7 HST is truncated by the sequence boundary of the V3 sequence (downcutting line in Figure 11 in the transitional and updip facies above which V3 LST strata are labeled). The two youngest sequences (V3 and V1; Figures 2, 4, 10B, 11) were deposited after the topography on the lower Morrow limestone was completely filled by the onlap of the older sequences (Figure 9). Unlike the older V7 compound valley fill, deposition of the incised-valley fills of the V1 and V3 sequences was not influenced by the surface developed at the top of the lower Morrow limestone, represented in Figures 8 and 9, and the valleys flowed obliquely across the trend of the older V7 valley system (Figure 10B).

The downvalley changes that are shown in Figure 11 significantly impact trap configurations, reservoir compartmentalization, and reservoir performance. Each facies tract is described here in detail.

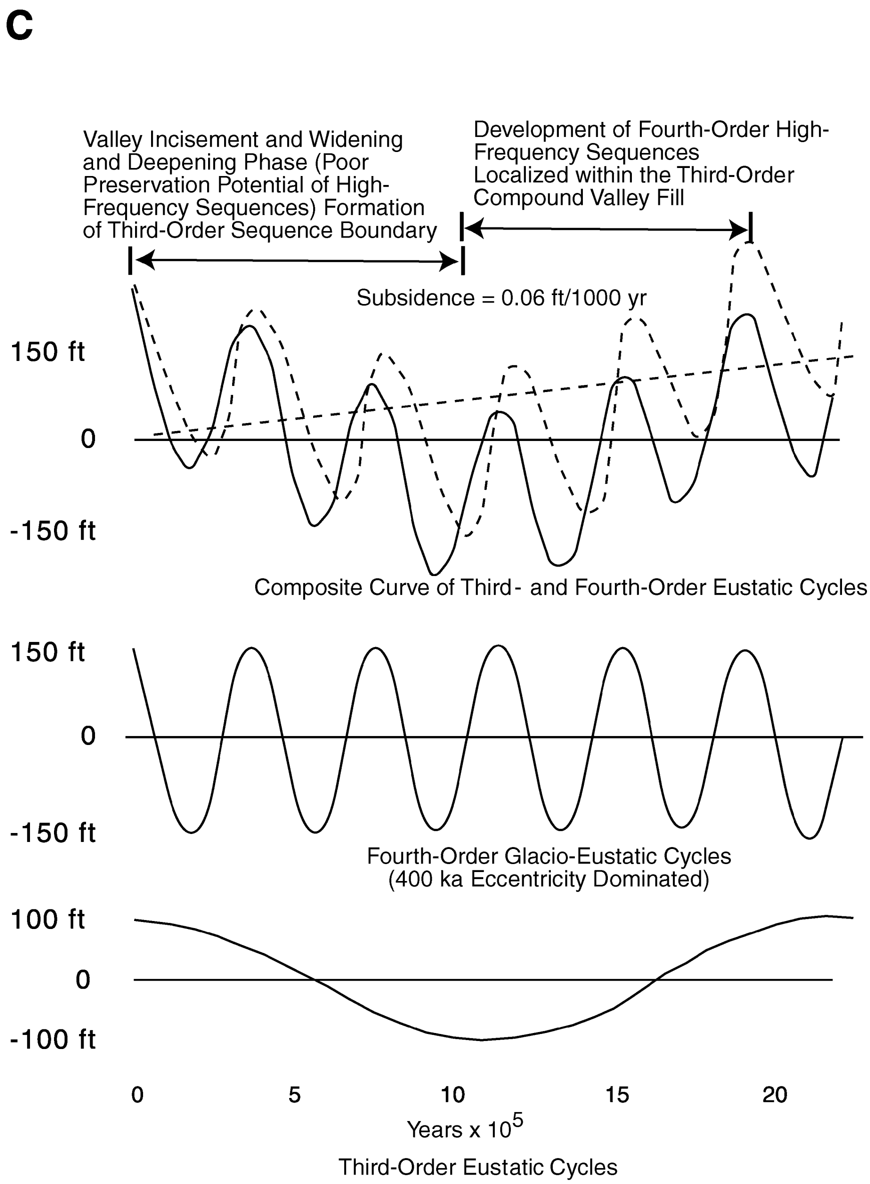
UPDIP FACIES TRACT

The updip facies tract encompasses the valley system from northwest of Clifford field to the intersection of the valley system with the Las Animas arch (Figures 1, 10, 11, 15, 16). The dominant rock type in the valley-fill strata of this segment is medium- to coarse-grained, massive to trough cross-bedded, multi-storied, fluvial channel sandstones. These sandstones are laterally continuous down the axis of the valley fill (Figures 10, 11).

Two key surfaces are significant in the updip segment and bound the valley fill: the sequence boundary at the base of the valley and the major flooding surface at the top of the valley fill (Figures 5A, 11, 17). The other possible surfaces internal to the valley-fill strata cannot be discerned in this setting.

Production characteristics of updip segment fields are excellent and listed in Tables 2 and 4. Traps in this segment of the valley are combination structural/stratigraphic traps. Trapping occurs where the valley-fill deposits cross anticlines, or the trend of the valley-fill deposits bends against structural strike. The traps thus express structural closure of the reservoir strata along the valley axis (Figures 15, 16) (Bowen et al., 1990, 1993). Reservoirs compartments are not isolated along this segment, but baffles do occur as a function of precipitation of cements in the reservoir at Bledsoe Ranch field and Sorrento field (Mark, 1998). Pressure data from drillstem tests taken during both field extension work and exploration subsequent to field production demonstrate that depletion of reservoir pressure has occurred as far as 5.5 mi (8.0 km) from the nearest producing wells (Figure 18). This reservoir-pressure depletion and the complete lack of any purely stratigraphic traps in this segment of the valley fill indicate very good lateral reservoir continuity down the axis of the V7 system.

Figure 12. Continued.



TRANSITION FACIES TRACT

The transition facies tract is located from the downdip limit of the updip facies tract to the northern limit of Second Wind field and encompasses most of the Stateline trend (Figures 1, 10, 11, 15, 16). From bottom to top in each high-frequency sequence, valley-fill strata in this segment consist of (1) medium- to coarse-grained, massive to cross-bedded, multistoried fluvial channel sandstones, (2) wavy to flaser-bedded, heterolithic, estuarine, fine-grained sandstones, siltstones, and shales, and (3) fine- to medium-grained, cross-bedded, estuarine sandstones (Figures 5B, 13B). There are a few exceptions to this pattern.

The most deeply incised region of the valley in this segment is filled with amalgamated fluvial strata (these are labeled as ''V7a'' in the transition facies tract segment of Figure 11). Fluvial fill of the incised valley was incomplete, and flooding of the valley subsequent to fluvial deposition created a long, narrow estuary. Fill of this estuary by the downdip progradation of bayhead delta facies created a complex mix of fluvial and estuarine sandstones, siltstones, and shales deposited in the valley (shown as the lower zones of the V7 in Figure 11 and labeled as ''high-frequency fine-grained estuarine HST strata'' in the transition facies tract). A high-frequency, relative fall of sea level occurred after the HST estuarine fill had prograded to

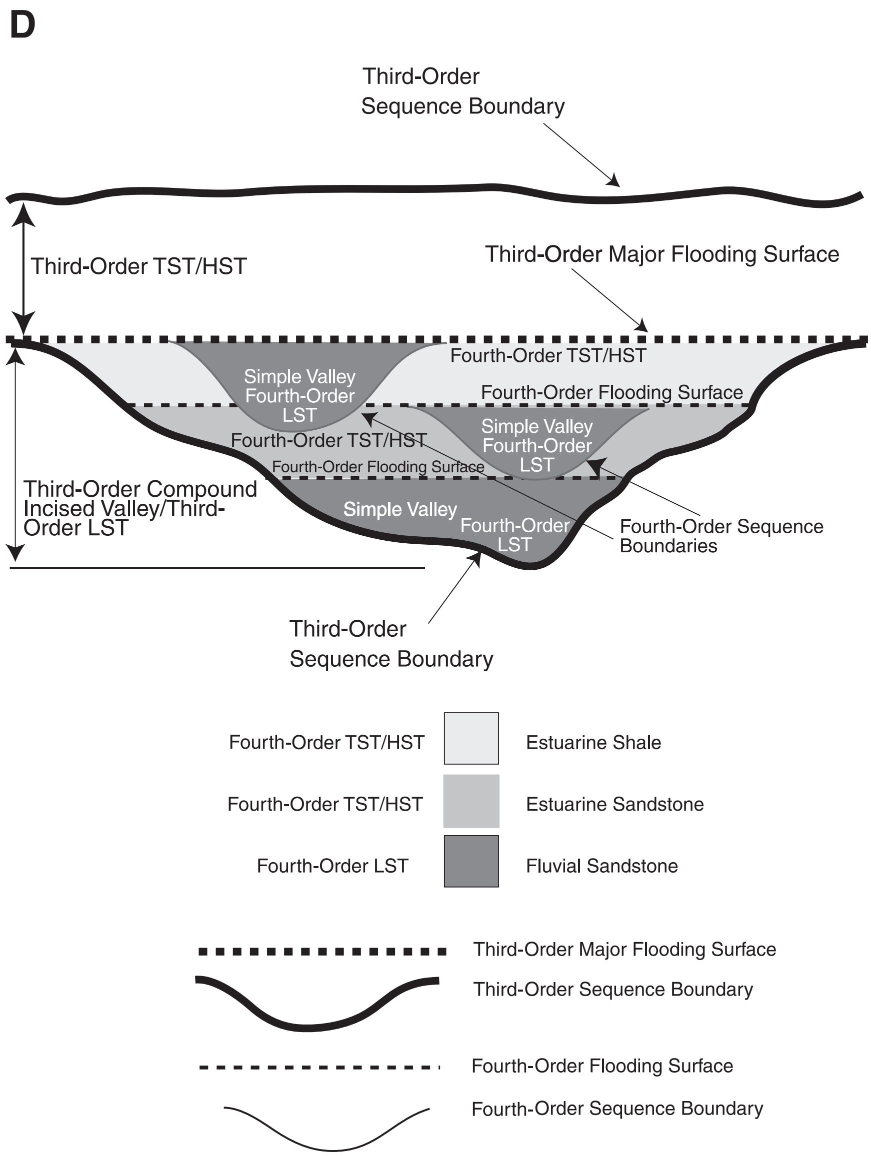


Figure 12. Continued.

at least the northern limit of Second Wind field. Note the location of Second Wind field and the corresponding limit of the estuarine sandstone facies in Figure 11 (transition facies tract). The estuarine sediments were subsequently incised by the V7b LST. Strata of a second valley fill (V7b) were deposited in the V7 compound valley, forming a compound incised-valley fill. This V7b valley fill was subsequently flooded, leading to a second phase of estuary development that, again, was partially filled by progradational bayhead delta lithofacies (again, note the limit of HST estuarine strata in Figure 11). This process of reincisement, estuarine development, and fill was repeated two additional times (V7c and V7d, Figure 11), completing fill of the V7 compound valley. The compound valley was then transgressed and a series of backstepping parasequences were deposited over the transition facies tract of the valley fill (labeled ''V7 TST Parasequence'' and intermittently occurring immediately above the MFS at the top of the V7 LST along the transition facies tract of Figure 11).

Key surfaces in the transition facies tract are especially important to recognize, because they bound the key lithofacies associations and compartmentalize the different reservoirs (Figures 4, 11, 13). The key surfaces are (1) V7 sequence boundary at the base of the valley, (2) high-frequency flooding surfaces internal to the valley at the tops of the V7a–d fluvial fills, (3) diastems at the base of each bayhead delta lobe filling the estuary, (4) three higher frequency sequence boundaries (base of V7b–d) that separate overlying fluvial deposits basinward from estuarine strata, (5) a major

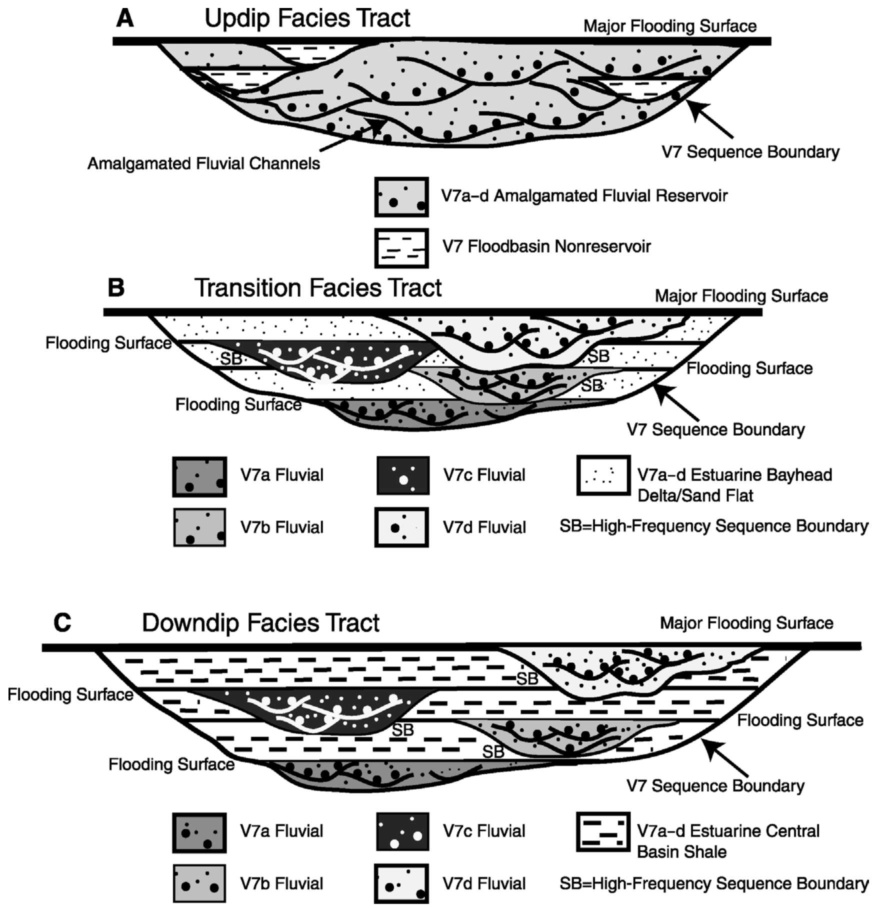


Figure 13. Schematic cross sections perpendicular to the axis of the V7 compound valley fill. These cross sections show facies variations and the key surfaces in each of the three informal facies tracts: (A) updip facies tract, (B) transition facies tract, and (C) downdip facies tract.

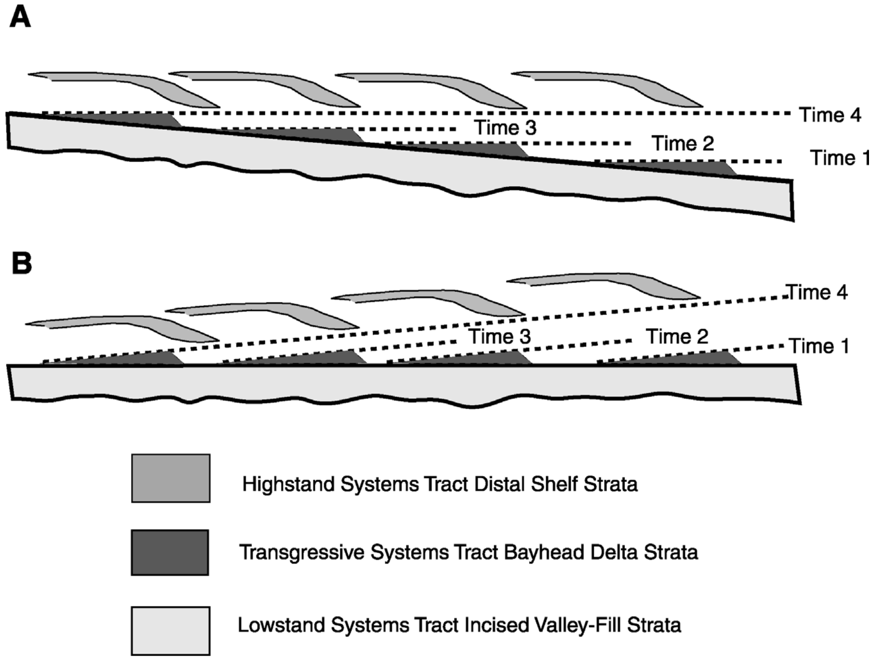


Figure 14. Schematic cross sections of the transition and downdip facies tracts showing the effects of using different datums and how these influence the interpretation of stratal stacking patterns. (A) Downvalley cross section using a gently inclined datum (the major marine-flooding surface) illustrating the gentle dipping gradient of the top LST. Note the backstepping and onlapping geometry of the transgressive systems tract bayhead delta strata onto the inclined surface and the clinoform geometry of the highstand systems tract strata. (B) Representation of the same cross section using the datum of the top of the lowstand systems tract (major marine-flooding surface, same as Figure 11). Note that the backstepping parasequences of the transgressive systems tract now appear as mounded bodies above the lowstand tract. The time lines indicated in (A) would not be interpreted because the TST sand bodies are mounded and appear to be coeval. In addition, the highstand systems tract clinoforms appear as convex-upward stratal geometries.

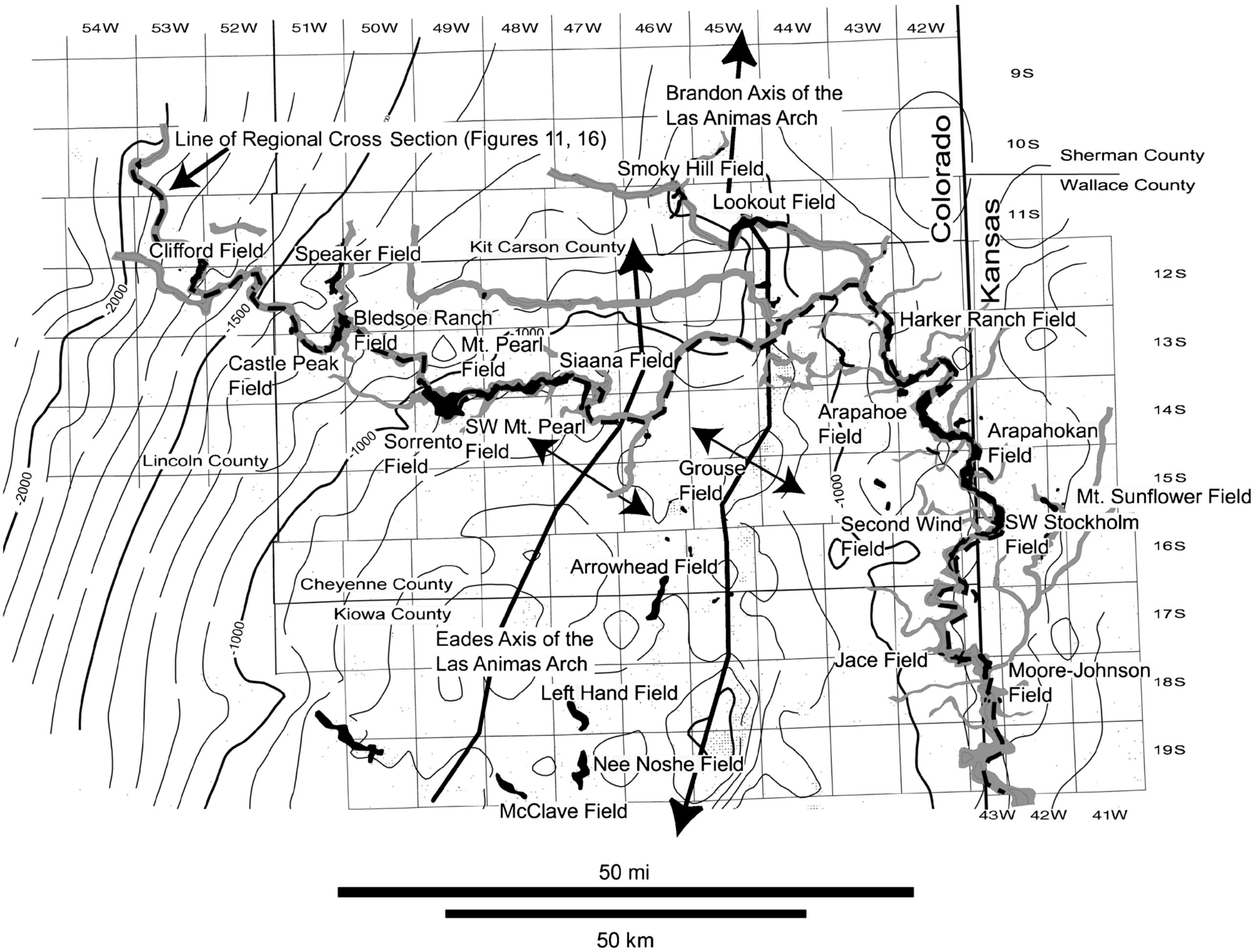


Figure 15. Structure contour map on the top of the Morrow Formation. Morrow Formation oil and gas fields are shaded black. The arrows show the two major structural features of the study area, the Eades axis of the Las Animas arch and the Brandon axis of the Las Animas arch. The V7 valley fill is shaded gray. Production occurs where the valley fill crosses anticlines or bend against structural strike. The line of the regional cross section (Figures 11, 16) is shown by a dashed line.

flooding surface that separates marine depositional systems from the top of the compound valley and interfluve regions, (6) higher frequency flooding surfaces that cap each of the backstepping parasequences of the transgressive systems tract, and (7) diastems at the base of the bayhead deltas that form these backstepping parasequences.

Production statistics and characteristics of the transition facies tract fields are given in Tables 2 and 4. Fields in the transition facies tract are found along a combination stratigraphic/structural trap that results from the valley-fill reservoir strata draping over the Las Animas arch, then paralleling the eastern limb of the arch, and finally trending southeast downdip into the Hugoton embayment of the Anadarko basin (Figures 10, 11, 15, 16). The individual reservoirs in this region of traps are often highly compartmentalized because of the juxtaposition of dissimilar rock types across each of the key surfaces. Development drilling (40–80-ac [0.16–0.32-km^2] offsets) resulted in several wells demonstrating virgin initial reservoir pressure, even when an adjacent compartment had been significantly depleted (Figure 19). In addition, in this area, gas/oil and oil/water contacts demonstrate reservoir segregation. In adjacent wells, gas is often found at lower structural elevations than oil, and water occurs structurally higher than oil. However, it is often difficult to resolve individual reservoir compartments in this segment of the valley fill because many compartments are smaller than the 80-ac (0.32-km^2) well-spacing units. A dramatic separation of compartments can be seen between Stockholm Southwest field and Second Wind field (Bowen and Weimer, 1997). Stockholm Southwest field was depleted to a reservoir pressure of less than 300 psi

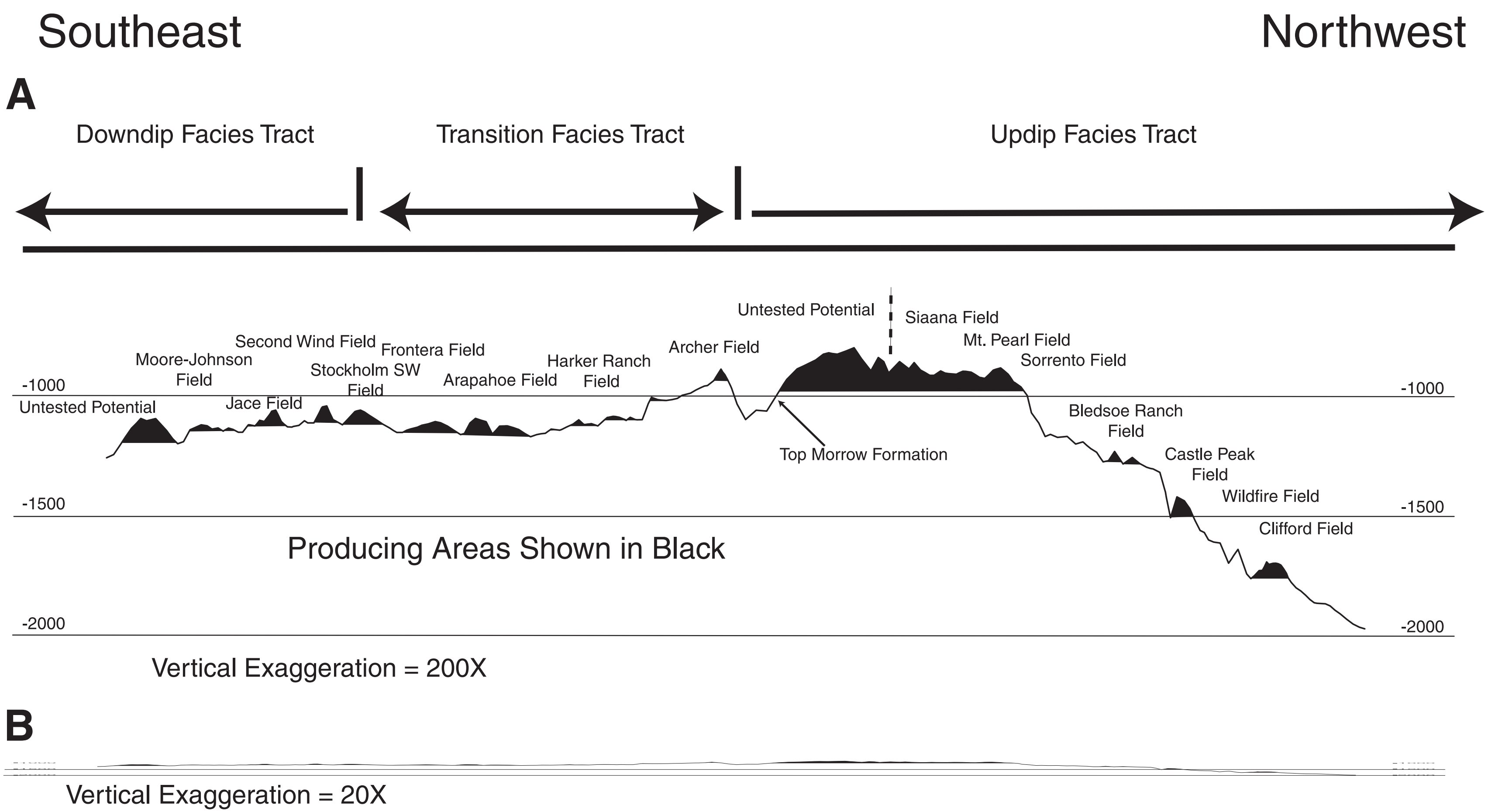


Figure 16. Structural cross section through one single valley-fill system, the V7 compound valley fill. The line of section intersects the same wells as the stratigraphic cross section shown in Figure 11. Regions of the valley fill that produce oil and/or gas are shaded black. Note that all production is associated with closure along the axis of the valley fill. This closure can result from the valley-fill–crossing anticlines or bending against structural strike (see Figure 15). The line of section is shown in Figures 1, 10, and 15. (A) 200× = vertical exaggeration. (B) 20× = vertical exaggeration.

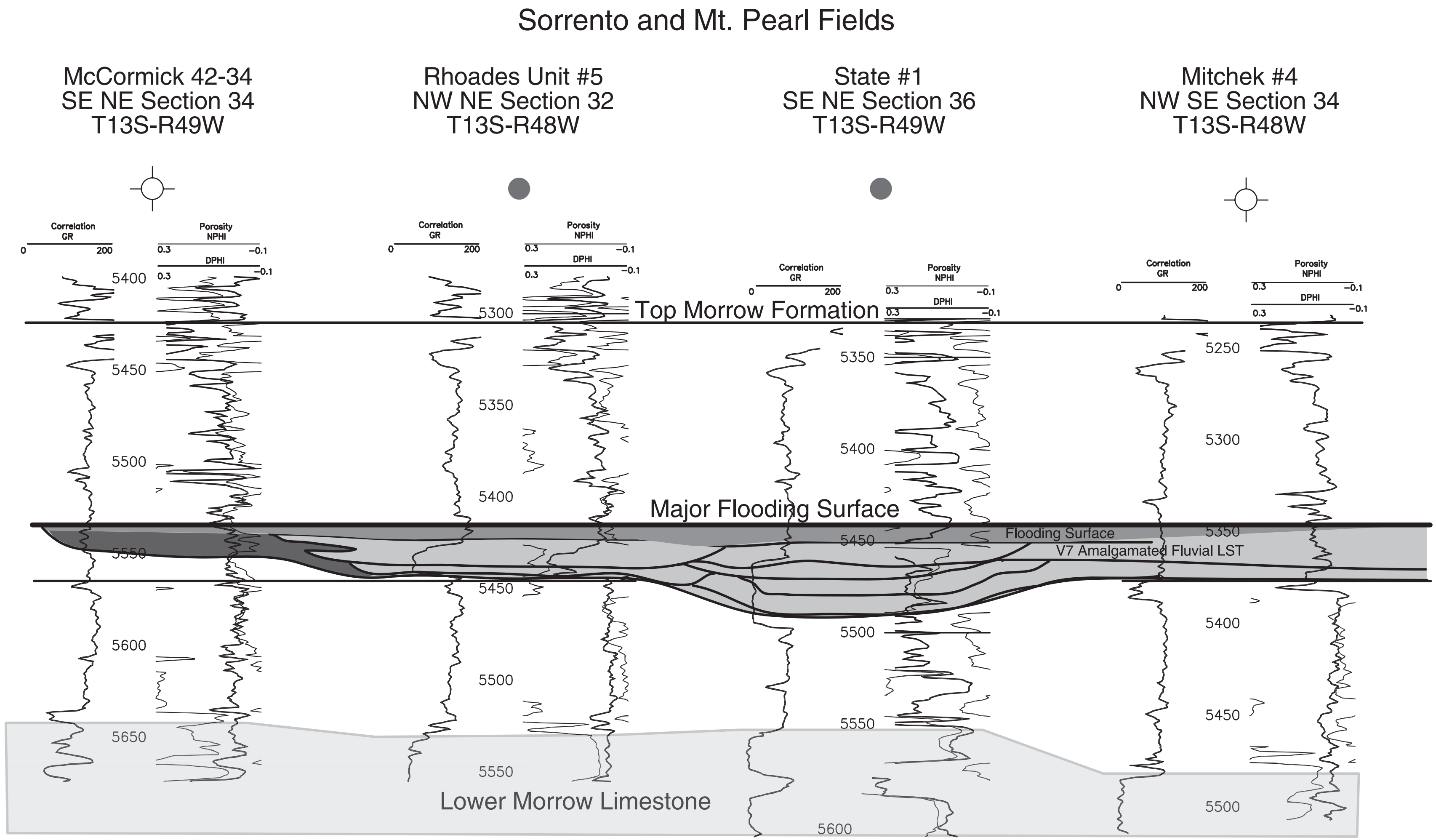


Figure 17. Stratigraphic cross section of the Morrow Formation at Mt. Pearl field illustrating the sequence-stratigraphic framework in the updip facies tract. The upper Morrow siliciclastic interval lies unconformably on lower Morrow limestone. Individual high-frequency sequences are not recognized in this updip facies tract because the sequences amalgamate fluvial sandstone facies. The V7 compound valley fill is capped by a major flooding surface, across which the V7 interfluve regions are flooded. Location of the cross section is shown in Figure 18.

Table 4. Summary of Reservoir Performance by Facies Tracts of V-7 Valley Fill, Morrow Formation, Southeastern Colorado

Facies Tracts	Lithofacies/ Environments	Reservoir Continuity	Fluid Distribution	Storage Capacity	Production Values	Degree of Compartmentalization
Updip	amalgamated fluvial	good lateral and vertical (Figures 5A, 11)	simple relationships depending on structural position in traps	high	highest	low
Transition	mixed fluvial/ estuarine	fluvial-good lateral along axis, may be poor vertically because of tight estuarine sandstone layers (Figures 5B, 11)	highly variable because of complex baffling and some barriers to flow	moderate	middle (facies dependent)	moderate
Downdip	fluvial	narrower in cross section than updip and transitional, isolated vertically (Figures 5C, 11, 13)	thinner columns and areally less extensive than updip reservoirs	low because of estuarine shale replacing estuarine sandstone	lowest	high because of vertical separation of fluvial reservoirs by estuarine shale

(2.06×10^6 Pa) when a direct 40-ac (0.16-km^2) offset to the west discovered Second Wind field with an initial reservoir pressure of greater than 1000 psi (6.89×10^6 Pa). However, these dramatic boundaries only occur in a few places, most of the transition facies tract is efficiently drained at 80-ac (0.32-km^2) spacing.

DOWNDIP FACIES TRACT

The downdip facies tract occupies the valley system south of Second Wind field to south of Moore-Johnson field (Figure 15). Medium- to coarse-grained, trough cross-bedded sandstone formed by the amalgamation of fluvial channels dominates the deepest incised area of this valley segment, but the overlying fill reflects the stronger marine influence in the lower reaches of the valley (note the high shale content of the V7 compound valley fill in Figure 7A and B, the downdip facies tract of Figure 11, and Figure 13C). Shales deposited in the central basin region of the estuary overlie the fluvial sandstones deposited in each of the four high-frequency valleys comprising the V7 compound valley fill (Figure 7, downdip facies tract of Figure 11, and Figure 13). A major flooding surface separates the compound valley fill from overlying TST strata. The overlying strata are a series of backstepping parasequences derived from bayhead delta deposition in which isolated reservoir compartments may occur (see the downdip facies tract in Figures 11, 14).

Key surfaces in the downdip facies tract are also important to recognize because they also bound the key lithofacies associations and compartmentalize the different reservoirs (Figures 7, 11, 13, 20). The key surfaces are (1) V7 sequence boundary at the base of the valley and across the interfluve regions, (2) flooding surfaces, across which estuarine central basin mudstones overlie amalgamated fluvial deposits for each of the four high-frequency valley fills of the V7 compound valley fill, (3) higher frequency sequence boundaries of the V7b–d that erode into the central basin mudstones and merge with the initial V7 sequence boundary across the interfluves, (4) a flooding surface that marks

Drainage Efficiency	Pressure Maintenance	Recovery Factors	Production Problems	Fields (This Study, Figure 16)
high	highly successful, local reinjection of gas	>60%	coning of gas and water caused by high *K*, thin fluid column	Clifford, Wildfire, Castle Peak, Bledsoe Ranch, Sorrento, Mt. Pearl, Siaana, Archer
limited by thief zones, baffles, and barriers	limited by seals and baffles associated with flooding shales and tight estuarine sandstones	highly variable-facies dependent	production attempts in low permeability estuarine sandstone, coning of gas and water because of thin fluid columns, pressure maintenance complications because of thief zones and barriers to flow	Second Wind, Stockholm SW, Frontera, Arapahoe, Harker Ranch
high	limited because of stratigraphic complexities	variable because of unsuccessful pressure maintenance attempts and reservoir compartmentalization	pressure maintenance complications because of injection into vertically separated reservoirs, limited areal extent of reservoirs	Jace, Moore-Johnson

the top of the valley and merges with the composite sequence boundary on the interfluves (major flooding surface), (5) flooding surfaces that bound parasequences in the transgressive systems tract, and (6) diastems at the base of bayhead delta deposits in these parasequences.

Production characteristics of the downdip facies tract fields are given in Tables 2 and 4. Trapping in the amalgamated fluvial strata of the downdip facies tract is a continuation of the larger trap configuration shown in Figure 16 and described above for the transition facies tract. The laterally continuous fluvial facies in the V7a–d valleys produce from combined structural/stratigraphic traps with the central basin shales forming the top and, in places, bottom and lateral seals for this reservoir (note the valley fills V7a–d are isolated in the estuarine shales in the downdip facies tract of Figure 11). Each of these high-frequency valley fills is commonly laterally separated from the others by estuarine shales and can form separate compartments in fields. This relationship is demonstrated at Moore-Johnson field (Greeley County, Kansas) where three high-frequency valley fills in the V7 compound valley fill each had a separate pressure regime (Figure 21) (Bowen and Weimer, 1997).

Additional confirmation of this reservoir stratigraphy was demonstrated by production operations in the Moore-Johnson field. Two key responses to fluid injection were noted. In one case (Figure 22), water injected into the V7c reservoir in the Duncan Energy Co. Lang 34–35 (SE SW of Section 35, T17S-R43W) broke through in the V7c reservoir of the HGB Oil Co. Witt A-2 well (SW NW of Section 2, T18S-R43W). No response was noted in the intervening well, the HGB Oil Co. Witt A-1 well (NW NW of Section 2, T18S-R43W), producing from a V7b reservoir. In the second case, gas injected into the V7c reservoir in the HGB Oil Co. Witt B-1 well (NW SW of Section 2, T18S-R43W) broke through to the HGB Oil Co. Witt A-2 well with no response noted in the Murfin Drilling Co. Coyote 1 well (SE SW of Section 2, T18S-R43W), a V7b producing reservoir. The Murfin Drilling Co. Coyote 2 well (NE SW of Section 2, T18S-R43W) was not producing at this time.

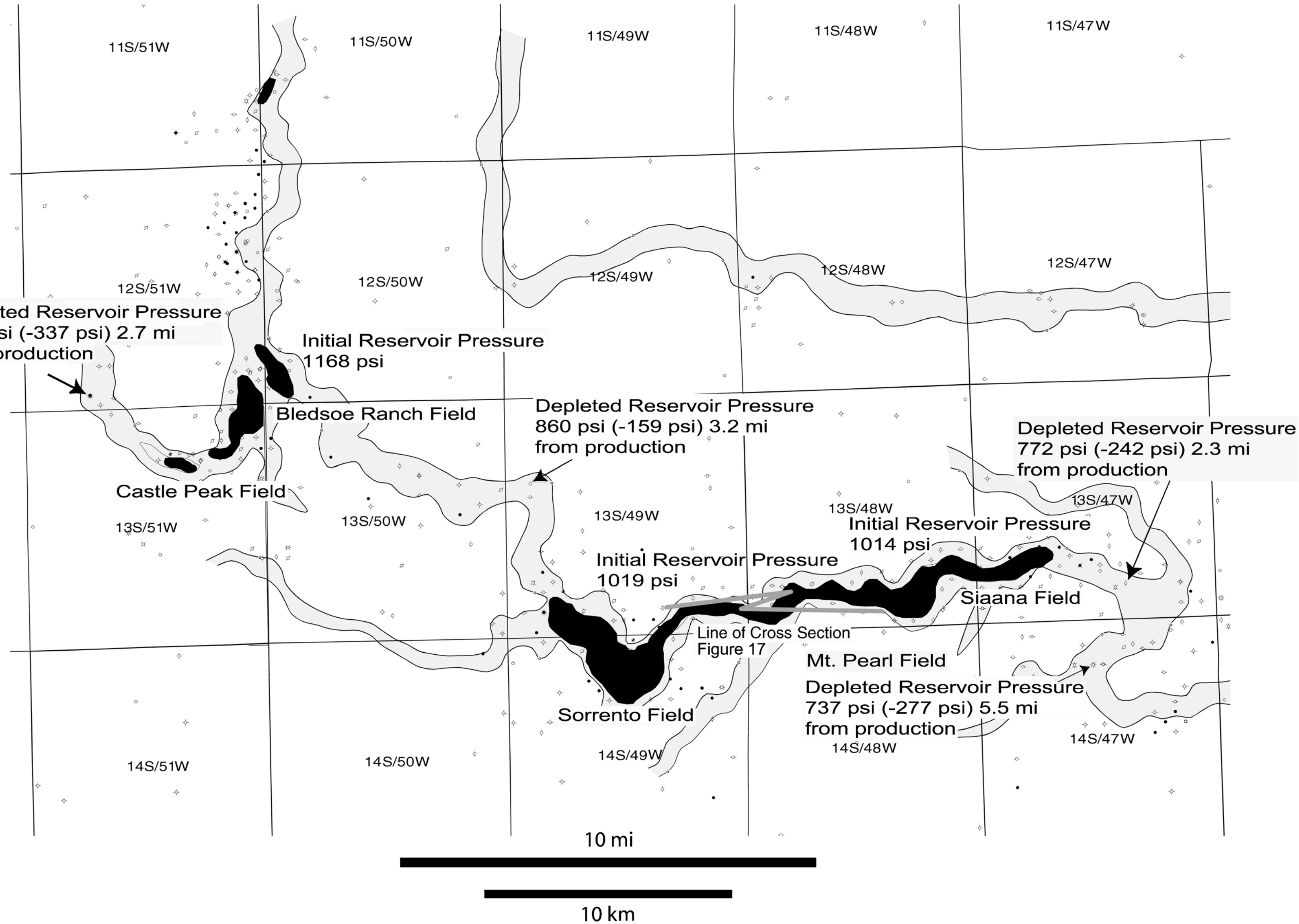


Figure 18. Map showing the updip facies tract from west of Castle Peak field to east of Siaana field. The locations are shown of drillstem tests demonstrating reservoir-pressure depletion significant distances from fields producing from the V7 incised-valley-fill system. Fields producing from the V7 are shaded black, and the V7 incised-valley-fill system is shaded gray. This figure demonstrates the high degree of lateral continuity down the axis of the valley fill in the updip facies tract.

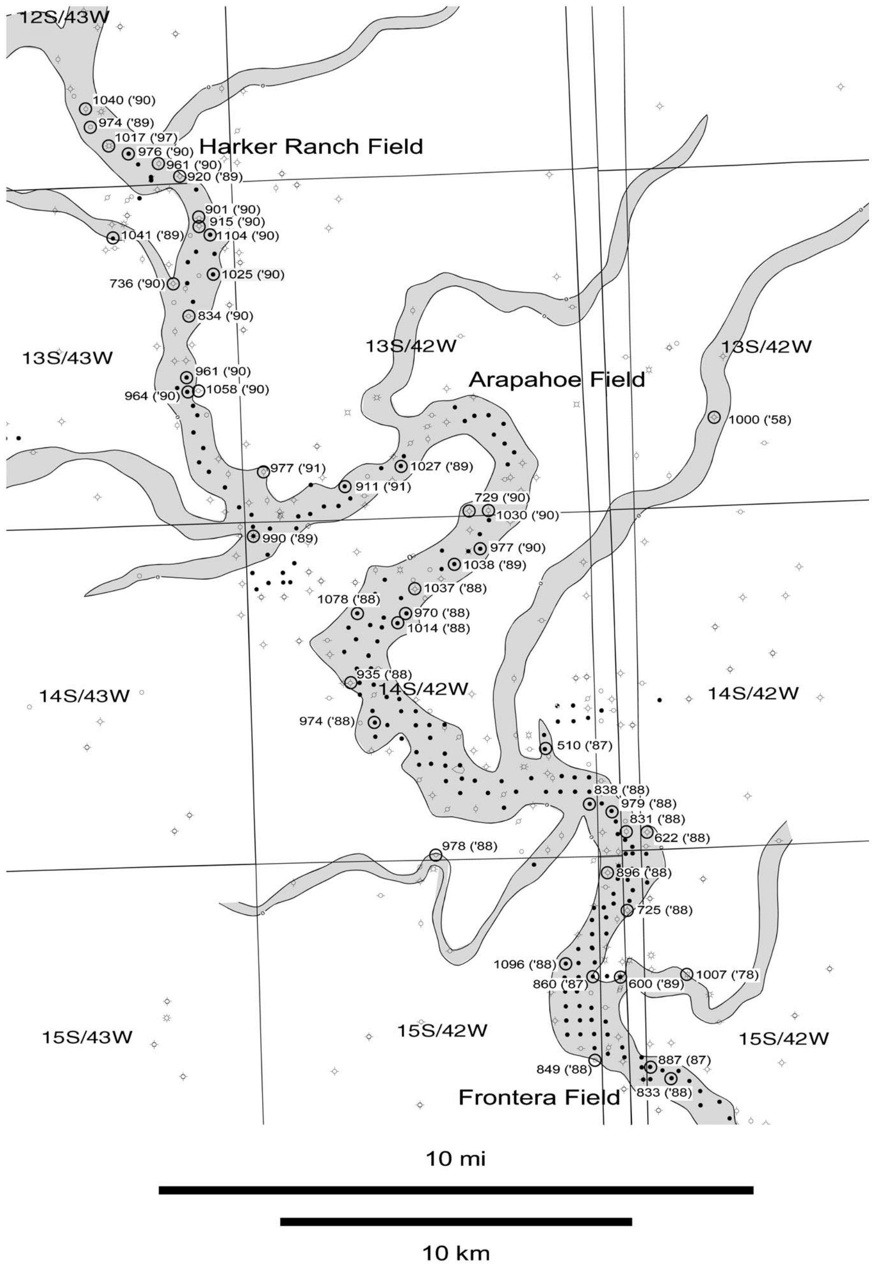


Figure 19. Map of the northern part of the transition facies tract showing the reservoir-pressure values of drillstem tests plotted with the years the data were collected. Open circles highlight the wells where pressure data were collected. Note the variable nature of the pressure test data across the area, reflecting the highly baffled, and occasionally compartmentalized, reservoir system. The V7 valley fill is shaded gray.

INCISED-VALLEY-FILL MODEL

Zaitlin et al. (1994) present a generalized model for the stratigraphic organization in incised-valley systems associated with relative changes in sea level (Figure 23A). In contrast, an idealized model for valley-fill evolution on stable shelves during icehouse time is shown in Figure 23B, based on the results of this study.

Three significant variations from the general model should be noted. These differences result from the low accommodation on a stable shelf, and high-frequency/high-amplitude sea level changes as a function of glacio-eustasy during an icehouse period of Earth's history. First, in the Morrow Formation of the study area, the systems tracts are stretched in comparison with the idealized model. Elongated facies tracts caused by low accommodation and low sediment supply control that sandstone-rich highstand deposits never prograded across the top of the valley system in the region of the study area. The high amplitude of sea level rise forces the highstand shoreline far inland to a point where the rate of sediment supply is not sufficient for the sand-rich strata of the highstand systems tract to prograde south into the study area. HST sandstone strata may be present to

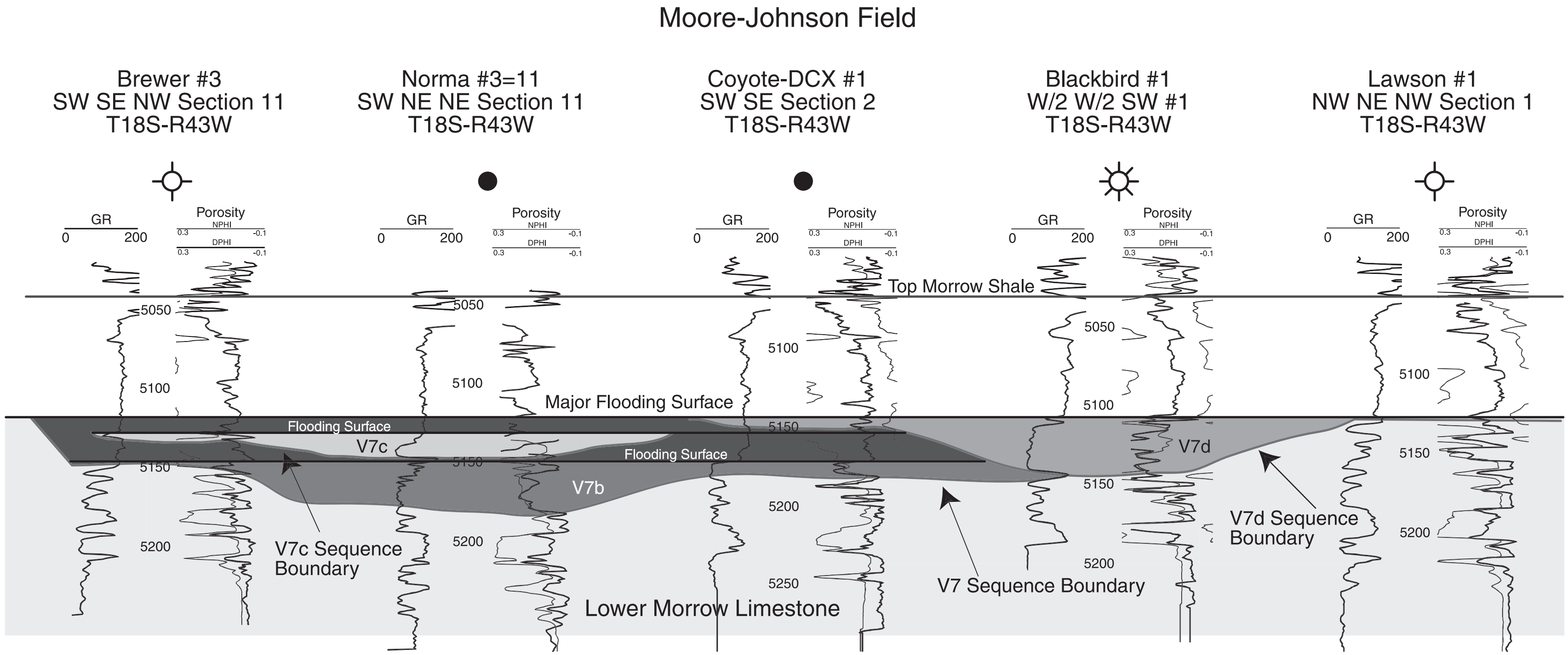


Figure 20. Stratigraphic cross section of the Morrow Formation at Moore-Johnson field illustrating the sequence-stratigraphic framework in the downdip facies tract. The upper Morrow siliciclastic interval lies unconformably on lower Morrow limestone. Individual high-frequency sequences are distinct with lowstand fluvial units (V7 a–d) encased in estuarine shale. The V7 compound valley fill is capped by a major flooding surface, across which the V7 interfluve regions are flooded. Location of the cross section is shown in Figure 22.

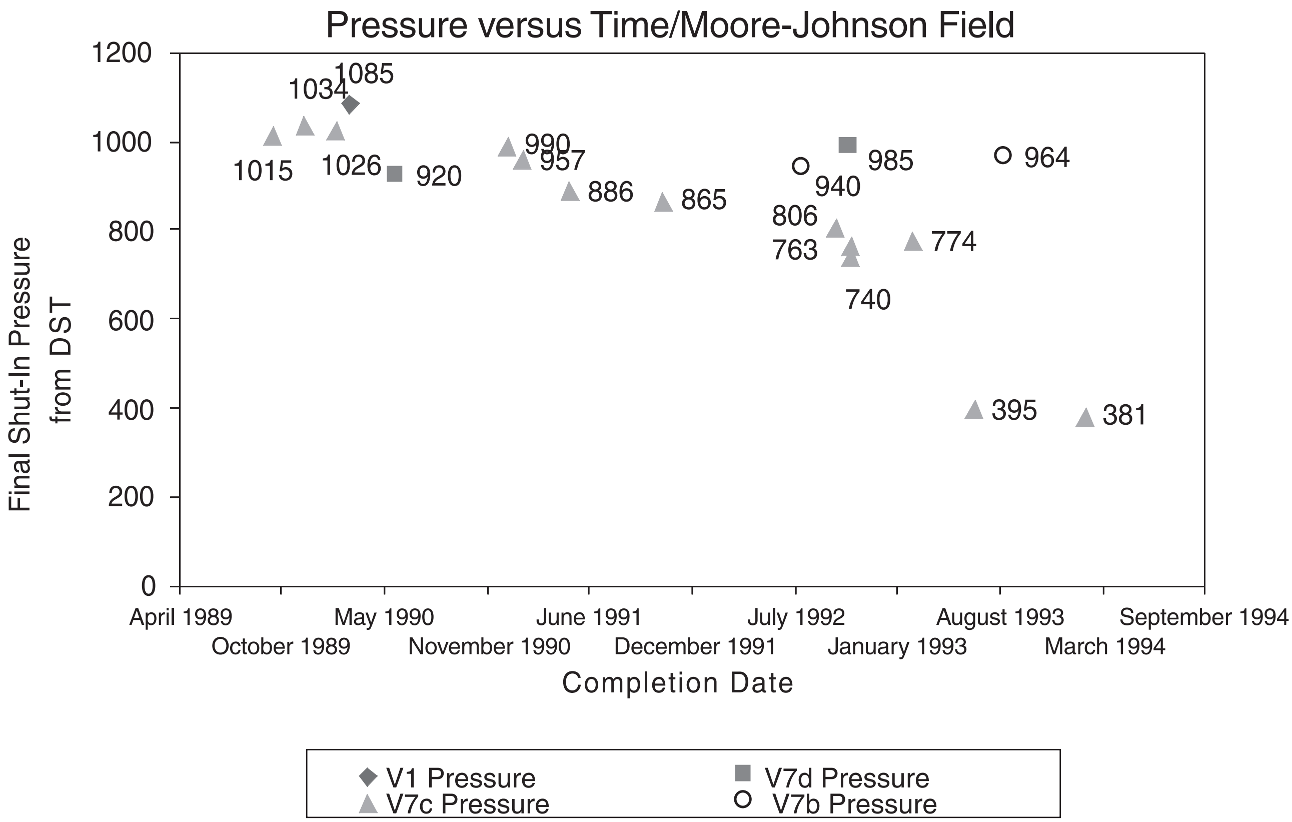


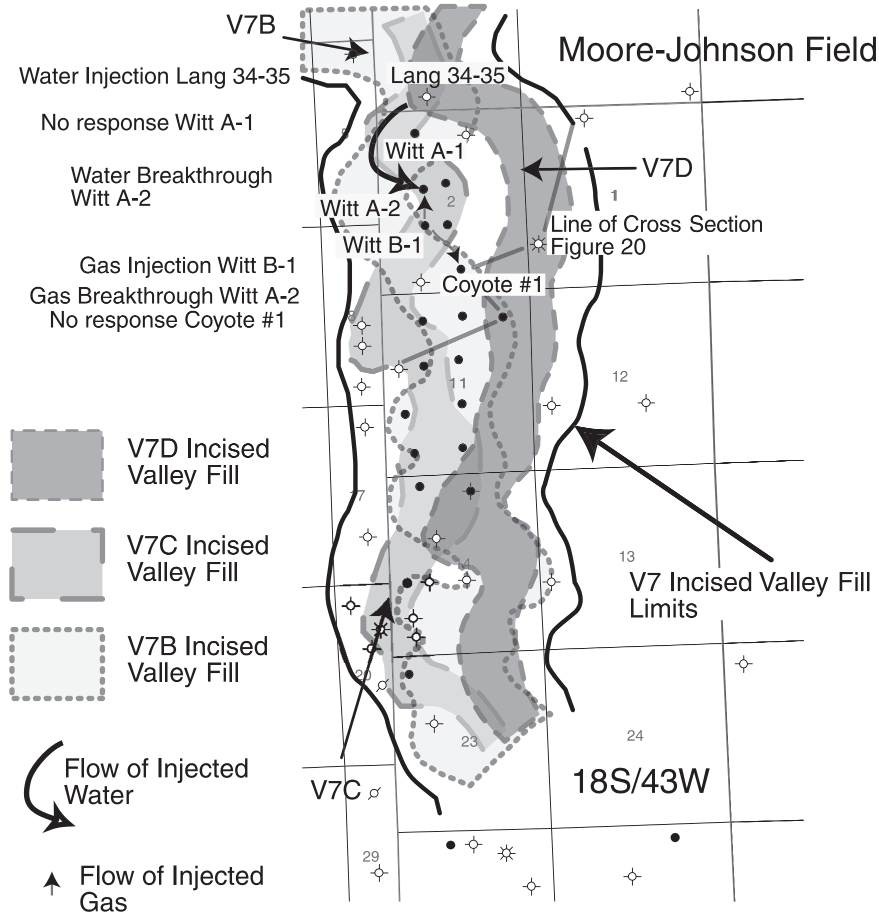
Figure 21. Graph of drillstem test values versus time for V7 high-frequency sequences in Moore-Johnson field (located in Figure 22). Note the three separate reservoir compartments depicted by the pressure relationships, and the V7c reservoir lies stratigraphically between the V7b and V7d reservoirs as shown in Figures 11 and 19.

the north in the subsurface of the Denver basin. In the Zaitlin et al. (1994) model (Figure 23A), HST sandstone shorelines prograde over segment 1 (outer incised-valley-fill) deposits. In the Morrow systems of the study area, if HST sandstones do prograde, it is either over the most hinterland positions of segment 3 (inner incised-valley fill) or over the nonincised fluvial system (Figure 23B).

Second, the top of the LST is interpreted to be the major flooding surface that inundates the interfluve regions (transgressive surface of Van Wagoner et al., 1990) (Figure 23B). The reasoning for this is that systems tracts are defined as linkages of contemporaneous depositional systems (Posamentier et al., 1988), and depositional systems are defined as a three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments. The amalgamated fluvial fill of the updip facies tract is below the first and major flooding surface across the top of the incised valley and interfluves and is, in part, contemporaneous with backstepping parasequences located below the major flooding surface across the top of the incised valley and interfluves in the downdip facies tract (Figure 23B). These backstepping parasequences (bayhead delta environment), below the major flooding surface, are genetically linked to the updip fluvial environments in the LST and are thus part of the LST. Although higher frequency flooding surfaces can be preserved and resolved internal to valley-fill strata in the transition facies tract and downdip facies tract, these flooding surfaces die out into the updip facies tract. Thus, in the Morrow model, backstepping parasequences (bayhead delta depositional environments) may exist in the LST as an integral part of the valley fill in the transition and downdip facies tracts and also exist as part of the TST with bayhead deltas prograding across the major flooding surface both at the top of the incised-valley fill and parts of the interfluve areas. The bayhead deltas of the TST are separated from fluvial LST environments by a disconformity, the major flooding surface at the top of the LSTs (Figure 23B).

Third, barrier and inlet facies are not represented in Morrow valley systems in the study area. This is interpreted to be a function of (1) the elongate nature of the facies tracts present on the shelf (segments 2

Figure 22. Map of the downdip facies tract showing the V7 compound valley (solid line) with internal high-frequency lowstand strata (shaded smaller scale valley-fill units). The lowstand units are labeled. Location of the cross section in Figure 20 is shown.



and 3 of Figure 23B) and (2) rapid transgression during flooding events; this is a common characteristic of sea level rises during icehouse climates. For example, Thomson et al. (2000) demonstrated three sea level rises during the past 350 k.y. of greater than 365 ft (120 m). Each sea level rise occurred from glacial lowstands to interglacial highstands in less than 5 k.y. Sand-rich coastal systems were likely to develop in the Morrow only at the lowstand terminus of incised valleys and at highstand shorelines. This is because, in the Morrow Formation of the study area, transgressive shorelines develop on muddy shelf deposits with limited sand supply, and because most available sand is trapped in estuaries at earlier stillstands. Barrier and inlet facies probably exist near the location of lowstand shorelines south of the study area (Andrews et al., 1995), but during rapid transgression, the shoreline shifts landward away from a marine source of sand that might be available for this facies association. Muddy transient shorelines, which are difficult to discern with a subsurface data set, are interpreted to be the equivalent of these units between the lowstand shoreline and the highstand shoreline. Sand-rich coastal systems would only expand and become reestablished during the lowstands of high-frequency fourth-order sequences at the terminus of valleys (Figure 23B).

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 175 mi (283 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.

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 ribbonlike sandstones draped across

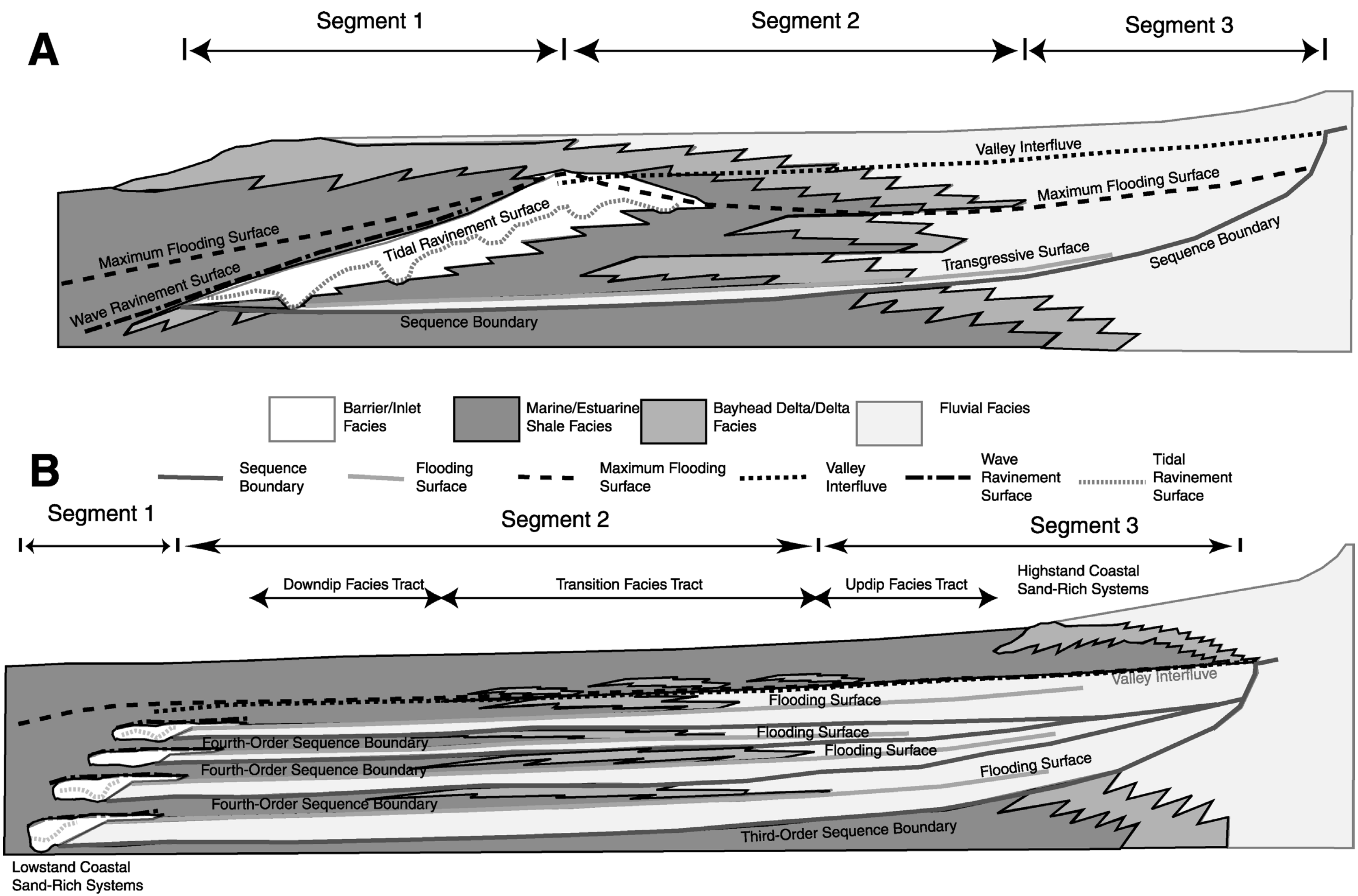


Figure 23. (A) Schematic cross section showing an idealized incised-valley-fill model (modified from Zaitlin et al., 1994). (B) Schematic cross section showing the incised-valley-fill model of the Morrow Formation. This model is more applicable for specific situations of glacio-eustatic sea level changes and incised-valley fills formed on relatively stable cratonic shelf regions. See text for discussion.

structures and bending updip against structural strike. The reservoirs in this facies tract have demonstrated the best production performance and most efficient response to pressure maintenance.

High-frequency sequences are discernible in the transition facies tract, which is characterized by high-frequency, lowstand fluvial sandstones in a matrix of estuarine sandstones and volumetrically less-significant, estuarine shales. Oil and gas fields result from combination structural/stratigraphic trapping. However, baffles are common in the reservoirs because of differences in permeability between fluvial sandstones and less-permeable estuarine sandstones, and occasional barriers result from estuarine mudstones. Less oil and gas 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 in the reservoirs.

High-frequency lowstand fluvial sandstone units that are encased in 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 in 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.

REFERENCES CITED

Adams, C. W., 1990, Jace and Moore-Johnson fields, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 157–164.

Andrews, R. D., 1999, Morrow gas play in western Oklahoma, *in* R. D. Andrews and W. J. Hendrickson, eds., Morrow gas play in the Anadarko basin and shelf of Oklahoma: Oklahoma Geological Survey Special Publication 99-4, p. 1–20.

Andrews, R. D., R. M. Knapp, and B. Zahid, 1995, Fluvial-dominated deltaic (FDD) reservoirs in Oklahoma: the Morrow play: Oklahoma Geological Survey Special Publication 95-1, 67 p.

Birkeland, P., 1999, Soils and geomorphology: New York, Oxford University Press, 372 p.

Blakeney, B. A., L. F. Krystinik, and A. A. Downey, 1990, Reservoir heterogeneity in Morrow valley-fills, Stateline trend— implications for reservoir management and field expansion, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 131–142.

Bowen, D. W., 2001, Regional sequence stratigraphic setting and reservoir geology of Morrow incised valley sandstones (Pennsylvanian), eastern Colorado and western Kansas: Ph.D. dissertation, Boulder, University of Colorado, 230 p.

Bowen, D. W., and P. Weimer, 1997, Reservoir geology of incised valley-fill sandstones of the Pennsylvanian Morrow Formation, southern stateline trend, Colorado and Kansas, *in* K. W. Shanley and B. F. Perkins, eds., Shallow-marine and nonmarine reservoirs, sequence stratigraphy, reservoir architecture and production characteristics: Gulf Coast Section SEPM Foundation 18th Annual Research Conference, p. 55–66.

Bowen, D. W., L. F. Krystinik, and R. E. Grantz, 1990, Geology and reservoir characteristics of the Sorrento-Mt. Pearl field complex, Cheyenne County, Colorado, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 67–78.

Bowen, D. W., P. Weimer, and A. J. Scott, 1993, The relative success of siliciclastic sequence stratigraphic concepts in exploration: examples from incised valley fill and turbidite systems reservoirs, *in* P. Weimer and H. Posamentier, eds., Siliciclastic sequence stratigraphy: AAPG Memoir 58, p. 15–42.

Brown, L. G., W. A. Miller, E. M. Hundley-Goff, and S. F. Veal, 1990, Stockholm Southwest field, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 117–130.

Crowell, J. C., 1999, Pre-Mesozoic ice ages: their bearing on understanding the climate system: Geological Society of America Memoir 192, 106 p.

Crowley, T. J., and S. K. Baum, 1991, Estimating Carboniferous sea-level fluctuations from Gondwanan ice extent: Geology, v. 19, p. 975–977.

Harland, W. B., R. L. Armstrong, A. V. Cox, L. E. Craig, A. G. Smith, and D. G. Smith, 1990, A geologic time scale 1989: New York, Cambridge University Press, 263 p.

Krystinik, L. F., and B. A. Blakeney, 1990, Sedimentology of the Morrow formation in eastern Colorado and western Kansas, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 37–50.

Mark, S. M., 1998, Reservoir compartmentalization of the Morrow sandstone at Sorrento field, southeastern Colorado, *in* R. M. Slatt, ed., Compartmentalized reservoirs in the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 99–130.

Maynard, J. R., and M. R. Leeder, 1992, On the periodicity and magnitude of Late Carboniferous glacio-eustatic sea-level changes: Journal of the Geological Society (London), v. 149, p. 303–311.

Mitchum Jr., R. M., and J. C. Van Wagoner, 1991, High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles: Sedimentary Geology, v. 70, p. 131–160.

Moriarity, B. J., 1990, Stockholm northwest extension: effective integration of geochemical, geological, and seismic data, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle,

and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 143–152.
Nolte, C. J., 1990, Anomalous mechanical well log resistivities in the middle Morrow sandstones of southeast Colorado, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 227–231.
Posamentier, H. W., M. T. Jervey, and P. R. Vail, 1988, Eustatic controls on clastic deposition I— conceptual framework, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea level changes— an integrated approach: SEPM Special Publication 42, p. 109–124.
Rascoe Jr., B., 1978, Late Paleozoic structural evolution of the Las Animas Arch, *in* J. D. Pruit, ed., Energy resources of the Denver basin: Rocky Mountain Association of Geologists, p. 113–127.
Rascoe Jr., B., and F. J. Adler, 1983, Permo-Carboniferous hydrocarbon accumulations, Mid-continent, U.S.A.: AAPG Bulletin, v. 67, p. 979–1001.
Ross, C. A., and J. R. P. Ross, 1988, Late Paleozoic transgression-regression deposition, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea level changes— an integrated approach: SEPM Special Publication 42, p. 227–247.
Shannon, L. T., 1990, Clifford field: a fluvial valley-fill reservoir in Lincoln County, Colorado, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 101–108.
Shumard, C. B., 1991, Stockholm southwest field— U.S.A., Anadarko basin, Kansas: AAPG Treatise of Petroleum Geology, Atlas of oil and gas fields, stratigraphic traps II, p. 269–309.
Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–113.
Sonnenberg, S. A., 1985, Tectonic and sedimentation model for Morrow sandstone deposition, Sorrento field, Denver basin, Colorado: Mountain Geologist, v. 22, p. 180–191.
Sonnenberg, S. A., and W. F. Von Drehle, 1990, Morrow gas composition in southeast Colorado, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 233–235.
Sonnenberg, S. A., L. T. Shannon, K. Rader, and W. F. Von Drehle, 1990, Regional structure and stratigraphy of the Morrow Series, southeast Colorado and adjacent areas, *in* S. A. Sonnenberg, L. T. Shannon, K. Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 1–8.
Swanson, D. C., 1979, Deltaic deposits in the Pennsylvanian upper Morrow Formation of the Anadarko basin, *in* Pennsylvanian sandstones of the Mid-continent: Tulsa Geological Society Publication, v. 1, p. 115–168.
Thomson, J., S. Nixon, C. P. Summerhayes, E. J. Rohling, J. Schoenfeld, R. Zahl, P. Grootes, F. Abrantes, L. Gasper, and S. Vaqueiro, 2000, Enhanced productivity of the Iberian margin during glacial/interglacial transitions revealed by barium and diatoms: Journal of the Geological Society (London), v. 157, p. 667–677.
Tweto, O., 1975, Laramide (Late Cretaceous–early Tertiary) orogeny in the southern Rocky Mountains, *in* B. F. Curtis, ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 75–94.
Van Wagoner, J. C., R. M. Mitchum Jr., K. D. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: AAPG Methods in Exploration 7, 55 p.
Van Wagoner, J. C., D. C. Jeannette., P. Tsang, G. P. Hamar, and I. Kaas, 1995, Applications of high-resolution sequence stratigraphy and facies architecture in mapping potential additional hydrocarbon reserves in the Brent Group, Statfjord field: International conference on sequence stratigraphy: advances and applications for exploration and production in northwest Europe, February 1–3, 1993, Norwegian Petroleum Society.
Wallace, K. J., and J. J. Heinz, 1992, Speaker field: an integrated exploration effort for the Morrow sandstone in southeast Colorado: AAPG Bulletin, v. 75, p. 1270.
Wheeler, D. M., A. J. Scott, V. J. Coringrato, and P. E. Devine, 1990, Stratigraphy and depositional history of the Morrow Formation, southeast Colorado and southwest Kansas, *in* S. A. Sonnenberg, L. T. Shannon, Kathleen Rader, W. F. Von Drehle, and G. W. Martin, eds., Morrow sandstones of southeast Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 9–35.
Zaitlin, B. A., R. W. Dalrymple, and R. Boyd, 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level change, *in* R. W. Dalrymple and B. A. Zaitlin, eds., Incised-valley systems: origin and sedimentary sequences: SEPM Special Publication 51, p. 45–60.