Reconstruction of Paleoenvironments through Integrative Sedimentology and Ichnology of the Pennsylvanian Strawn Formation*

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Abstract

Kinder Morgan's Katz Oil Field miscible CO_2 flood (Katz Strawn Unit; KSU) is located on the Eastern Shelf of the Permian Basin and covers portions of northeastern Stonewall, King, Knox, and Haskell counties of north-central Texas. Four cores from the Pennsylvanian Strawn Formation in the Katz Field were logged with particular attention given to identifying lithofacies and ichnofacies. A combination of core observations and well log data were used to reconstruct paleoenvironments to clarify probable sandbody geometries, shale continuity, and spatial and temporal trends in porosity and permeability.

All cores contain facies and trace fossil assemblages typical of a mixed siliciclastic-carbonate continental-to-shelfal transitional succession found along a complex embayed coastline. Six petrophysically distinct lithofacies were identified: (1) lenticular to wavy-bedded mudstone, (2) flaser to wavy-bedded sandstone, (3) carbonate-rich sandstone, (4) ripple-to trough cross-laminated sandstone with common convolute bedding, (5) trough cross-laminated sandstone with abundant mud rip ups and mud balls, and (6) heavily bioturbated sandstone. Trace fossils include, Asterosoma, Diplocraterion, Chondrites, Conichnus, Cosmorhaphe, Cylindrichnus, Helminthopsis, Phycosiphon, Rhizocorallium, Rosellia, Skolithos, Teichichnus, and Zoophycus, indicating a combination of Skolithos, Cruziana, mixed Skolithos-Cruziana, and rare Zoophycus ichnofacies. Combined lithofacies and

ichnofacies observations suggest that paleoenvironments of the Katz Field included a bayhead delta, back-barrier estuary-embayment, flood tidal delta, tidal flat, and upper to middle shoreface. Conodonts collected from a crinoid-bryozoan-brachiopod wackestone-packstone in two of the cores include age-diagnostic species (Neognathodus expansus and Gondolella pohi, Idiognathodus aff. I delicates) indicating mid-Desmoinesian with CAI values of 1 to 1.5.

Selected References

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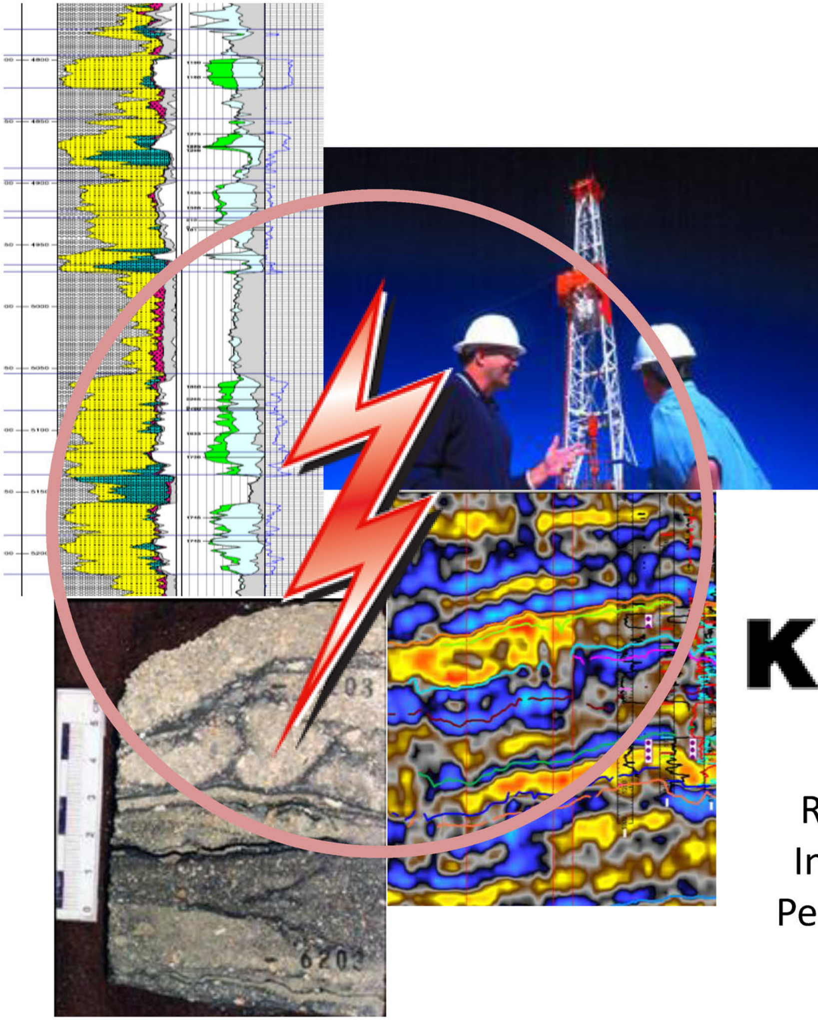

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Reconstruction of Paleoenvironments Through Integrative Sedimentology and Ichnology of the Pennsylvanian Strawn Formation in the Katz field, North-Central Texas

Presented to the SWS-AAPG 5/13/14 at 8:30 am
Midland, Texas

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Outline

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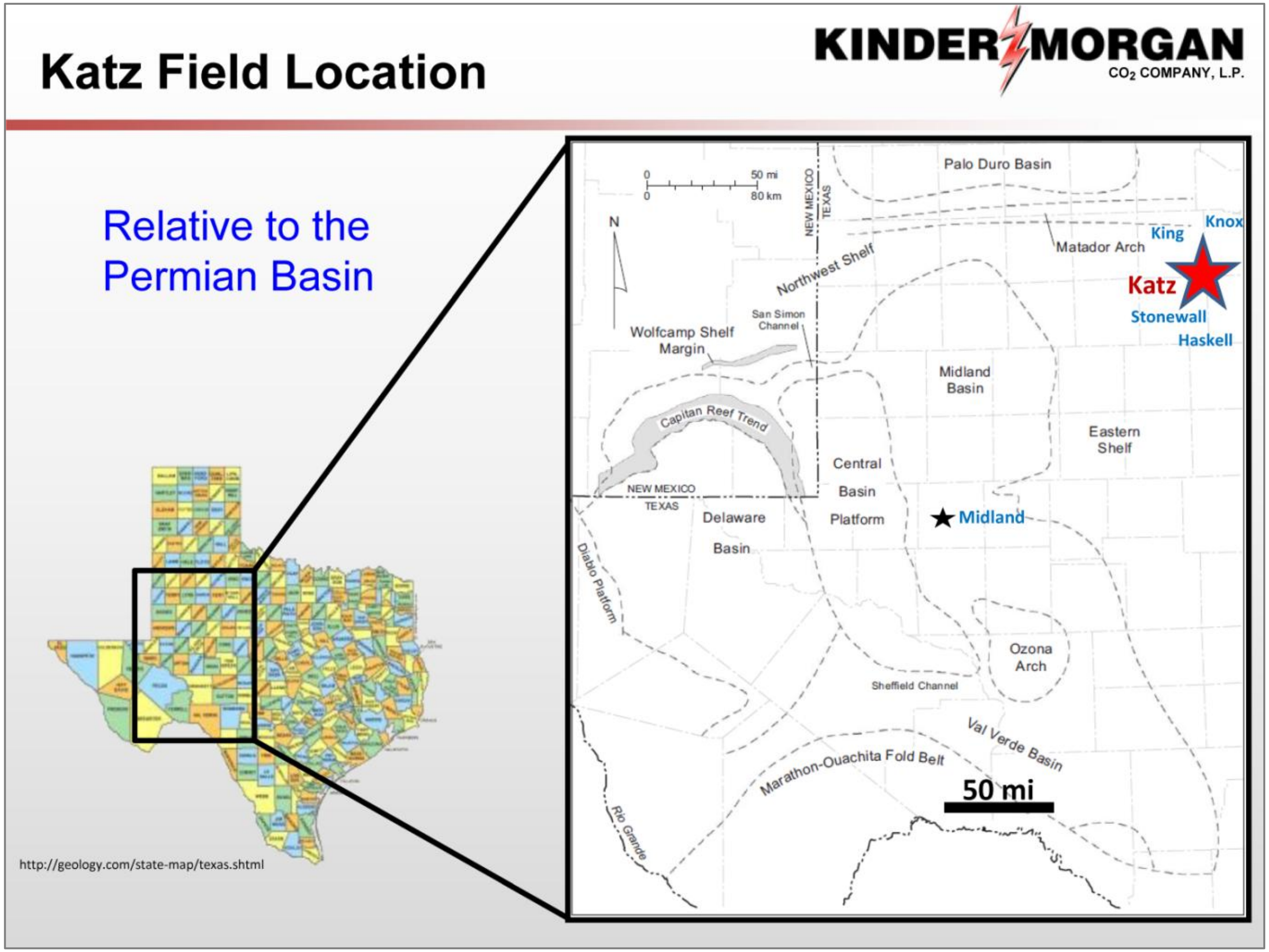
- Katz field location
- Conodont data
- Regional and local paleogeography
- Type log and cross section
- Core observations
- Conclusions
- Acknowledgments



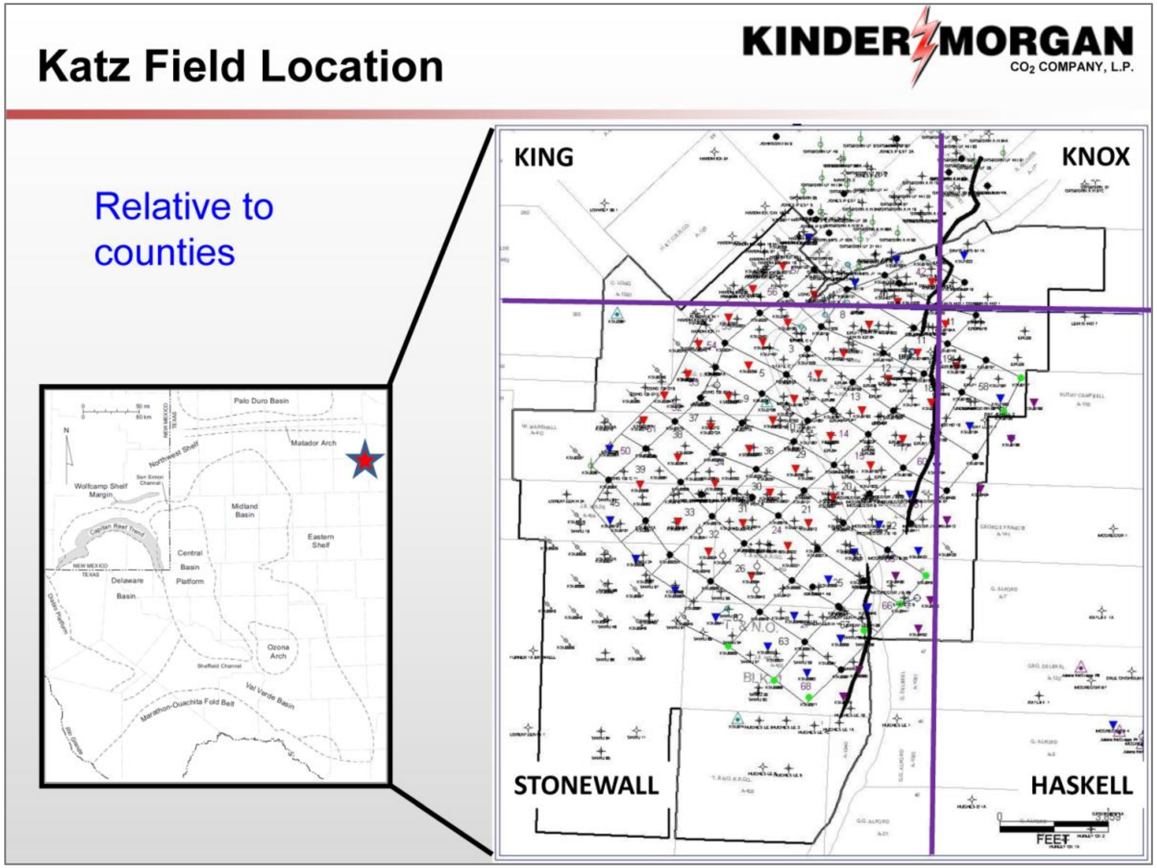
Presenter's notes: The Katz Field is located in north-central Texas near Knox City at the 4 corners junction of King, Knox, Stonewall, and Haskell Counties north of Abilene between Wichita Falls and Lubbock. Inset map taken from http://geology.com/state-map/texas.shtml *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

It is northeast of the Midland Basin and south-southwest of the Wichita-Amarillo uplift.

History of the Katz Field Unit:

Jan. 1951 Katz Field discovered by Katz Oil Co, H.D. Dozier No. 1 (current well name, ERU No.59).
Mar. 1951 Katz (5100) Field discovered by T.D. Humphrey, Mattie Davis No. 1 (located on theOrsborn Unit).
Jul. 1983 Katz (Day) Field discovered by Getty Oil Co, Roy Day No. 4 (current well name, SWRUNo.35).
Oct. 1984 Orsborn Unit waterflood began into the Katz and Katz (5100) Fields (Conoco, operator).
Oct. 1987 ERU unitized in the Katz and Katz (5100) Fields (Standard Oil Production Co, operator).
Nov. 1989 SWRU unitized in the Katz, Katz (Day), Katz (5100) Fields (BP Exploration, operator).
Nov. 1989 CBLU unitized in the Katz and Katz (5100) Fields (Phillips Pet. Co, operator).
May 2006 Kinder Morgan Production Co. became operator of ERU, CBLU, and SWRU.
Nov 2009 Consolidated 3 fields into the Katz (Strawn) Field.



Presenter's notes: Map of the Katz Field Unit at the corner of the 4 counties (King, Knox, Stonewall, and Haskell showing the location of county lines (solid purple lines), field boundary (solid black outline), wells locations (new and vintage), 5 spot CO2 injector centered patterns (approximately 40 acre spacing), the Brazos River that cuts right though the center of the field, and some major Caddo Limestone faults (solid black en-echelon normal fault lines) that extend up into the some of the sands in the unit and likely play a role in the fields location and oil accumulation.

The Katz Field is roughly 6900 acres with 60 well patterns accounting for approximately 3200 of those acres.

Conodont Data

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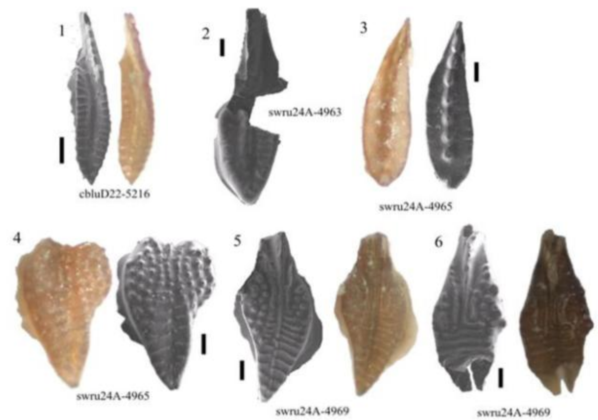
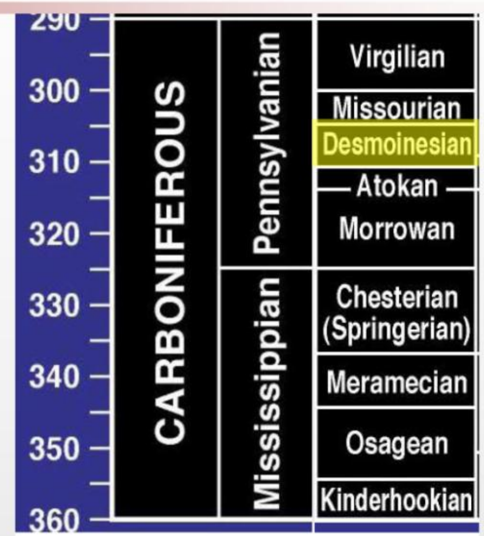


PLANE LIGHT & SECONDARY SEM IMAGES OF CONODONTS COLLECTED FROM THE KATZ FIELD. SCALE BAR = 0.1 mm

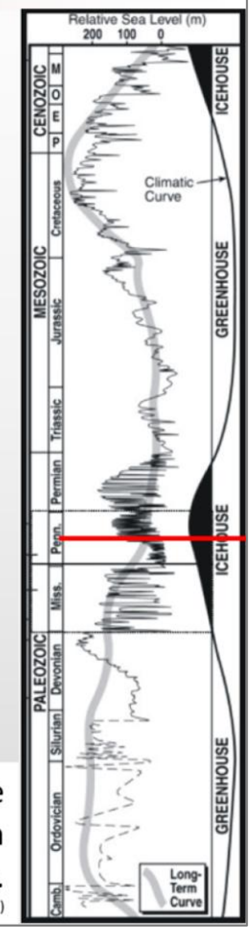
– Figure 1.1
Genus ADETOGNATHUS Lane, 1967
***Adetognathus lautus* (Gunnell, 1933)**
CB Long Unit D22-5216
Adetognathus lautus has a wide occurrence from **the Morrowan** through **middle Desmoinesian.**

– Figure 1.2
Genus NEOGNATHODUS
***Neognathodus expansus* Jones, 1941 ssp. B Rosscoe, 2005**
South West River Unit 24A-4967
This taxon is typical of the **mid-Desmoinesian**.

- Figure 1.3
Genus GONDOLELLA Stauffer and Plummer, 1932
***Gondolella pohli* Von Bitter and Merrill, 1998**
South West River Unit 24A-4965
Lower –mid Desmoinesian



Pennsylvanian stratigraphy of North America and important stratigraphic units associated with the Katz Field Unit. (Modified from Waite, 1993)



Relative Sea Level Curve from Paleozoic through Cenozoic. (Longmann et al., 1996))

Presenter's notes: Conodonts were extracted from 8 samples of muddy bio-wackestone and mud-dominated packstone in KSU cores. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

Cores were split and 1 or 2 kg of material was crushed to 1 cm long-dimension and dissolved in buffered 10 % formic acid for 24 hours. The residue was sieved, and conodonts recovered from a 0.125 mm (US 120 mesh) screen. This fraction was dried and heavy separated using Lithium Metatungstate with a specific gravity of 2.74-2.78 g/cm3, rinsed, dried, and picked using a fine paint brush and binocular microscope.

Macrofossils were obvious on the cut faces of the cores, consisting of brachiopods, bryozoans, and crinoids.

The carbonate interval in CB Long Unit D#22 yielded three conodonts or fragments from 8 kg processed, of which only one is identifiable: *Adetognathus lautus* (Gunnell, 1933; Figure 1.1). This taxon is relatively long ranging through the upper Carboniferous.

The carbonate interval from the South West River Unit #24A yielded eleven conodonts from 7 kg of rock processed. Several taxa are identifiable: *Gondolella pohli* Von Bitter and Merrill, 1998, several species of *Idiognathodus*, including *I.* aff. *I. delicatus* Gunnell, 1931 as well as *I*. cf. *I. claviformis* Gunnell, 1931, and *Neognathodus expansus* Merrill, 1972 (Fig 1.2-1.6). This unit also had abundant fish remains.

The fauna in the South West River Unit #24A 4962 to 4969 carbonate interval is indicative of the upper Cherokee Group, within the Inola through Verdigris cycles in the Midcontinent – mid-Desmoinesian, based on the smooth platform species of *Gondolella*. The other species are consistent with this assignment. The taxa in this interval are in need of revision and there is disagreement among experts on many taxonomic assignments (see Barrick et al., 2011, in press).

The conodonts in the two core intervals are dominated by robust P elements where the free blades have been broken off, suggesting some reworking. These elements are otherwise well preserved and light amber to medium amber in color, CAI 1 to 1.5 (Epstein et al.,1967) indicative of low thermal maturity.

Atokan-Desmoinesian Earth

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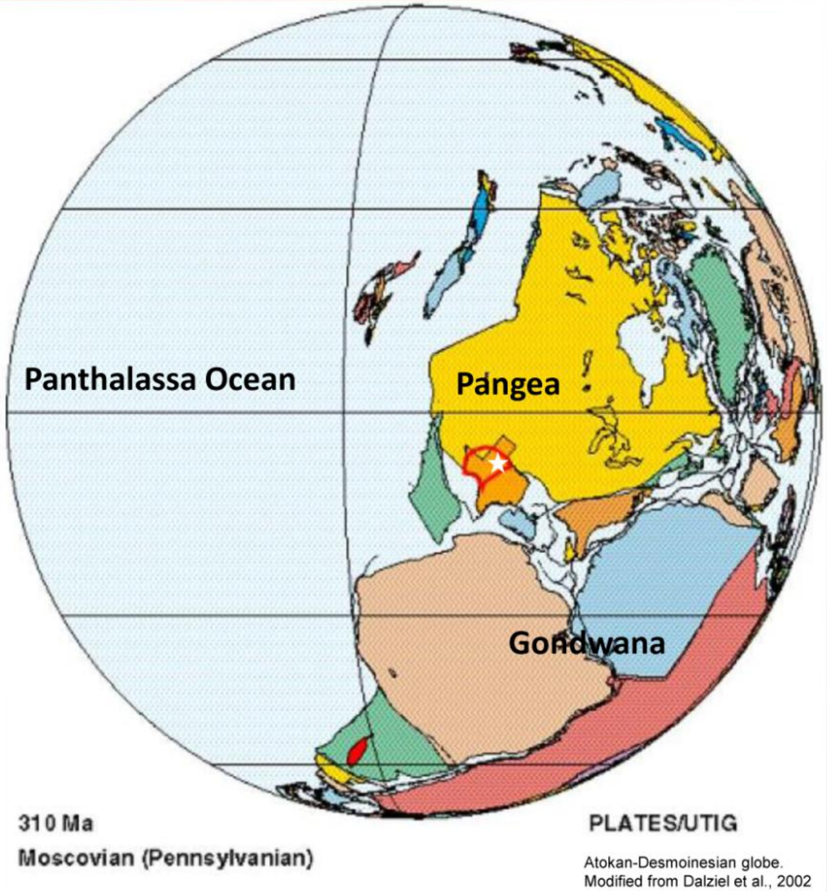

Atokan-Desmoinesian globe.
Modified from Dalziel et al., 2002

Presenter's notes: The Katz Field Unit location is represented by the white star on the state of Texas. The red outline indicates the location of the Greater Permian Basin. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

From Wright, 2011:

Desmoinesian-age sediments in the Permian Basin are characterized by being deposited at a near (8 to12^{o} south) equatorial position during the middle stages of icehouse, high-amplitude, high-frequency eustatic sea-level fluctuations.

It was an area undergoing increased tectonic activity of both uplift and subsidence related to Ouachita-Marathon orogeny and birth of the greater ancestral Rocky Mountains.

Desmoinesian-age sediments within the Permian Basin include those termed Strawn Formation (predominantly carbonates)—those of the Strawn Group and the underlying Caddo Limestone. Within the Permian Basin, most Desmoinesian-age sediments are referred to as Strawn Formation, and they are overwhelmingly carbonates. However, **on the Eastern Shelf, the stratigraphy is more complicated, with multiple carbonate and siliciclastic units having been cyclically deposited during the Desmoinesian.**

Desmoinesian

Two paleodepositional reconstructions are used to describe the Desmoinesian stage.

The first is an early to middle Moscovian time slice approximately equivalent to the Caddo-Odom and early Strawn depositional period, and the second is a late Moscovian to early Kasimovian reconstruction equivalent to the Capps-Anson and late Strawn depositional period. Desmoinesian units in the Permian Basin record gradual second-order transgression. Overall transgression is punctuated by numerous high frequency, high-amplitude, third-order, and higher order regressive and transgressive events. From the Desmoinesian through the Virgilian, carbonate lithologies dominated reservoirs within the Permian Basin.

(Presenter's notes continued on next slide)

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Lower Desmoinesian (Upper Moscovian)

Lower Desmoinesian siliciclastics dominated deposition only at the margins of the GPB (Greater Permian Basin). Marginal marine to deltaic sediments were on the ES-LU (Eastern Shelf – Llano Uplift), a band of marine open-shelf siliciclastics was to

the west-northwest of the NWS (Northwest shelf), a trough of marginal marine to deltaic sediments was in the northeastern Permian Basin (Fisher to Baylor County; termed **Knox–Baylor trough**), and alluvial to marine siliciclastics were in the southeastern Permian Basin in Kinney, Uvalde, and Zavala Counties (Kerr Basin).

Multiple episodes of deltaic expansion and westward migration occurred during the Desmoinesian. However, associated coarser grained siliciclastic facies occur primarily to the east of the Permian Basin. The ES records cyclic, siliciclastic, carbonate deposition, with only distal delta-front facies reaching the east margin of the Permian Basin (Dutton, 1977; Boring, 1993).

In general, siliciclastics on the ES reached their farthest westward extent during the early Desmoinesian (Shannon and Dahl, 1971; Gunn, 1979; Cleaves, 1993).

A lower Desmoinesian carbonate-ramp succession is extensively developed across most of the Permian Basin, with relatively uniform thickness (James, 1985;Marquis and Laury, 1989; Mazzullo, 1989; Waite, 1993; Montgomery, 1996; Saller et al.,1999a; Cleaves, 2000; Silvas, 2002; Newell et al., 2003; Saller et al., 2004). The CBP, not undergoing uplift at this time, was also blanketed in carbonate sediments (Yang and Dorobek, 1995).

Upper Desmoinesian (Upper Moscovian to Lower Kasimovian)

The upper Desmoinesian reflects a sedimentation pattern similar to that of the lower Desmoinesian; however, basin subsidence

(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

began in earnest during the middle to late Desmoinesian. Westward downwarping along the Fort Chadbourne Fault Zone (Ewing, 1990) as the proto-MB (Midland Basin) was initiated (Mazzullo, 1989) resulted in the first true Pennsylvanian carbonate shelf margin within the Permian Basin.

Major siliciclastic deltaic progradational episodes punctuated transgressive carbonate development on the ES and covered mostly the same areas but, in general, did not extend past the shelf edge of the previous cycle (e.g., marginal marine and alluvial siliciclastics of the Bowie and Perrin delta successions in Jack, Young, and Clay counties) (Cleaves, 1993) (Figure 6). Sediment supply and deltaic progradation on the ES was governed by continued convergence of the Ouachita thrust fold belt to the east and southeast of the FWB. Increased accommodation in the Permian Basin promoted aggradation of upper Desmoinesian carbonates (Strawn ~ Anson-Anson Bank-Capps formations). These sites of increased thickness tend to be sites of subsequent carbonate growth during the Missourian and Virgilian (Waite, 1993; Saller et al., 2004). An expansion in the variety of carbonate depositional architectures typifies the upper Desmoinesian, when the overall ramp configuration of the lower Desmoinesian diversified into shelf-interior banks, patch reefs, true shelf margins (rimmed shelf), and, to a much lesser extent, periplatform pinnacle reefs. These myriad new carbonate depositional environments and architectures are linked to increased subsidence in the proto-MB (Midland Basin) coupled with second-order sea level rise. The intensity and frequency of third-order eustatic events were also increasing, thereby creating a much more complex mosaic of facies than in the underlying succession.

The ES carbonate succession is represented by the Anson ramp to bank and Capps succession. To the west of the Anson bank, across a shallow basin, are thick aggradational carbonates on the Red River uplift (King County). **A shallow northeast-southwest–trending trough connected the Knox and Baylor County area (Knox-Baylor trough) to the proto-MB across Mitchell and Fisher counties**. Subsidence along the MA (Matador Arch/Uplift) led to the development of a carbonate shelf margin in Hockley and Lubbock counties, which would roughly correspond to the north margin of the incipient northern MB isolated platform, historically referred to as the Horseshoe atoll.

Regional Paleogeography

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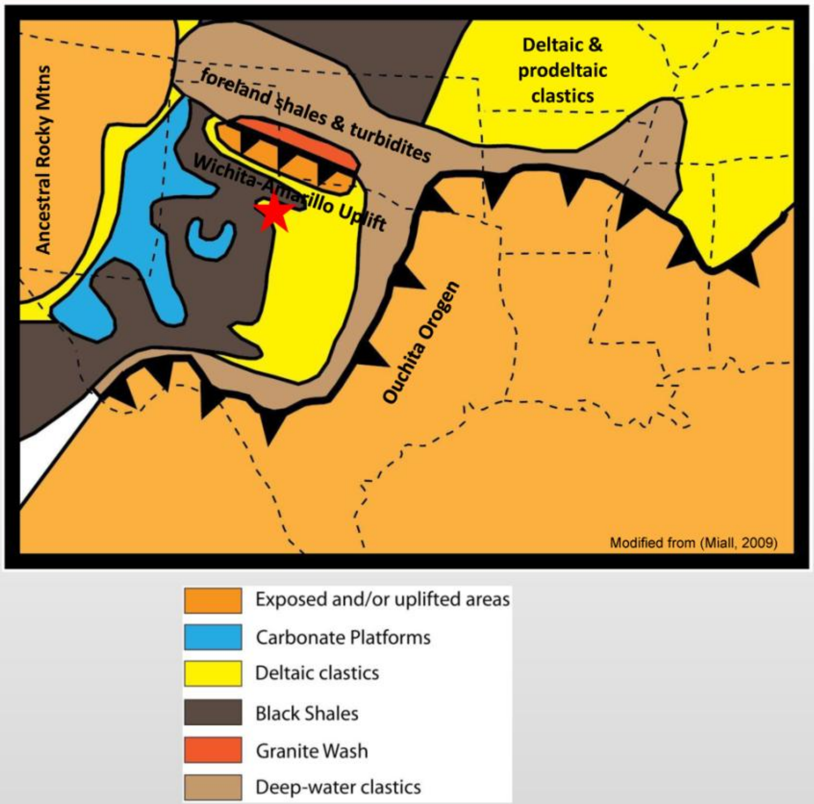

Regional paleogeography and structural geology from Mid-Late Pennsylvanian time (Atokan-Desmoinesian)

Diagram exhibits the Ouachita Orogeny, Wichita-Amarillo Uplift, associated foreland basins, and deltaic clastics associated with erosion from the WAU and OO.

Sediments of note in the Katz Unit field area include mixed carbonates & clastics and deltaic clastics.

Presenter's notes: Regional paleogeography and tectonics during Desmoinesian (Miall, 2009).
Katz is located northeast of the Midland Basin, south of the Wichita-Amarillo Uplift, and west of the Ouachita fold belt indicated by the red star.

Regional Paleogeography

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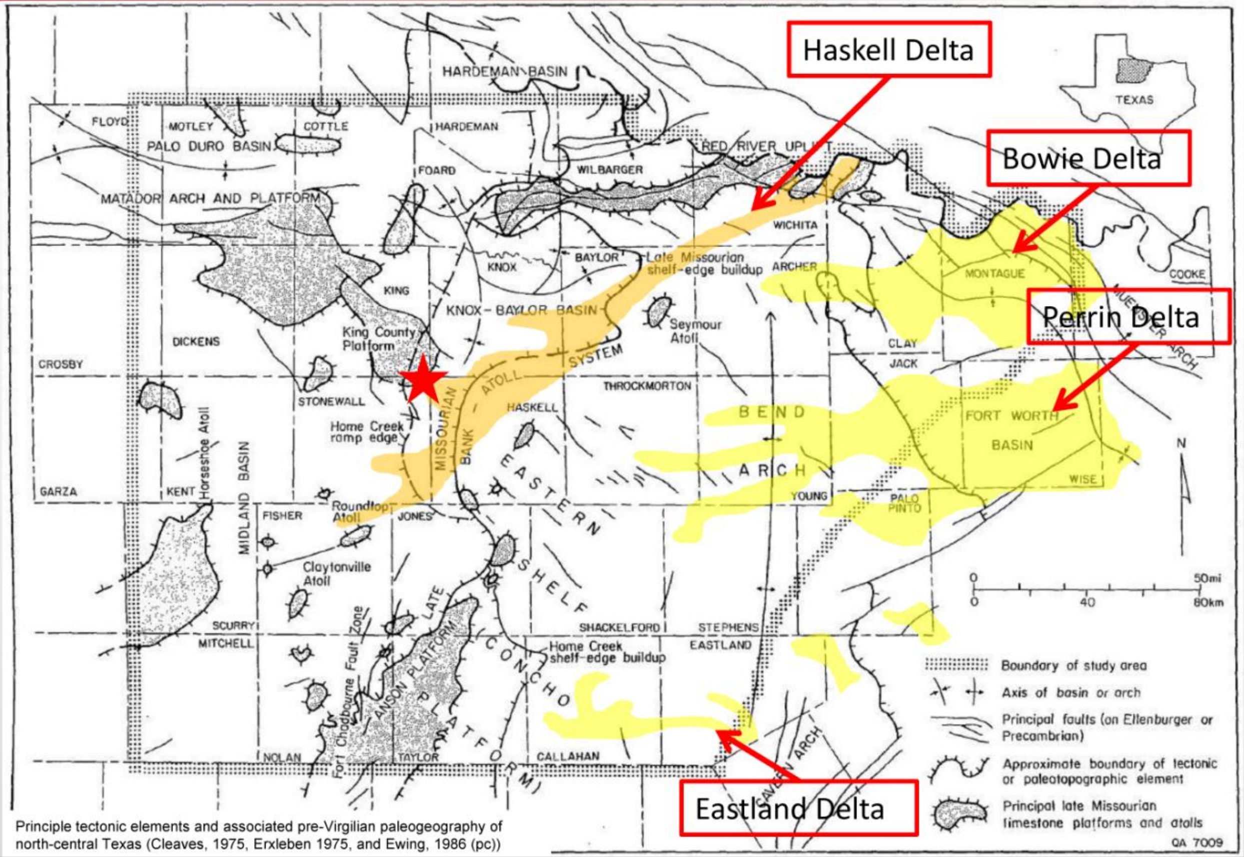


Principle tectonic elements and associated pre-Virgilian paleogeography of north-central Texas (Cleaves, 1975, Erxleben 1975, and Ewing, 1986 (pc))

Presenter's notes: Based on the conodont age of Desmoinesian the regional pre-Virgilian paleogeography of Cleaves and Erxleben gives you an idea of what the regions looked like around Desmoinesian-Missourian time from a tectonic and paleogeographic perspective. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

Note the locations of the Fort Worth Basin, the Bend Arch, the Eastern Shelf and Concho Platform, the Red River Uplift, and the Midland Basin.

Of immediate importance to the Katz Field Unit (represented by the red star) is the Knox-Baylor Basin (also called the Knox-Baylor Trough), the King County Platform, and the Haskell Delta System super imposed onto the map in orange.

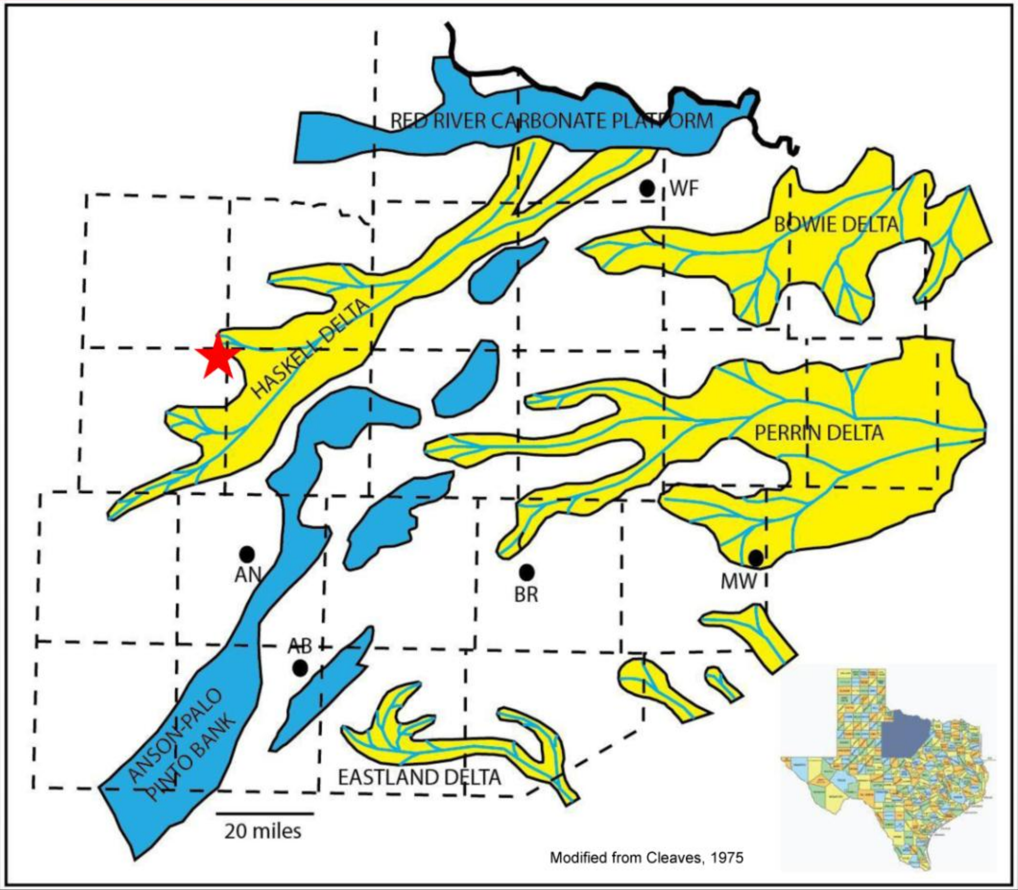
From Wright, 2011:

"Desmoinesian siliciclastic deposition is reciprocal with carbonate sedimentation and is largely restricted to the northern Eastern Shelf. A 2nd-order transgression appears to have dominated throughout the rest of the Desmoinesian; however 3^{rdth}-order, high-amplitude, sea-level fluctuations occurred at a high frequency. The result was an almost interlayered carbonate and siliciclastic stacking pattern on a 3rd-order scale.

Within King County, delta facies interfinger with the carbonate ramp and platform in Bateman and Anne Tandy fields (Boring, 1993). Two large regressive and transgressive cycles are present in this area of the Knox-Baylor Trough. Tandy 5400 (KATZ 5100/UPPER 3RD SAND) and Anne Tandy sandstones (KATZ 2C SAND) are in a basal cycle, and the Twin Peaks sandstone (KATZ 1ST SAND) is in an upper cycle. Desmoinesian-age limestones interfinger with and transgress deltaic sediments; however, correlation is not sufficient to identify the carbonate sequences.

The Tandy 5400 sandstone (KATZ 5100/UPPER 3RD SAND) may be equivalent to the Hog Mountain sandstone to the east. The Tandy 5400 is interpreted as a distributary bar finger comprising crossbedded sandstones, whereas the Anne Tandy is a lobate delta (KATZ 2C SAND) . The Twin Peaks sandstone (KATZ 1ST SAND) is thought to represent an offshore bar system (Boring, 1993). Most of this succession was previously interpreted as being deposited in deep-water conditions (Gunn, 1979). Given the regional geology gathered in this study, it appears that this succession is predominantly shallow water deltaic in origin."

Local Paleogeography



Presenter's notes: Another way of looking at the regional paleogeography without all of the fluff using a cartoon representation of the major delta systems during Strawn Genetic Interval 1 (Desmoinesian Series) modified from Cleaves, 1975.

Katz Field Type Log

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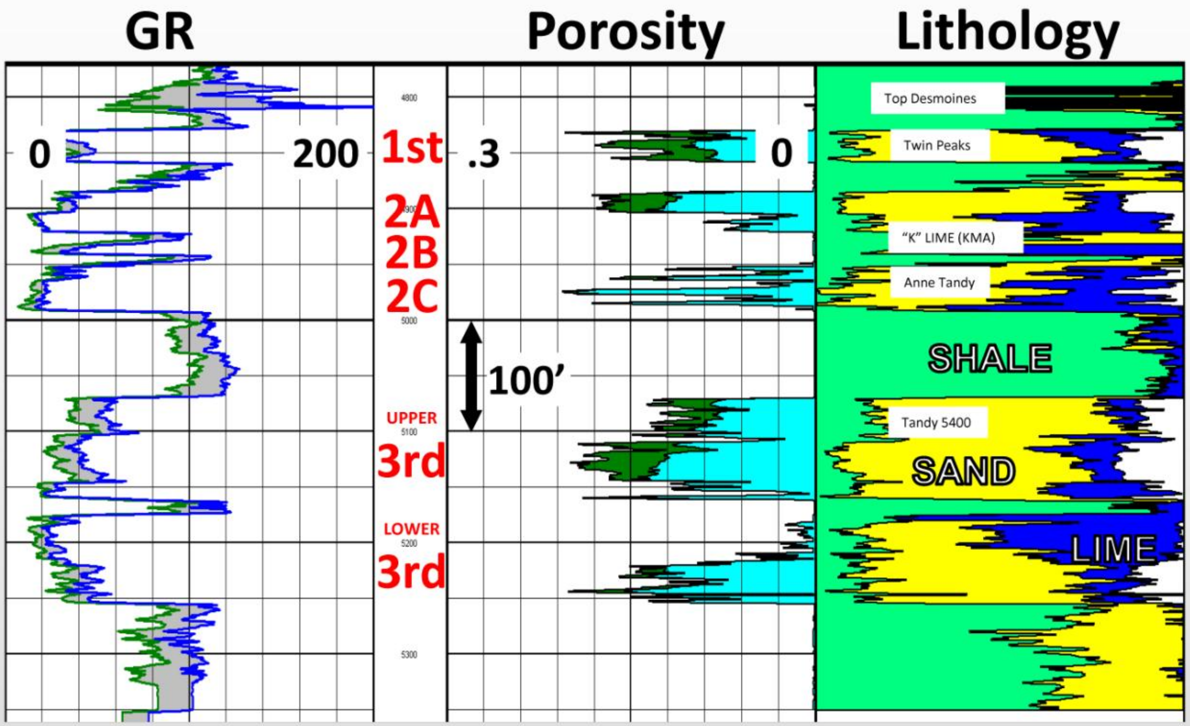


Presenter's notes: Type log in the Katz Field Unit.
Note the depth tract and the vertical scale bar. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

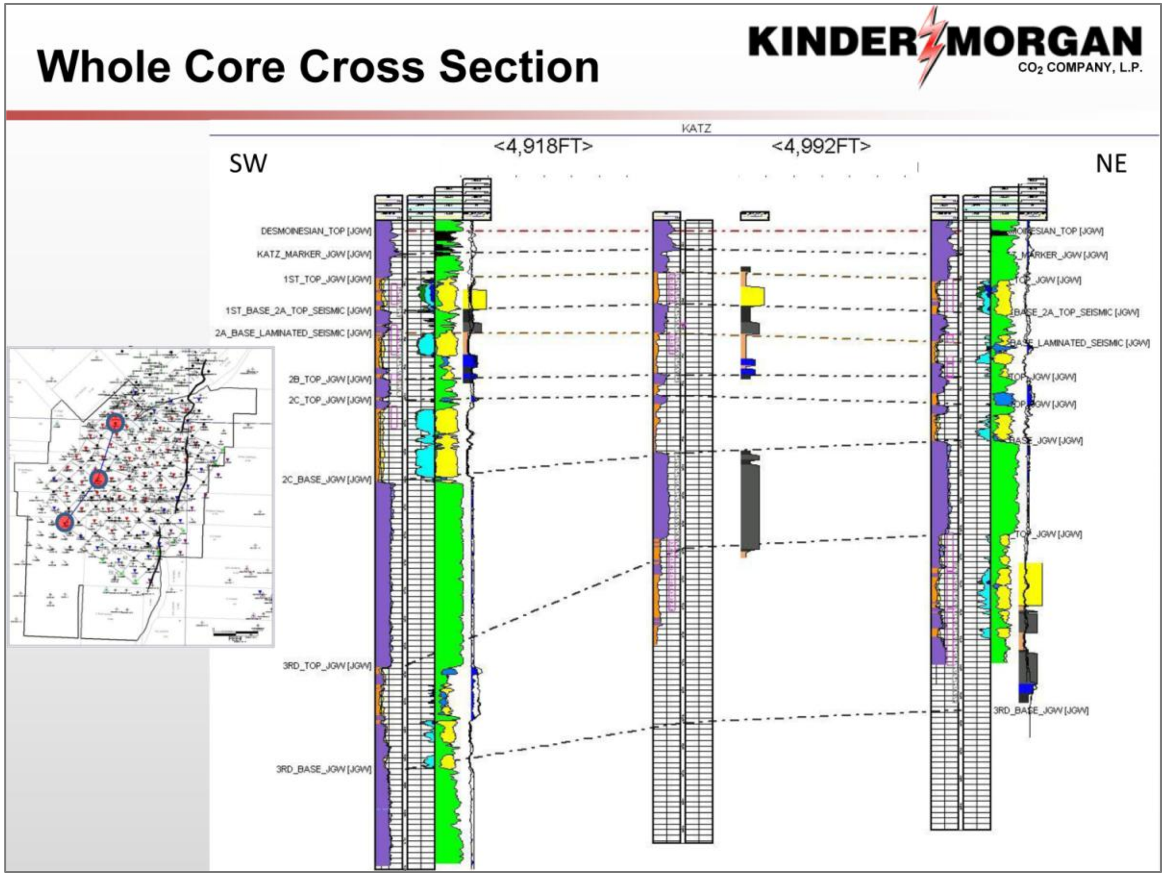
Depicted in this slide are the following logs:

In tract 1 – GR (CGR & SGR –CGR doesn't track uranium signature)
In tract 2 -- JSWE and oil in place
In tract 3 -- JCOAL, JSHALE, JLIME, & JSAND.

Note the GR and it's relationship to the sands and shales. Note the saturations of each sand and that the 2C and the lower 3RD SAND DO NOT SHOW ANY oil saturation.

Note the lithology log and percentages of different lithologies including PHI (white)

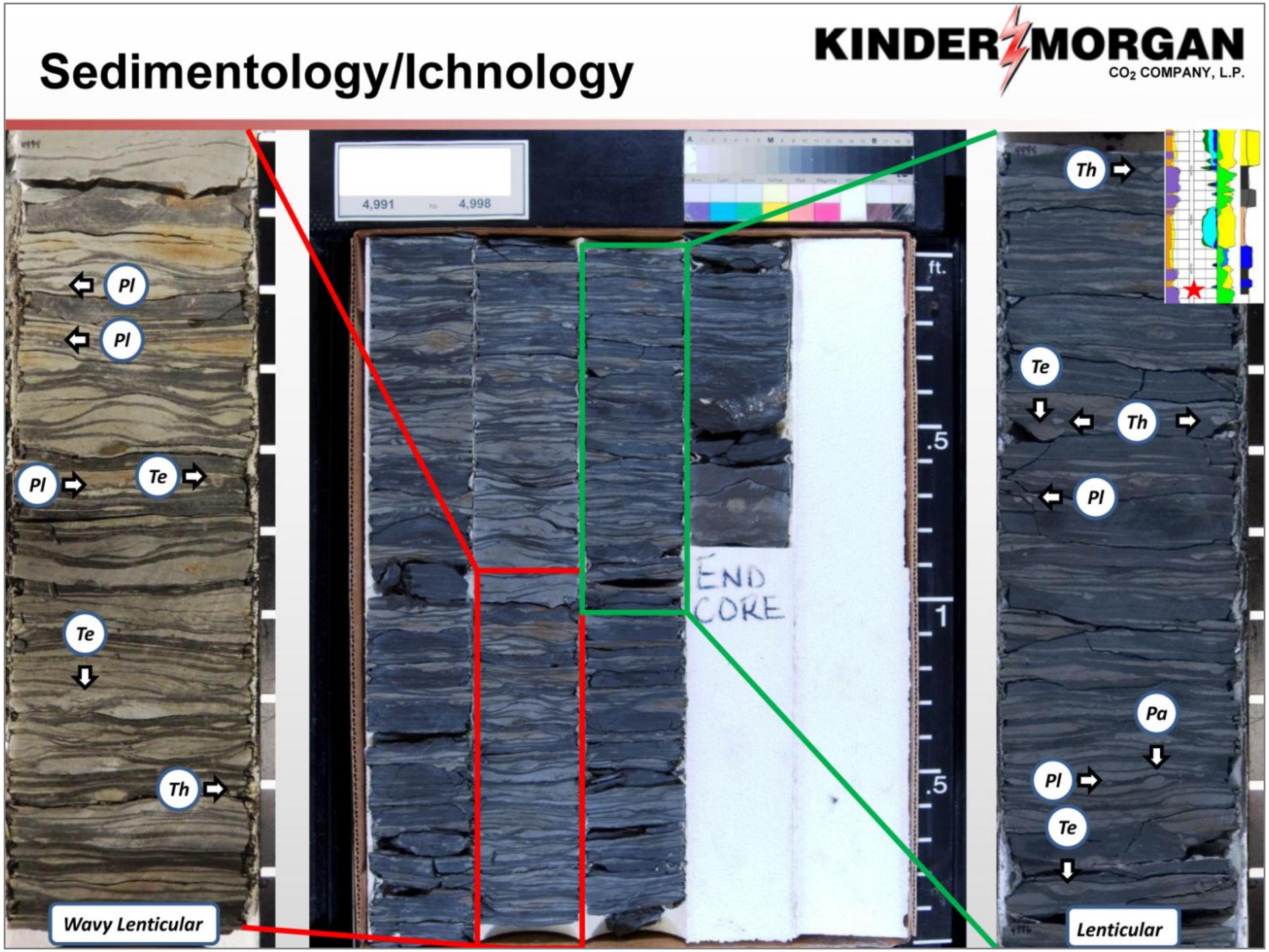
The 1st Sand is equivalent to the "UPPER KATZ" and/or "TWIN PEAKS" (interpreted as Offshore Bar system by Boring, 1993)
The 2C Sand is equivalent to the "ANNE TANDY SAND" (interpreted as Lobate Delta by Boring, 1993)
The Upper 3rd Sand is equivalent to the "KATZ 5100" and/or "TANDY 5400 SAND" (interpreted as distributary bar finger by Boring, 1993)



Presenter's notes: Whole core cross section in the Katz Field Unit.

Note the GR, JSWE and oil in place, lithology curve, PE curve, and generated depositional facies curve (generated from core logging facies and facies associations).

Note that the depositional facies curves cannot be correlated through the entire KSU section but that we do have good facies control in the 1st Sand through 2B top.



Presenter's notes: *(Presenter's notes on next slide)*

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4991 TO 4998*:*

4991.00 – 4997.4: Black to dark gray lenticular to wavy bedded mudstone encasing light gray lenticular siltstone to muddy very-fine sandstone. Abundant light gray calcareous horizons. Note zones of reddish color.

4997.4 – 4997.5: Burrowed transgressive bioclastic lag deposit? Abundant crinoid and bioclastic debris over burrowed laminated to contorted black shale.

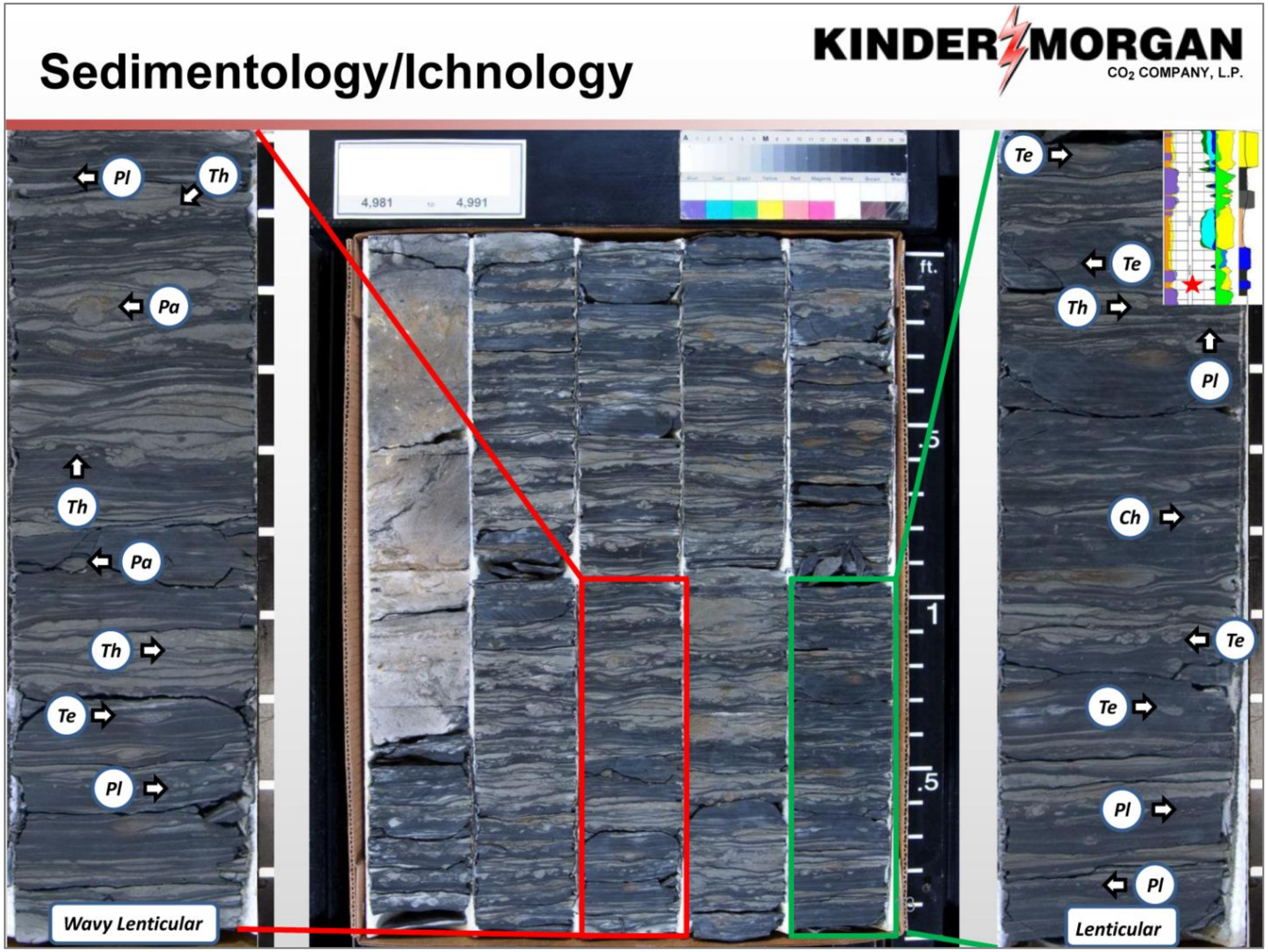
4997.5 - 4997.7: Black laminated shale

4997.7 - 4998.0: Dark gray to gray black crinoid mudstone interbedded with a single tan algal mudstone-wackestone hardground exhibiting mudcracks.

Trace fossils shown in blow-ups include *Paleophycus, Planolites, Thalassinoides* and *Teichichnus*.

Sedimentology infers **brackish water deposits** (Brackish water is water that has more salinity than fresh water, but not as much as seawater. It may result from mixing of seawater with fresh water, as in estuaries.

4991 - 4998: Estuary – embayment. Brackish water deposit. Muddy.



Presenter's notes: *(Presenter's notes on next slide)*

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<u>4981 to 4991:</u>

4981.00 - 4982.40: Light gray to tan-brown intraclast bioclast wackestone with slump? Thin whispy mud streaks. Burrow modified zones.

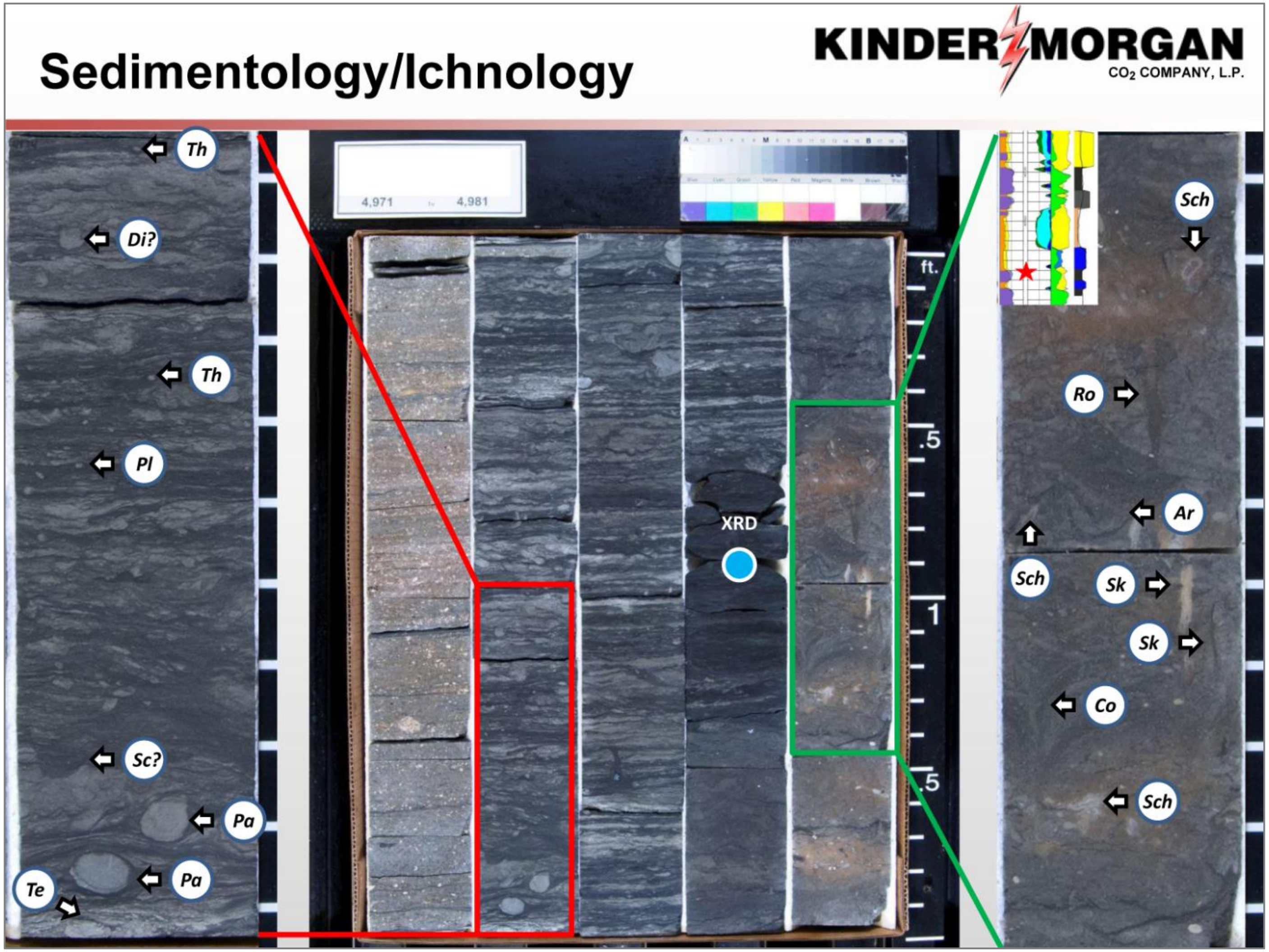
4982.40 – 4991.00: Black to dark gray lenticular to wavy bedded mudstone encasing light gray lenticular siltstone to muddy very fine sandstone. Some horizons are calcareous. Note reddish areas.

Trace fossils shown in blow-ups include *Paleophycus, Planolites, Thallasinoides,* and *Teichichnus*.

Sedimentology infers **brackish water deposits** overlain by **marine influenced** obscure lime mudstone-wackestone.

4978.5 – 4982.5: Interval is dominated by a distal subaqueous channel, most likely on a flood tidal delta sourced from a seaward direction through an embayment. Subaqueous distal tidal channel abandonment at top.

4982.5 – 4991: Estuary – embayment. Brackish water deposit. Muddy. Transitions upward into subaqueous limestone sedimentation possibly in the form of distal sediment plumes or storm deposits that arrive from seaward direction.



Presenter's notes: *(Presenter's notes on next slide)*

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<u>4971 to 4981:</u>

4971.00 – 4973.05: Low angle cross laminated shaley crinoid bivalve coral intraclast dolowackestone with thin shale foresets and mud drapes. Calcareous shale increases towards base of package. Not the thin calcareous hale crinoid bioclastic dolowackestone at the base of this package.

4973.05 - 4977.6: Burrow modified lenticular to wavy-bedded mudstone with minor sandstone and siltstone.

4977.6 – 4978.4: Black to dark gray shale with minor burrow modification at the base including *Planolites*.

XRD SAMPLE taken at 4977.80 by weight % is 37% clay (3% chlorite, 3% kaolinite, 16% illite/mica, 15% interstratified mixed-layer illite/smectite with approximately 20-30% expandable interlayers), 3% carbonate (2% calcite, 1% dolomite), and 60% other (40% qtz, 6% kspar, 10% plag, 1% pyrite, 1% apatite)

4978.4 – 4979.5. Dark to medium gray burrow modified whispy laminated shale with rare crinoid-bioclastic component.

4979.5 – 4981: Medium-light gray to reddish tan burrow modified chaotic intraclast crinoid bioclastic calcareous sandstone or limestone?

Trace fossils shown in blow-ups include *Schaubcylindrichnus, Rosellia, Skolithos, Arenicolites, Conichnus* on the right and *Thalassinoides, Diplocriterion* (?), *Planolites, Scolicia* (?), *Teichichnus*, and *Palaeophycus*.

Sedimentology infers **brackish water deposits** interfingering with **fully marine** influenced obscure lime mudstone-wackestone at the base with a possibility of an estuarine turbidity maximum or deeper water shale located at 4977.6 – 4978.4. **Fully marine influenced** carbonate transgressive tidal delta deposits dominated the top of the box.

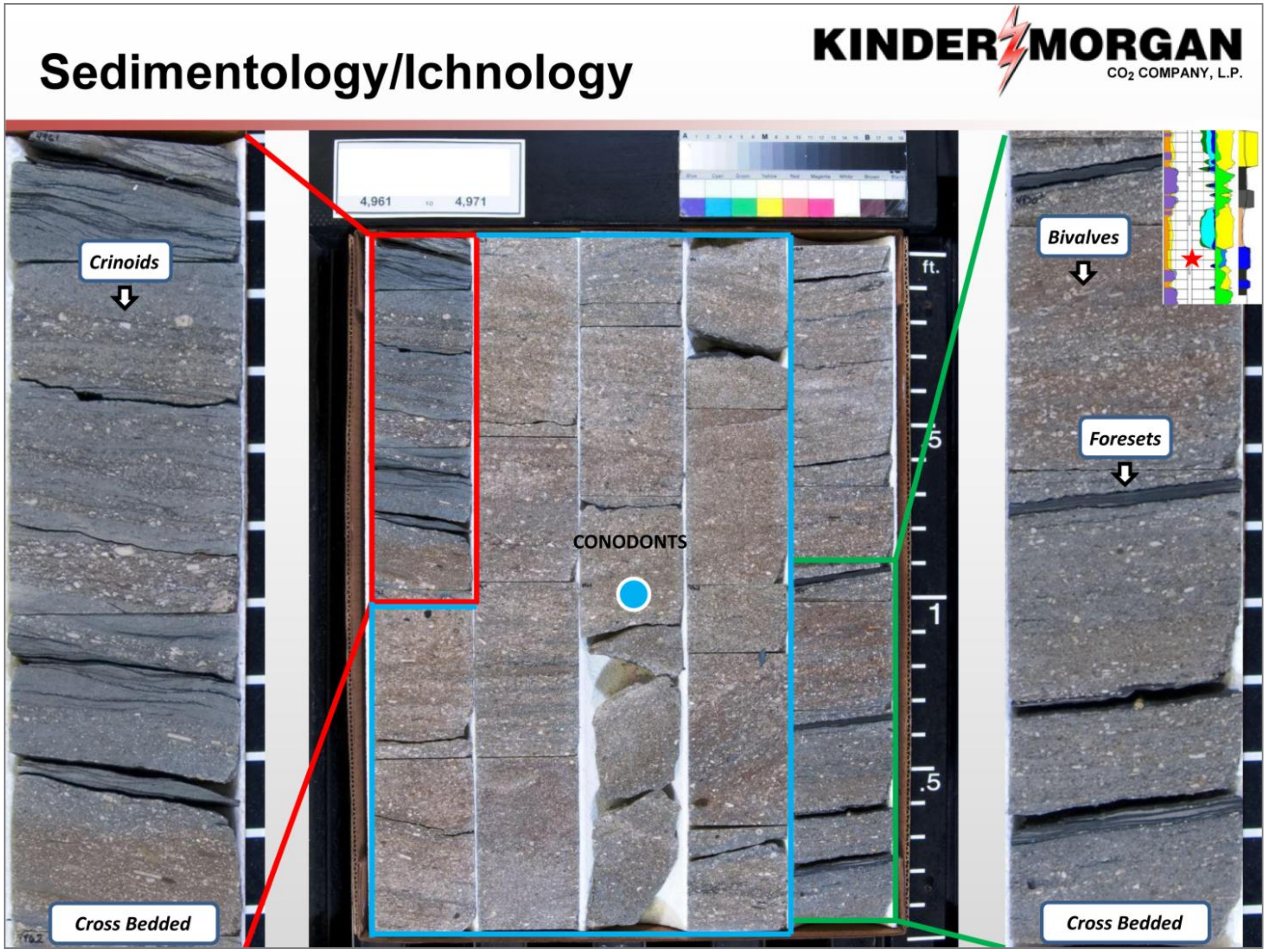
(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

4971 – 4973: Overall coarsening-upward succession similar to that expected for a delta (flood-tidal). Critter hash in carbonate-rich sandstone suggest sedimentation from a seaward position, likely on a flood-tidal deltas through a barrier.

4973 – 4978.5: Return to brackishwater muddy estuary- embayment - in middle of cored interval.

4978.5 – 4982.5: Interval is dominated by a distal subaqueous channel, most likely on a flood tidal delta sourced from a seaward direction through an embayment. Subaqueous distal tidal channel abandonment at top.



Presenter's notes: *(Presenter's notes on next slide)*

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4961 to 4971:

4961 – 4962: Inter-fingering of trough cross-laminated to ripple-laminated very fine grained to fine grained sandstone with mud or organic rich drapes with fine to very coarse grained crinoid-bivalve-bioclastic wackestone. Note that the dip is unidirectional.

4962.00 – 4964.20: Crinoid-bioclastic packstone. Faintly laminated to cross laminated. Thin 0.5cm carbonate mud horizon at 4964.20.

4964.20 – 4969.9: Crinoid-bioclastic packstone. Faintly laminated with shales. Note that the direction of dip changes so to very high angles. Increasing shale content towards the base of this section. Also note the faint reddish coloration.

4969.9 – 4971.00: Coarsening upward foreset packages of crinoid-bioclastic wackestone to packestone with thin shale foreset caps. Shale foreset caps are spaced from 2/10ths to 5/10ths of a foot. Increase in shale component within wackestone-packstone toward the base of the package. Basal shale foreset is lenticular laminated.

Note the lack of discernable trace makers in this section of core. This is likely due to rapid deposition of the constantly shifting carbonates where colonization of the sediment was not possible.

Sedimentology infers **fully marine influenced** carbonates with shale foresets indicating slackwater interfingering with **brackish water** deposits at the base. At the top of the box, the **fully marine influenced** carbonates are interfingering with very fine grained carbonaceous sandstones likely being deposited in **fresh-brackish mixing zone** water.

4962 – 4973: Overall coarsening-upward succession similar to that expected for a delta (flood-tidal). Critter hash in carbonate-rich sandstone suggest sedimentation from a seaward position, likely on flood-tidal deltas through a barrier.

Sedimentology/Ichnology

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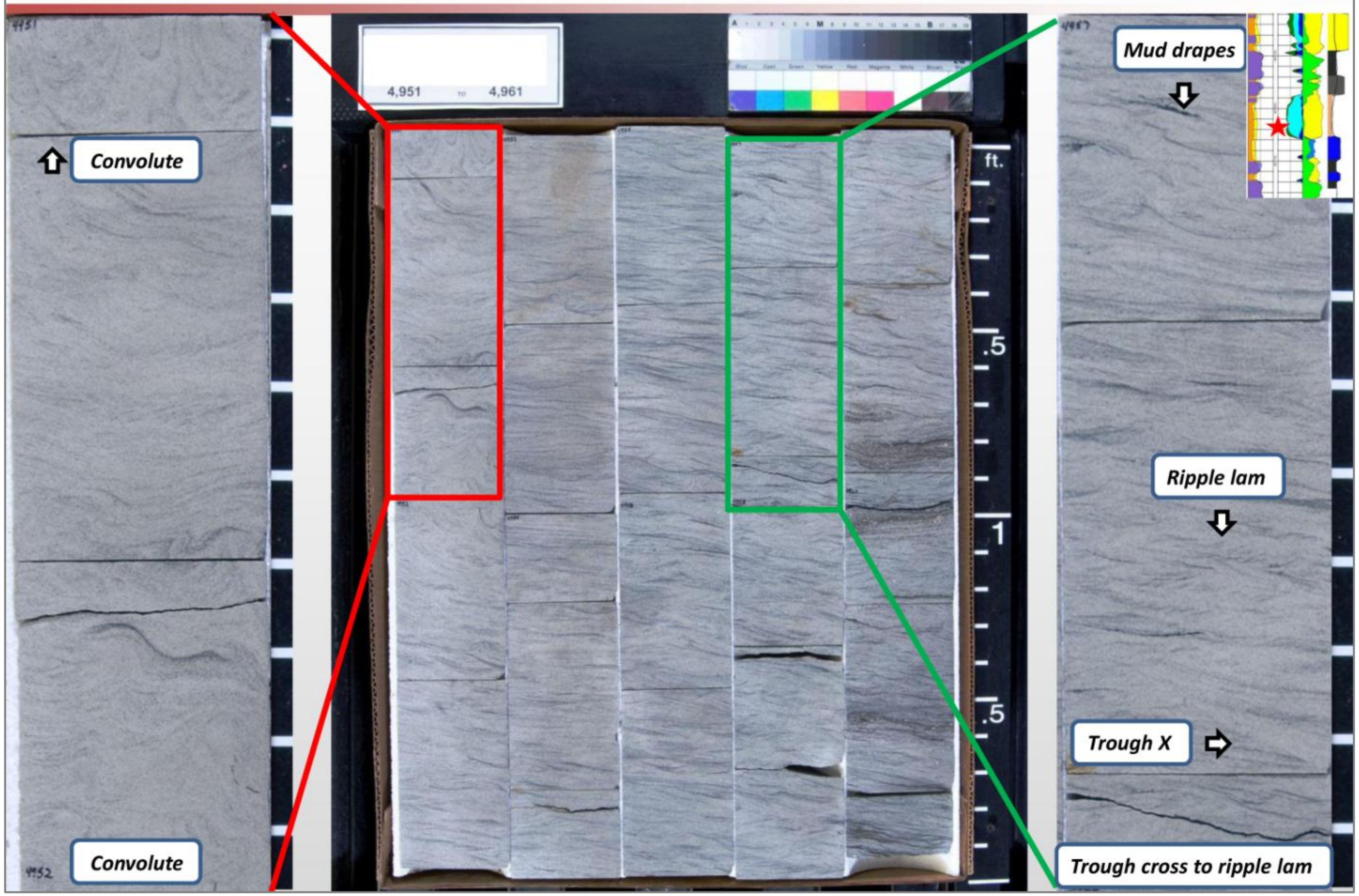

Presenter's notes: *(Presenter's notes on next slide)*

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4951 to 4961:

4951.00 – 4952.30: Convolute bedding in trough cross-laminated to ripple-laminated very fine grained sandstone with mud or organic rich drapes. Lacks bioturbation.

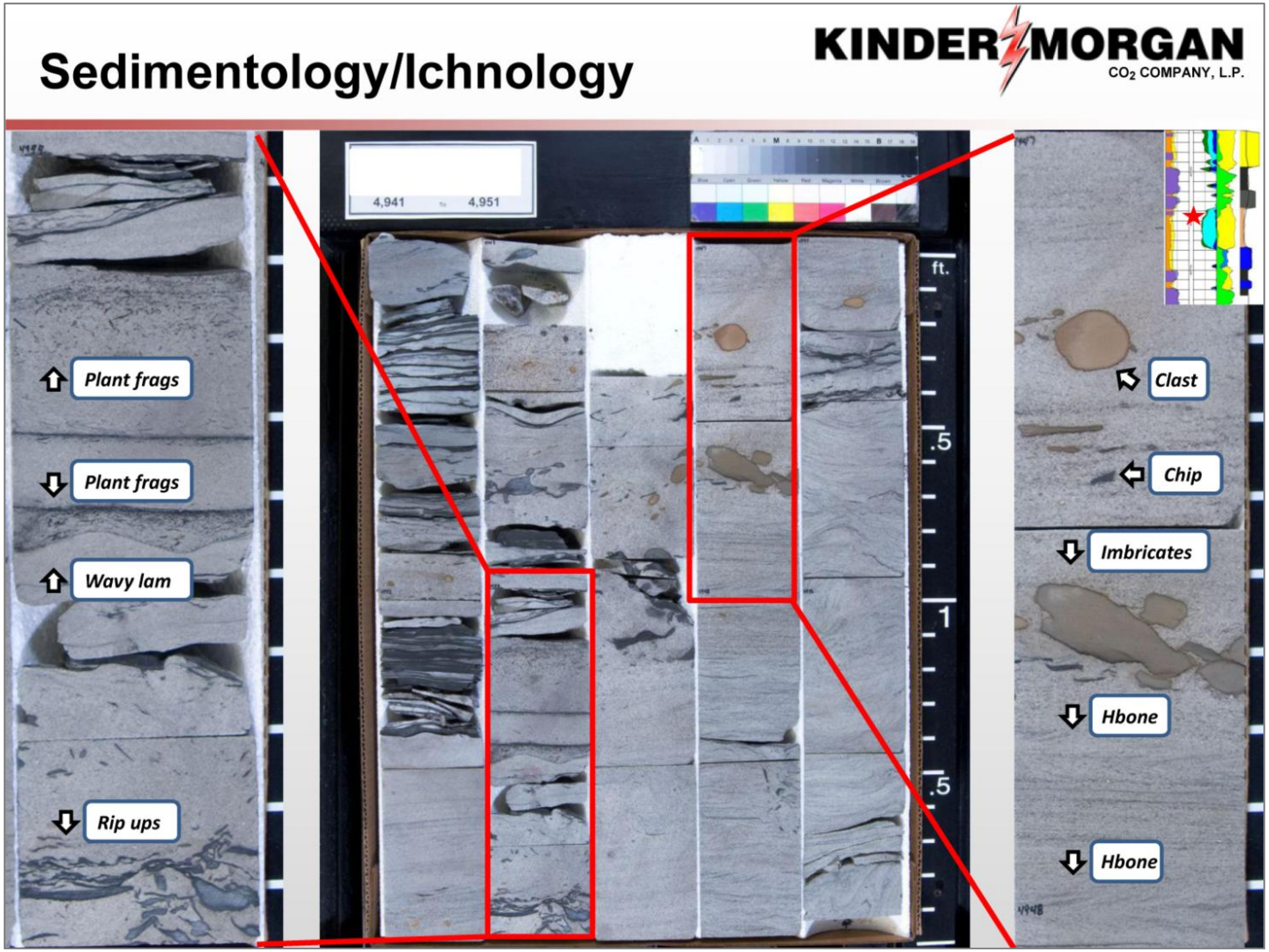
4952.30 – 4959.70: Trough cross-laminated to ripple-laminated very fine grained to fine grained sandstone with mud or organic rich drapes. Note unidirectional dips. Very rare and isolated tan pebble at 4959.40.

4959.70 – 4961.00: Thin intercalations of fine to coarse grained crinoid and bioclastic debris incorporated into the trough cross-laminated to ripple-laminated sandstone. Note burrow at 4960.

Note the lack of discernable trace makers in this section of core. This is likely due to rapid deposition of the constantly shifting sands where colonization of the sediment was not possible.

Sedimentology infers deposition in **fresh-brackish mixing zone water**.

4949 – 4962: New provenance combined with sedimentary structures (convolute bedding, ripples, low angle planar, trough cross stratification) suggests landward-source. Most likely from a bayhead-delta. Interval likely dominated by bayhead delta mouth bars and distal bayhead delta distributary channels, some subaqueous.



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<u>4941 to 4951:</u>

4941.00 – 4942.40: Flaser-to wavy-bedded sandstone with minor mudstone and calcareous shales. At 1491.7- 1491.9 note the well rounded tan pebble to gravel sized clasts and mud rip ups. Also note the surface at 4942.40 is a rippled surface.

4942.40 – 4943.40: Fining upward trough cross to parallel laminated coarse to fine grained sandstone with thin mud rip ups, rounded to sub-rounded tan pebble sized clasts, and bioclastic component. Bioclasts, pebbles, and mud rip ups are confined to the bottom of this sequence.

4943.40 - 4944.10: Trough cross laminated coarse to fine grained sandstone with mud rip ups and oblate to sub rounded pebbles. Note the pebbles are at the bases of troughs. Thin bedded shales some of which are contorted by burrowing.

4944.10 – 4944.50: Abundant thin chaotically organized organic (plant fragment & rootlet?) debris in ripple to trough cross laminated sandstone. Base of the sequence is a clearly defined ripple mark.

4944.50 – 49.51.00 Trough cross-laminated sandstone with mud rip-ups and well rounded to sub-rounded tan pebble to gravel sized clasts. Note that the tan clasts are imbricated at 4947.70. Wide burrow with mud chips from 4948.40 to 4948.70. Convolute bedding from 4949.7 to 4951.00.

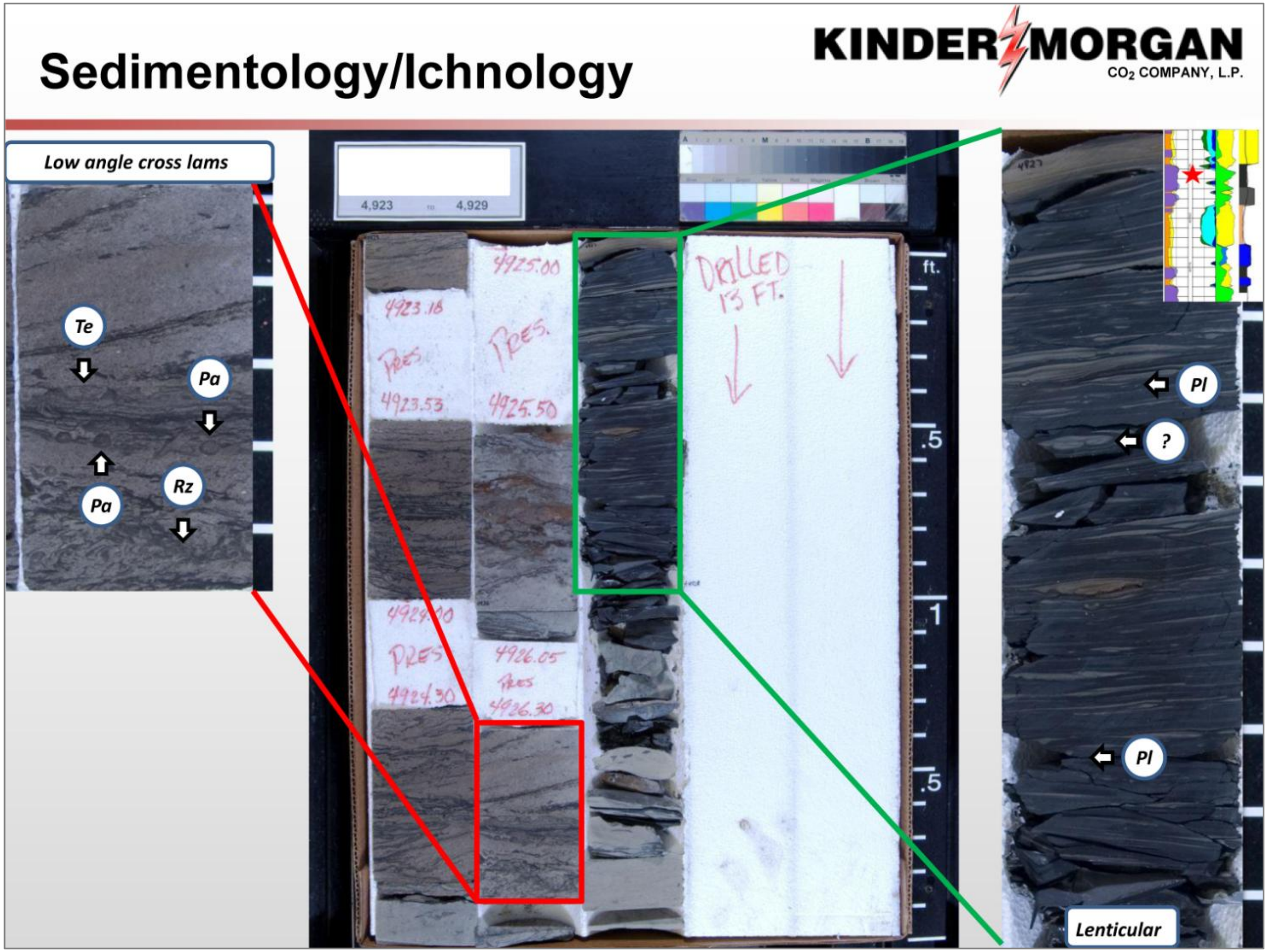
Note the lack of discernable trace makers in this section of core. This is likely due to rapid deposition of the constantly shifting sands where colonization of the sediment was not possible.

Sedimentology infers deposition in **fresh-brackish mixing zone water** to **brackish water**.

4942 – 4949: Convolute bedded sand at base suggest continued bayhead delta-mouth bar sedimentation. Trough cross-stratification and mud rip-ups become very common upward. Grain size may increase upward? Plant fragments become evident at intervals. This interval indicates a move toward mostly channelized flow. Just above this interval is a return to lenticular to wavy bedded, source likely becomes less significant at top. Muddier intervals indicate breaks in coarser sedimentation and return to muddy embayment background sedimentation. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

4949 - 4962: New provenance combined with sedimentary structures (convolute bedding, ripples, low angle planar, trough cross stratification) suggests landward-source. Most likely from a bayhead-delta. Interval likely dominated by bayhead delta mouth bars and distal bayhead delta distributary channels, some subaqueous.



Presenter's notes: *(Presenter's notes on next slide)*

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4923 to 4929:

4922.00 – 4923.18: Wavy to very low angle cross laminated very fine grained to medium grained sandstone.

4923.53 – 4924.00: Wavy laminated to laminated very fine grained to medium grained sandstone. Common ichnofauna includes *Planolites* & *Teichichnus*.

4924.30 – 4924.90: Wavy laminated to low angle cross laminated very fine grained to medium grained sandstone. Common ichnofauna includes *Planolites* & *Teichichnus*.

4924.90 – 4925.00: Mudstone (limestone) with mud chips.

4925.50 – 4926.05: Gray to rusty red burrow mottled very fine grained crinoid, bioclast, intraclast wackestone with thin shale laminations. *Planolites*? Note the rounded to subrounded intraclasts, zones of reddish discoloration, and alternating dips of mud drapes.

4926.30 – 4926.65: Low angle cross laminated calcareous sandstone with mud drapes and mud chips. Very fine grained bioclastic component. No evidence of burrowing.

4926.65 – 4927.00: Burrow mottled laminated to wavy bedded sandstone with mud drapes. Common ichnofauna includes *Teichichnus*, *Planolites*, and *?*

4927.00 – 4928.02: Coarsening-upward lenticular-to wavy-bedded black to dark gray mudstone encasing lenticular light gray siltstone to muddy very fine grained sandstone. Common ichnofauna is primarily *Planolites*. Note that the very top of this sequence is tan with hints of red compared with the remainder of the sequence. Very low angle laminations with dip changes.

4928.02 – 4929.00: Trough cross-laminated sandstone with mud-rip ups. Rare *Planolites*?

(Presenter's notes continued on next slide)

(Presenter's notes continued from slide)

Trace fossils shown in blow-ups include *Teichichnus, Palaeophycus, Rhizocorallium*, and *Planolites*.

Sedimentology infers deposition in **brackish water** to **fresh-brackish mixing zone water**

4903 – 4927: Highly bioturbated interval with higher-diversity trace fossil assemblage suggests influx of fully marine waters into embayment. Likely indicates major transgression-flooding event. May record the advancement of barrier bar into the estuary or the drowning and destruction of the barrier and reworking of barrier sands and tidal flats under fully marine, non-embayed conditions in the former position of the estuary-embayment

4927 – 4928: Background sedimentation within a muddy embayment

4928 – 4942.0: Source becomes less significant. Likely at the distal end of bayhead delta. Interval is dominated by sedimentation within a muddy embayment. Missing interval may be mostly mudstone.

Sedimentology/Ichnology

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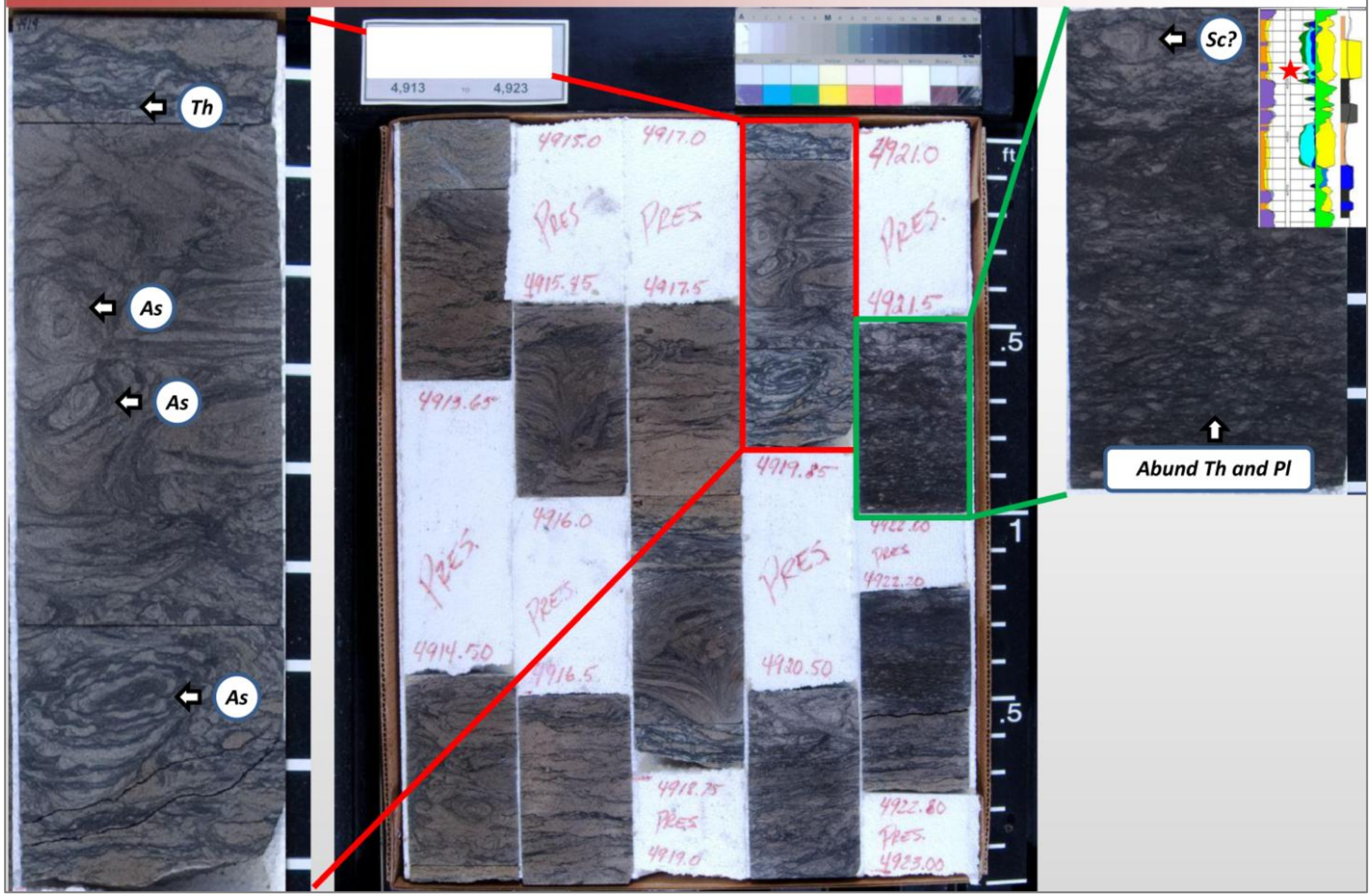

Presenter's notes: *(Presenter's notes on next slide)*

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<u>4913 to 4923:</u>

4913.00 – 4920.60: Heavily bioturbated sandstone with high-diversity trace fossil assemblage. Note that there is an abundance of mud in this facies. Common icnhofauna includes *Paleophycus, Planolites, Teichichnus, Asterosoma, & Rosselia* escape structures. Any original sedimentary structures seem to have been completely altered/destroyed by infaunal burrowers.

4920.60 – 4923.00: Burrowed sand and shale. Abundant *Planolites* and/or *Thalassinoides* ?

Trace fossils shown in blow-ups include *Thalassinoides, Planolites, Scolicia*, and *Asterosoma*

Sedimentology infers deposition in **brackish water** at the base of the box to **fully marine** through the remainder of the box**.**

4903 – 4927: Highly bioturbated interval with higher-diversity trace fossil assemblage suggests influx of fully marine waters into embayment. Likely indicates major transgression-flooding event. May record the advancement of barrier bar into the estuary or the drowning and destruction of the barrier and reworking of barrier sands and tidal flats under fully marine, non-embayed conditions in the former position of the estuary-embayment

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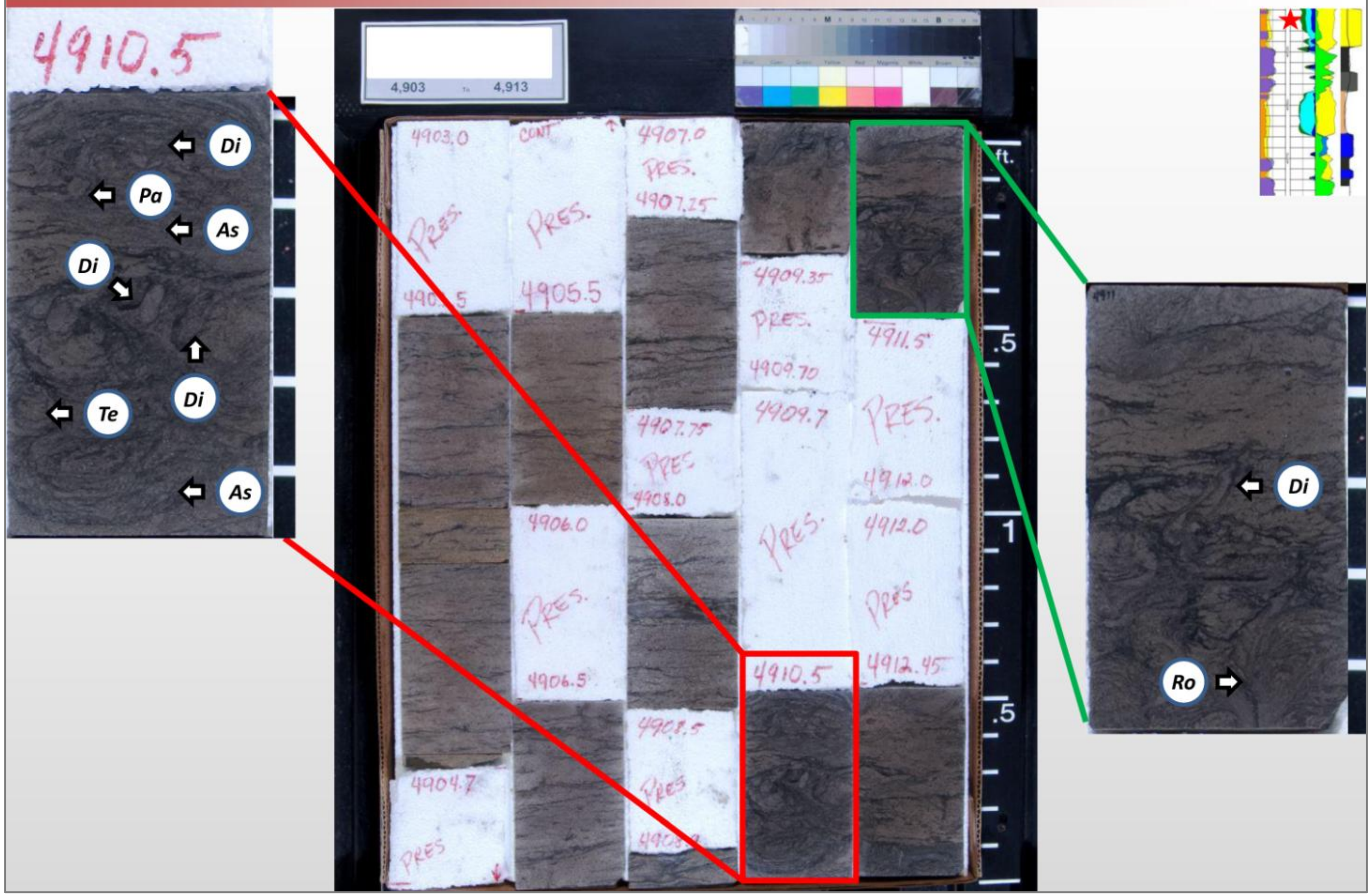
Sedimentology/Ichnology



Presenter's notes: *(Presenter's notes on next slide)*

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4903 to 4913:

4903.0 – 4908.5: Trough cross-laminated to ripple-laminated to low angle planar cross bedded very-fine grained to fine grained sandstone with thin mud/shale/organic rich shale drapes and convolute bedding. Minor bioclastic component. Note the slight discoloration of the sandstones. Rusty-reddish-marroon to tan. Burrowing evident in some areas.

4908.5 to 4913: Heavily bioturbated sandstone with high-diversity trace fossil assemblage. Common ichnofacies include *Asterosoma*.

Trace fossils shown in blow-ups include *Asterosoma, Palaeophycus, Diplocriterion, Teichichnus, and Rosellia.*

Sedimentology infers deposition in **fully marine water.**

4903 – 4927: Highly bioturbated interval with higher-diversity trace fossil assemblage suggests influx of fully marine waters into embayment. Likely indicates major transgression-flooding event. May record the advancement of barrier bar into the estuary or the drowning and destruction of the barrier and reworking of barrier sands and tidal flats under fully marine, non-embayed conditions in the former position of the estuary-embayment

Examples from other KSU cores

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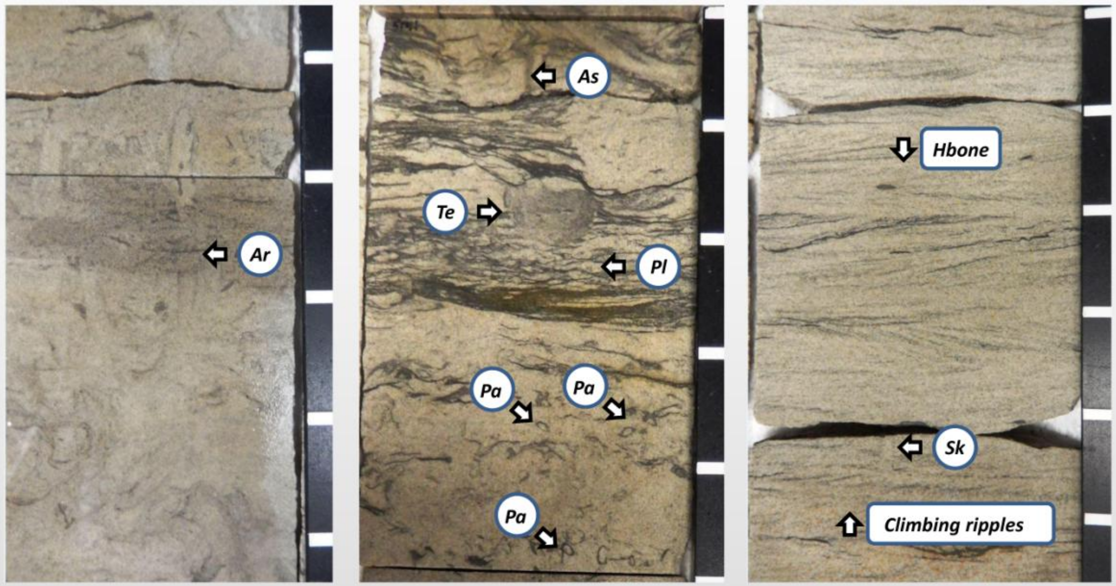

Presenter's notes: Trace fossils shown in blow-ups include *Arenicolites*, *Asterosoma*, *Palaeophycus, Skolithos, Diplocriterion, Teichichnus, and Planolites* (?).

Sedimentary structures of interest include herringbone cross stratification, climbing ripples, trough cross stratification, all with thin mud drapes.

Examples from other KSU cores

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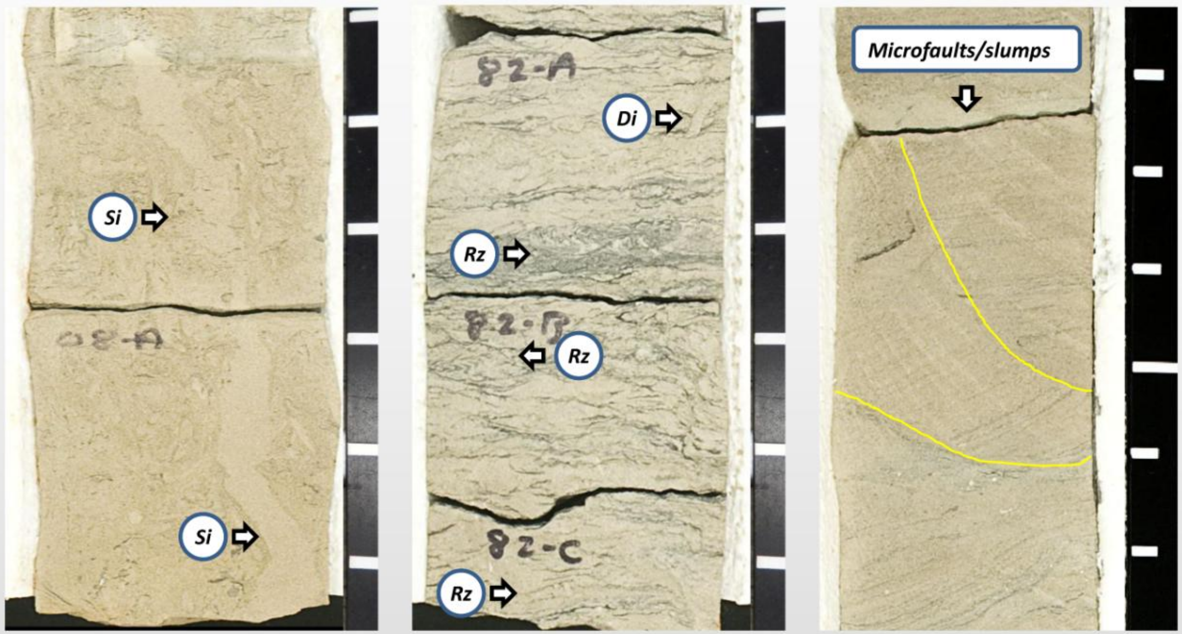

Presenter's notes: Trace fossils shown in blow-ups include *Siphonichnus, Rhizocorralium, and Diplocriterion.* Sedimentary structures of interest include microfaults/slumps.

Ichnotaxa distribution

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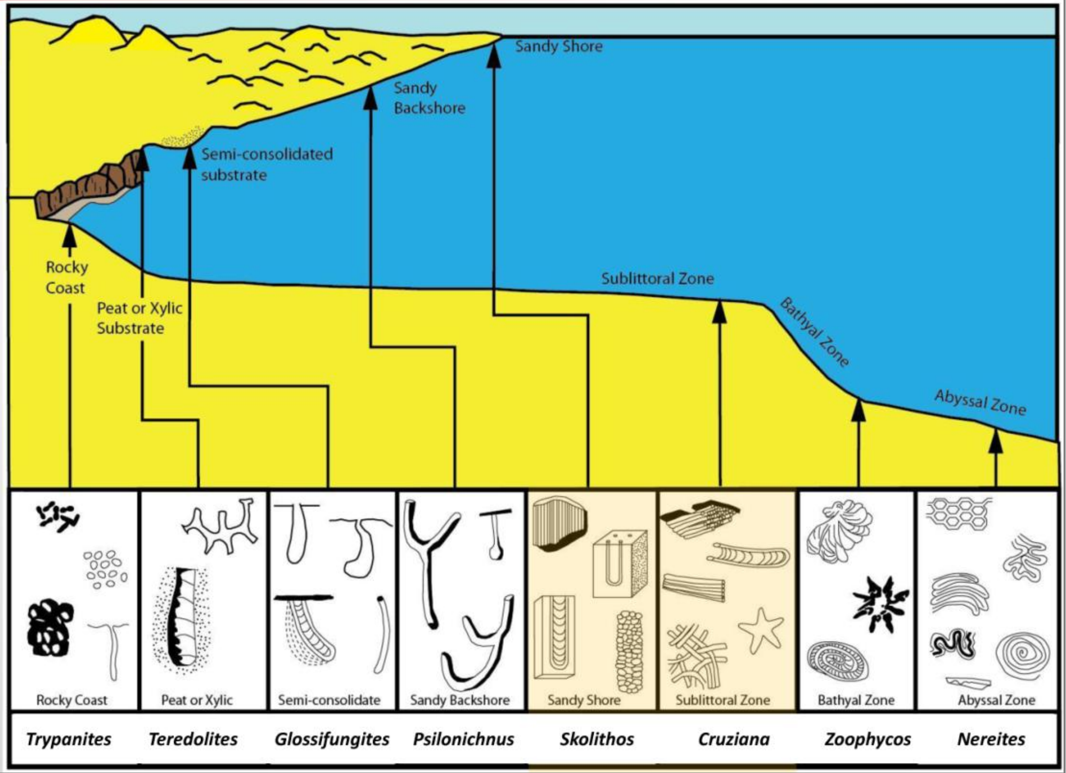

Presenter's notes: Cores in the KSU contain heterolithic strata with either siliciclastic sand- or mud-dominated lithologies composed of flaser, wavy, or lenticular bedding, herringbone cross stratification, and trough to hummocky cross stratification with no, occasional, common, abundant, or complete bioturbation that reflect fresh-, brackish-, or seawater conditions in back barrier bay (i.e., estuarine), bay head delta, or stream mouth bar deposits reworked by tidal influence. Tidal influence is recorded by lenticular, wavy, and flaser bedding, and herringbone cross stratification in mud-dominated to sand-dominated heterolithic successions. The most common trace fossils found here *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

are those of animals escaping upward through the sediment. Freshwater intervals of estuary and bay deposits have no bioturbation or contain rare burrows of small-diameter *Planolites* and/or *Palaeophycus*; these trace fossils are simple in morphology, represent facies breaking assemblages, and are not diagnostic of any particular environment. Note that no evidence of continental deposition, subaerial exposure, or pedogenesis was present in any of the core associated with these lithofacies. This interpretation is crucial in that that position of all three core was such that either (1) they did not capture sea level fluctuations large enough to drive facies into subaerial exposure or (2) sediment accumulation and accommodation rates where high enough to produce an aggradational or slightly retrogradational sequence of sedimentary facies patterns. Brackish water intervals contain mostly small- to medium-diameter, rare to few, or common trace fossil occurrences with low diversity. Fully marine seawater conditions contain the most diverse and abundant trace fossil associations and represent mixed Skolithos and Cruziana Ichnofacies assemblages. Tidal influence (i.e., likely lunar forcing rather than by diurnal wind directions) and direct connection of the back barrier bay to fully marine environments is interpreted from the succession of flaser, wavy, and lenticular bedding and double mud-draped sand laminae, as well as the planar bedded sand- and mud dominated heterolithic lithofacies with variable diversity and abundances of marine trace fossils with diameter size ranges typical of open marine assemblages.

The Skolithos Ichnofacies is represented vertical, cylindrical, or U-shaped burrows by *Arenicolites* (Ar), *Cylindrichnus* (Cy), *Conichnus* (Co), *Diplocraterion* (Di), *Rosselia* (Ro), *Palaeophycus* (Pa), and *Skolithos* (Sk). Some of these trace fossils are also part of the Cruziana Ichnofacies, which is represented by *Asterosoma* (As), *Chondrites* (Ch), *Helminthopsis* (He), *Phycosiphon* (Ph), *Rhizocorallium* (Rh), *Rosselia* (Ro), *Taenidium* (Ta),*Teichichnus* (Te), and *Thalassinoides* (Th). In some intervals trace fossils representing the Zoophycus Ichnofacies are present, including *Cosmorhaphe* (Cm), *Scolicia* (Sc), and *Spirophyton* (Sp). This trace fossil assemblage, however, is indicative of lower sedimentation rate, depositional energy, and nutrient availability in a proximal offshore position rather than a deep water setting.

Trace fossil assemblages dominated by the Skolithos Ichnofacies reflect higher energies, higher sedimentation rates, and shifting coarser grained sediment, recorded as sand-dominated heterolithic intervals. Trace fossil assemblages dominated by the Cruziana Ichnofacies reflect lower energies, relatively slower sedimentation rates, nutrient availability, and stable, finer grained sediments, recorded as silt- and mud-dominated heterolithic intervals. Trace fossil assemblages dominated by the Zoophycos Ichnofacies reflect higher energies, relatively slow sedimentation rates, and stable, finer grained sediment, recorded as mud-dominated heterolithic intervals.

Ichnotaxa distribution

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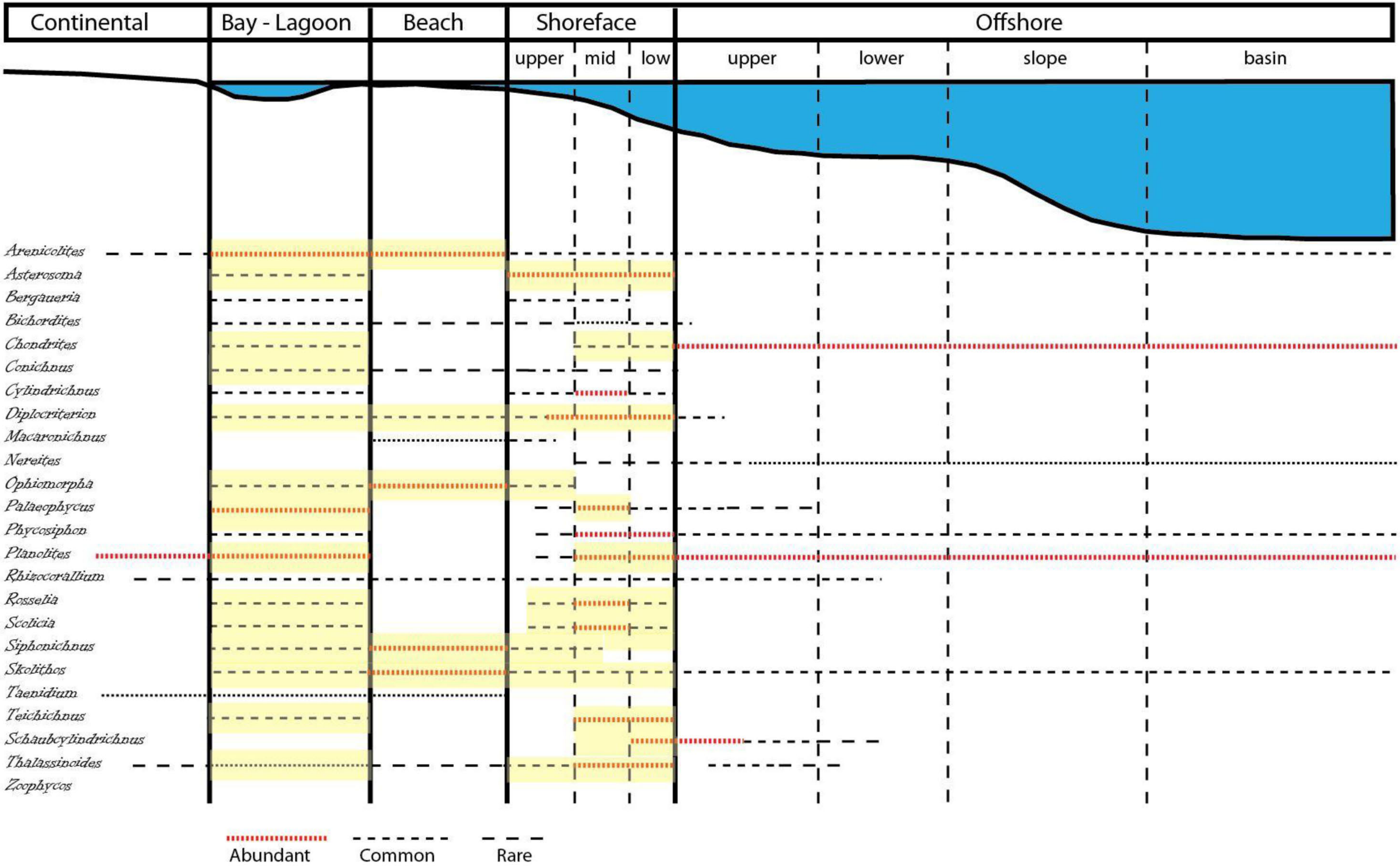

Modified after Gerard & Bromley, 2008

Depositional lithofacies in core

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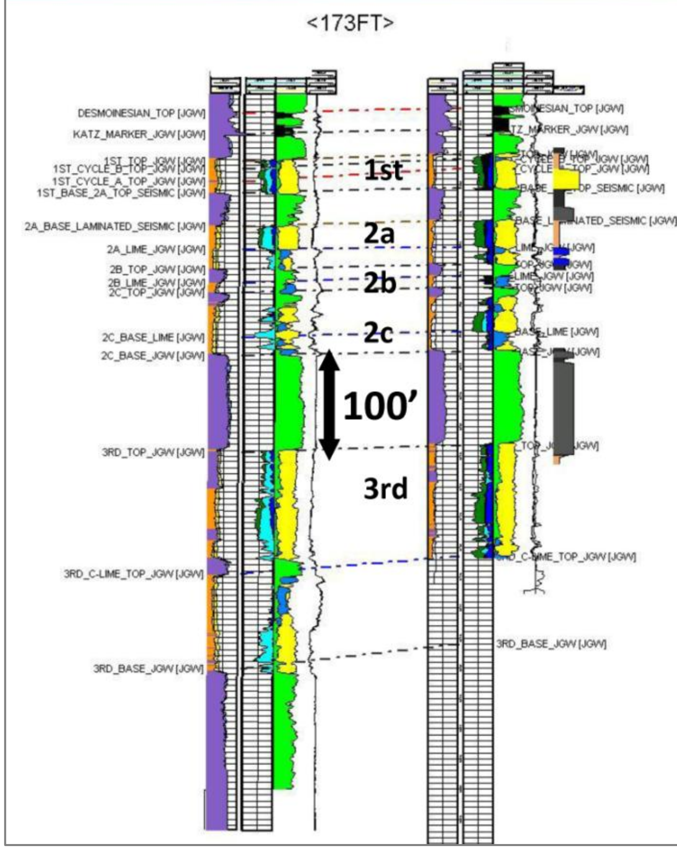

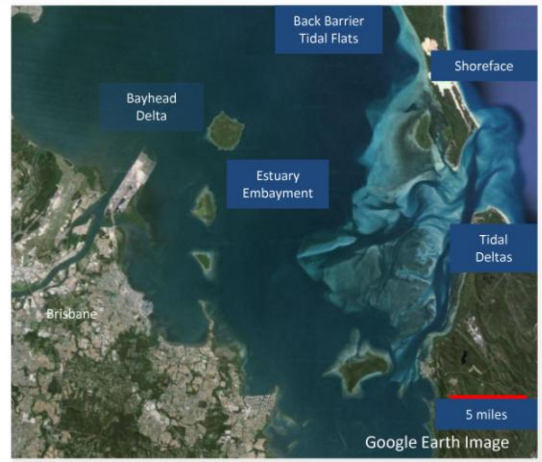

Depositional Facies Key

- Bayhead Delta
- Estuary Embayment – Lagoon
- Flood Tidal Delta – Carbonate-rich
- Back-Barrier Tidal Flats
- Shoreface (Bar)

Presenter's notes: This slide shows the same log tracts as slide 11 but in a more close up detailed view. Note the vertical scale and locations of the sands in the calculated lithologic column created by petrophysicist Leon Williams. Note that this well contains the 5 depositional facies found in the 3 KSU cores. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

The 5 depositional facies include:
Bayhead Delta, Estuary Embayment-Lagoon, Flood Tidal Delta – Carbonate rich, Back-Barrier Tidal Flats, and shoreface.

A modern setting that we propose to be analogous to these mixed siliciclastic and carbonate sedimentary facies would be the northeast coastline of Queensland, Australia, in the areas of Moreton Bay and Hervey Bay based on our assessment of the lithofacies, trace fossil associations, and ichnofacies relationships. Moreton Bay and Hervey Bay are composed of barrier shorelines of varying length and width, containing numerous openings that promote the formation of flood tidal deltas. Both bays also have one or more small bay head deltas that include stream mouth bars produced from the strongly seasonal flow emanating from the rivers that terminate there. Both areas are microtidal with tides fluctuating between 1.5–2.5 m. Both areas are open to the fully marine system of the Coral Sea, within which also lies the Great Barrier Reef systems as well as smaller reef systems. Both bays also have small coral reef systems on the marine side of the barrier shoreline. One could envision the breaching and annealing of the barrier shorelines to allow flood tidal deltas to form and then abandon. Flood tidal deltas would allow additional flow and sediment, including carbonate bioclastic grains from nearby reefs, to be washed into the interior of the bays. When these flood tidal deltas anneal, normal low-energy finer grained-dominated sedimentation would resume behind the barrier, interrupted only by fluvial input from bayhead deltas during seasonal high flow and by storm reworking and deposition. Other sedimentologic contributions would
be from wind-blown derived material that is deposited into the bays and estuaries from landward and seaward winds.

Both Moreton Bay and Hervey Bay, in our opinion, are excellent analogs for the environments of deposition (EOD) and facies successions preserved in all three core we examined. The complexity and dynamics of sea-level rise and fall that took place at this time near the end of Gondwanan glaciation would also provide the explanation for lithofacies and EOD variation in the core, which was likely tempered by a slightly aggradational sedimentation regime to produce repetitive and slightly retrogradational sedimentary facies.

Depositional lithofacies in core

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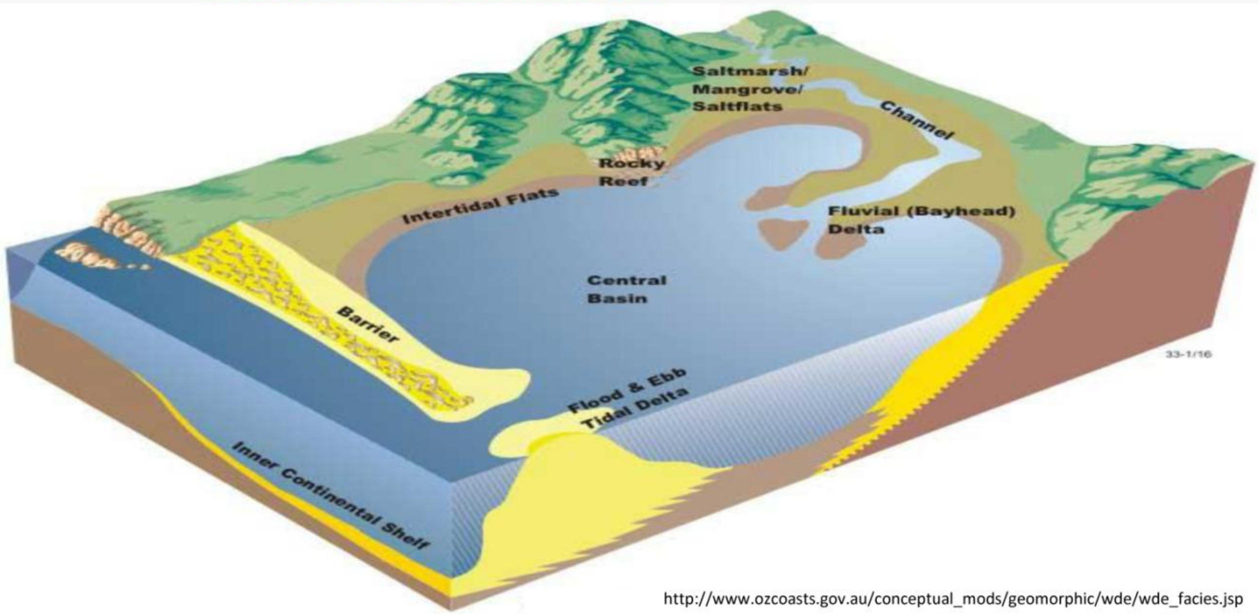
- Depositional facies from core observation
  - Tidally influenced estuarine embayment
  - Mixed carbonate-siliciclastic shelf



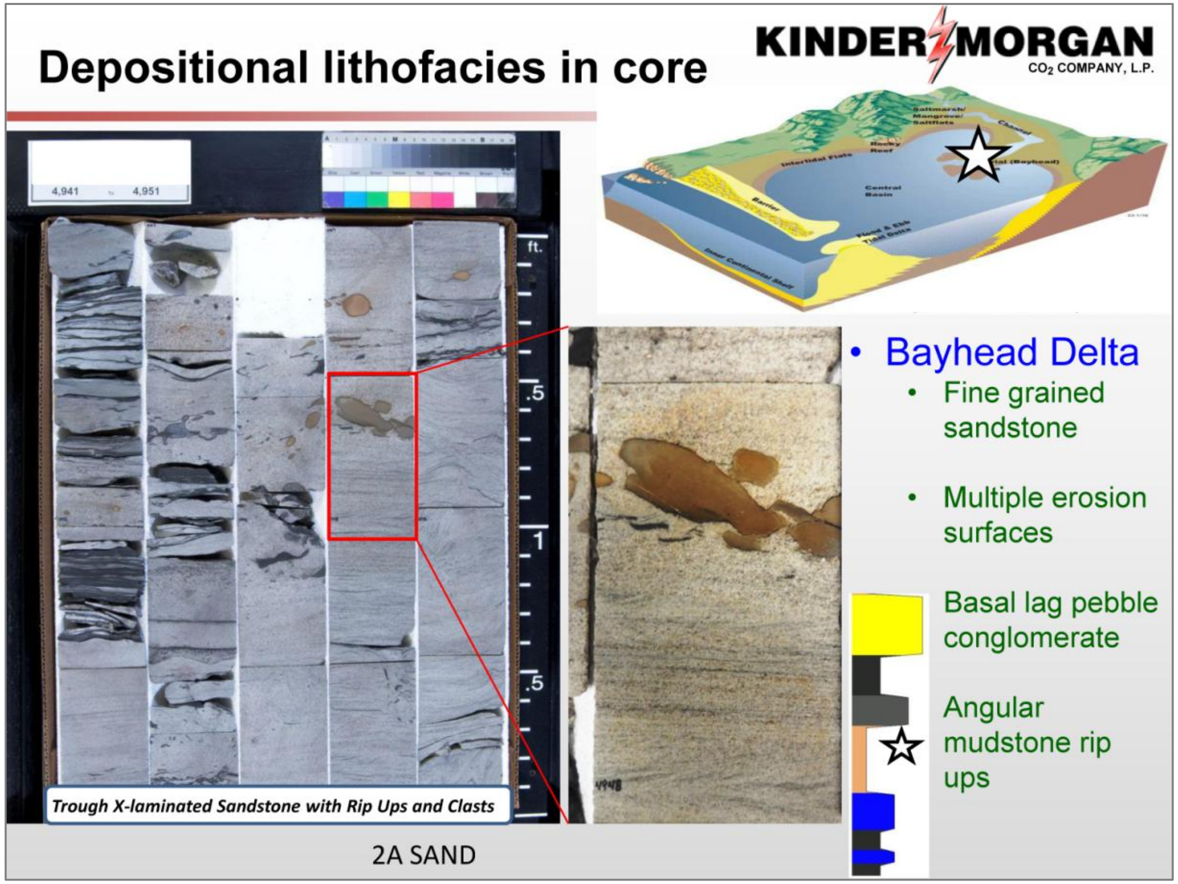
http://www.ozcoasts.gov.au/conceptual_mods/geomorphic/wde/wde_facies.jsp

Presenter's notes: The Katz Strawn Unit, based on core, FMI, and log data can be described as a tidally influenced estuarine embayment on a mixed carbonate siliciclastic shelf located on the Eastern Shelf of the Permian Basin. Note the land, sea, and what is above and below water. *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

This 3D cartoon taken from http://www.ozcoasts.gov.au/conceptual_mods/geomorphic/wde/wde_facies.jsp depicts a fluvial bayhead delta discharging fresh water and sediment into an brackish estuary and associated tidal flats that is partially enclosed by sand bars and/or barrier islands. Partially enclosed meaning that the estuary has a free connection to the open sea. This free connection between the estuary and the open sea is where tidal deltas form. In this cartoon the tidal deltas depict both the ebb and flood deltas that are rich in sand and carbonate. The sand supply for the tidal deltas and sand bar is likely deposited by longshore drift and the carbonate supply is being incorporated into the tidal deltas from nearby seaward carbonate buildups. The sandbar is effected by open ocean waves on the seaward side but behind the sandbar where the back-barrier tidal flats are deposited, this area is largely protected from ocean waves with the exception of storm washover.

The bayhead delta is fluvial and depositing sand into the estuary. The estuary is a mucky brackish zone where muds, fine grained silts, and sands are being deposited from the bayhead delta. The tidal deltas are swashing back and forth daily between the barrier bars incorporating sand, carbonate, and carbonate rich sea-water into the system. The carbonate buildups are alive with crinoids, bryozoans, bivalves, echinoderms, algea, etc…and the barrier bar is also alive with all kinds of burrowing organisms.



Presenter's notes: Note the star on the depositional profile and on the depositional facies log
Bayhead Delta depositional facies.
The sand is fine grained and exhibits basal conglomerate lag deposits laid down in small distributary channels.
Note the mud rip ups, plant material, very fine shale lams, and ripple lams. Also note the fining upward nature of the deposit and interfingering of facies from the bayhead delta into the estuary.
Phi and K are good. Reservoir facies

Depositional lithofacies in core

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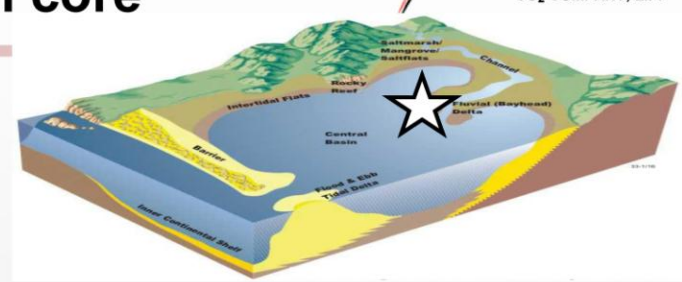


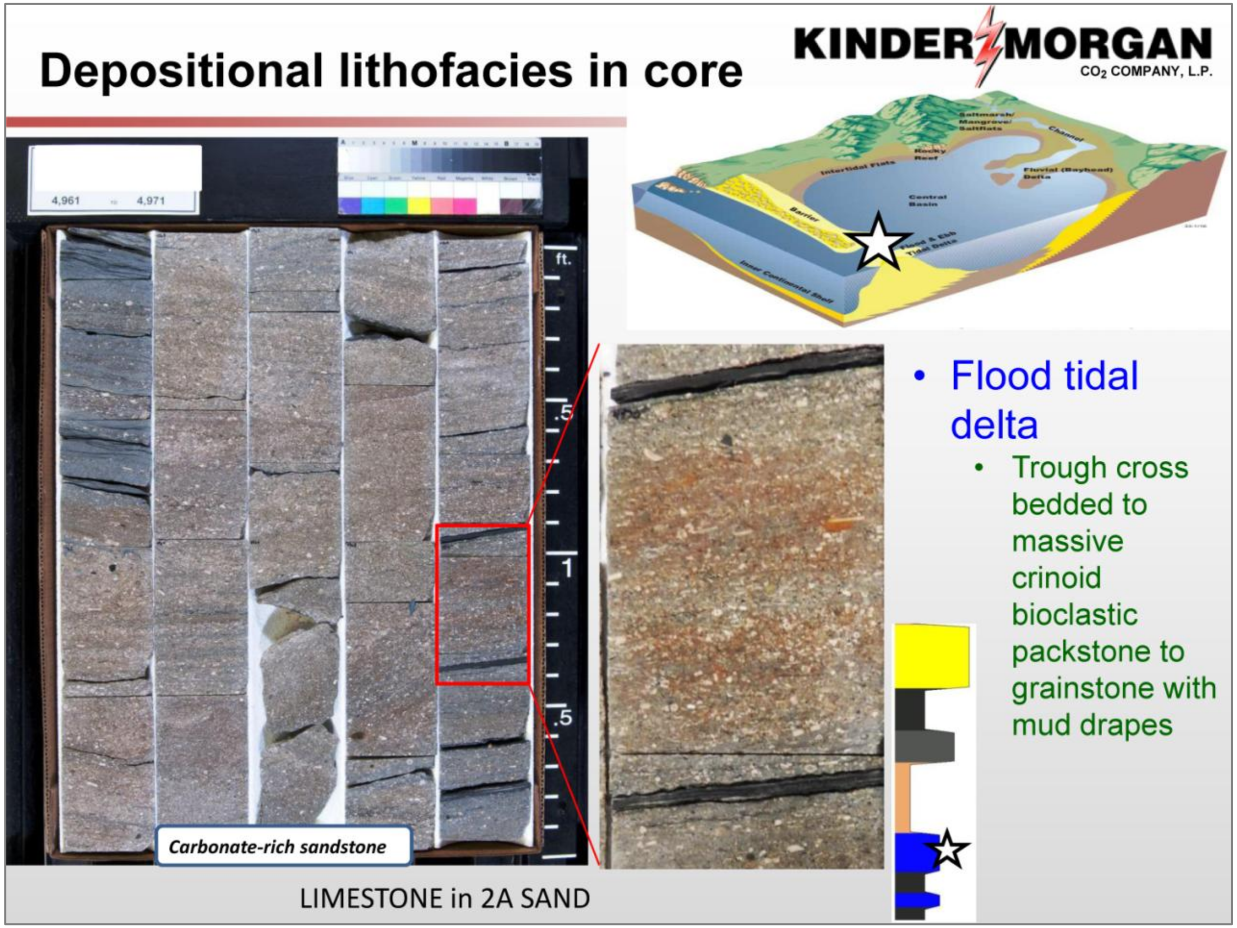
- Bayhead Delta
  - Ripple cross laminated sandstone
  - Low angle cross strat

Abundant soft sediment deformation

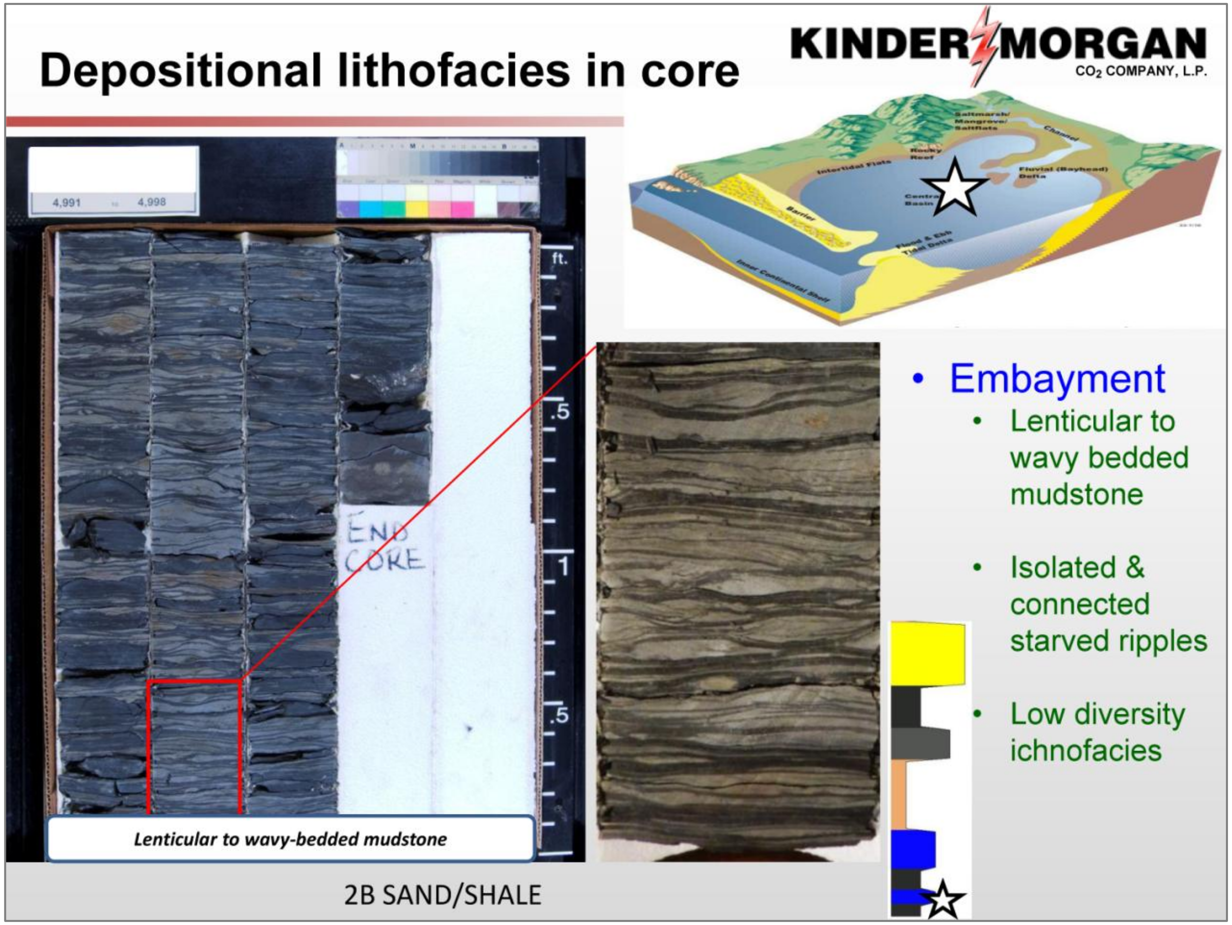
Mud drapes

2A SAND

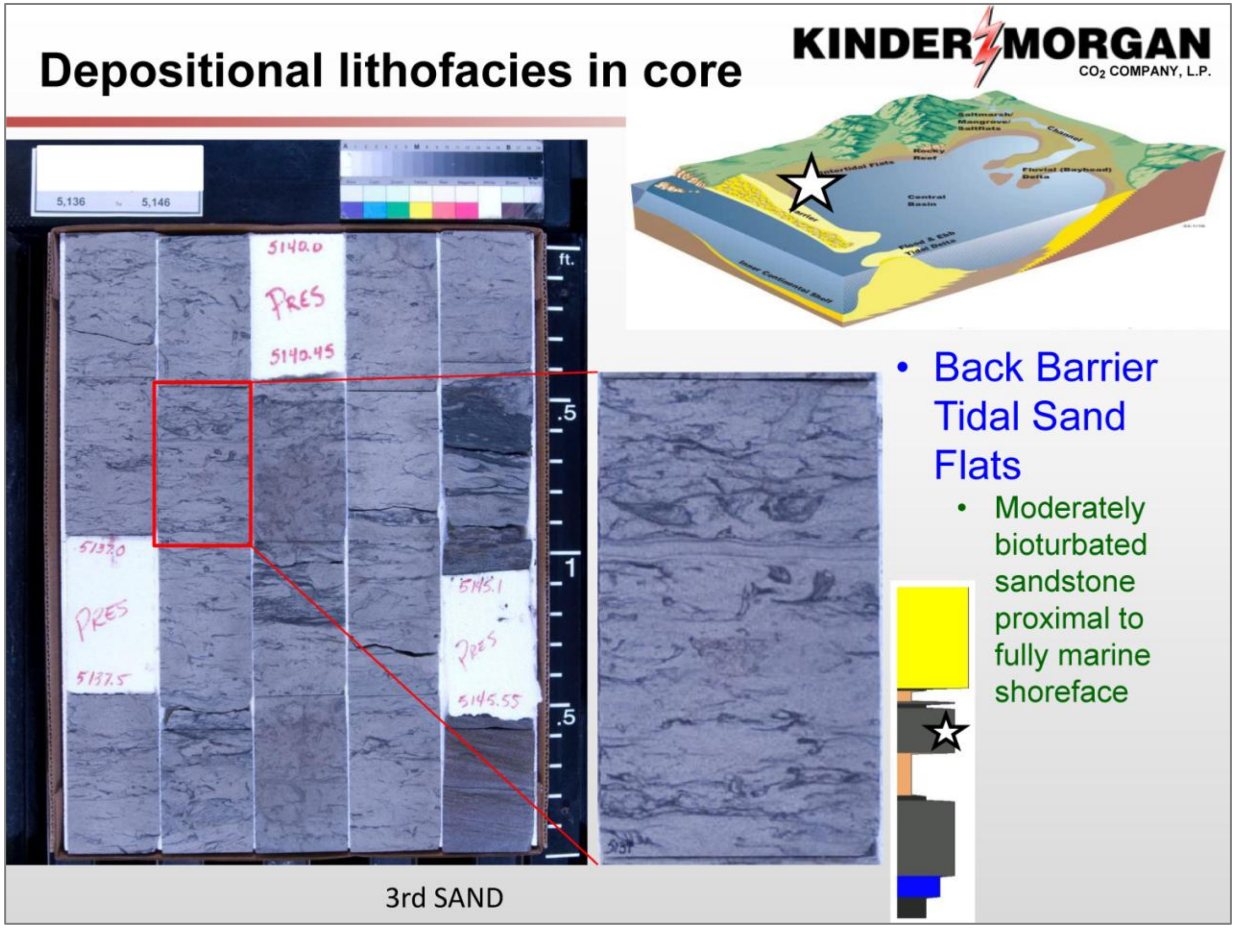
Presenter’s notes: Note the star on the depositional profile and on the depositional facies log.



Presenter’s notes: Note the star on the depositional profile and on the depositional facies log.
Flood tidal delta.
Note the interfingering with shales from the estuary embayment tidal flats. The grains are primarily crinoids, bivalves, bryozoans, and algae with some small mud intraclasts.
This facies can be thought of as a barrier to flow and is a non-reservoir facies.



Presenter's notes: Note the star on the depositional profile and on the depositional facies log.
Estuary embayment facies.
Note the interfingering nature of the thin sands and shales. The sands tend to be wavy to lenticular and are likely sourced from the bayhead delta.
This facies is poorly oxygenated

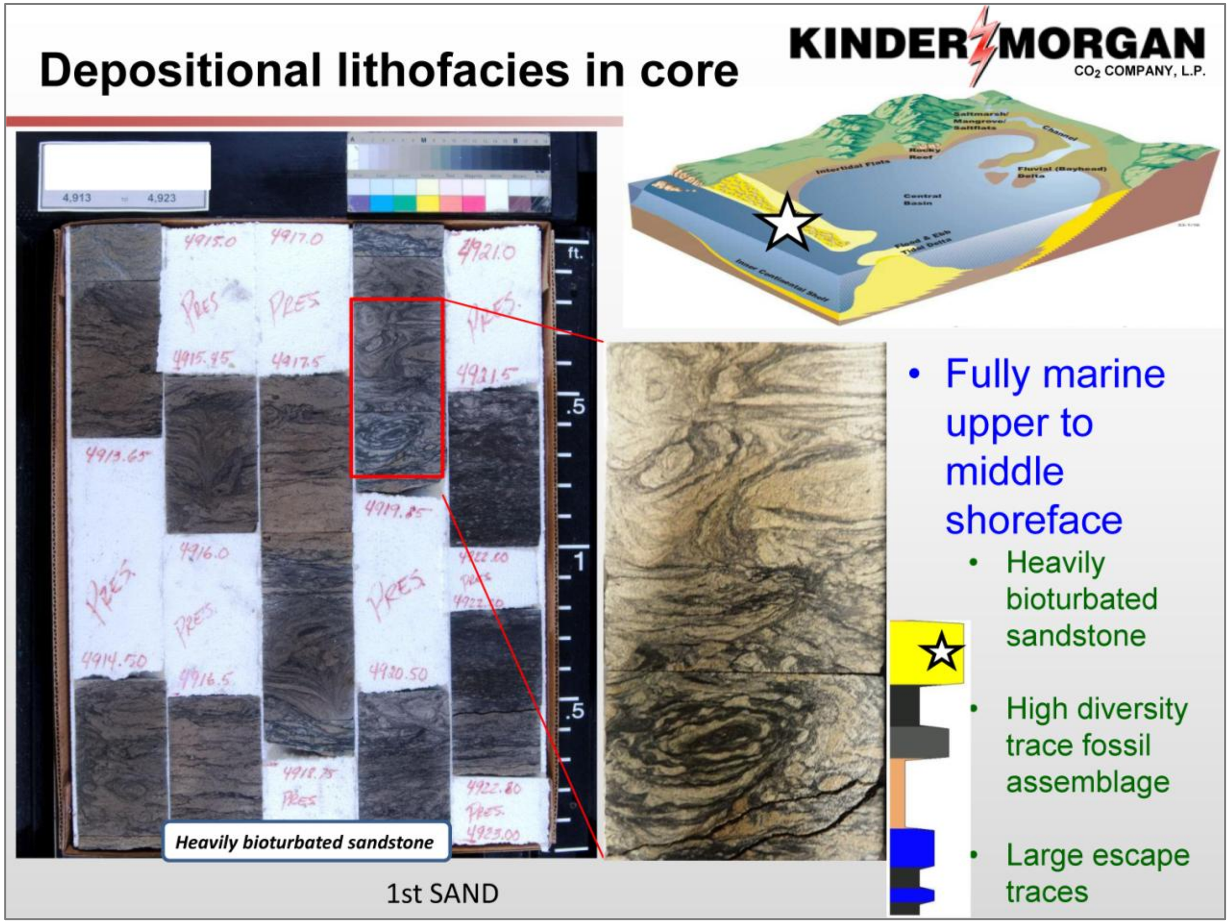


Presenter's notes: Note the star on the depositional profile and on the depositional facies log.

Back barrier tidal sand flats.

Note that this fine grained sand is burrowed and the burrowers are incorporating shale into the system.

Note the carbonate cemented zones. Phi and K are good with exception of cemented zones. Reservoir facies.



Presenter's notes: Note the star on the depositional profile and on the depositional facies log
Shoreface facies.
This facies is heavily bioturbated and well oxygenated.
How is the bioturbation effecting porosity, permeability, and CO_2 flood efficiency?
Phi is partially destroyed by burrowers.

Conclusions

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- Conodonts in the Katz Field core reveal an age of mid-Desmoinesian
- Lithofacies in core indicate a mixed siliciclastic-carbonate continental to shelfal transition along a complex embayed coastline
- Distinct lithofacies and ichnofacies in the core suggest that the paleoenvironments of the Katz Field included a bayhead delta, back-barrier estuary embayment, flood tidal delta, tidal flats, and fully marine upper to middle shoreface.

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