

Climate Control on Reservoir Distribution in the Upper Devonian Three Forks Formation, North Dakota and Montana*

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Abstract

The Three Forks Formation is currently one of the main targeted reservoirs in the Williston basin. Estimates go as high as 2 bbl of recoverable oil in this unit; however, a detailed sedimentology of the Three Forks is still lacking. Here we introduce a process-oriented model for this Upper Devonian formation and show how its sediment architecture reflects climate fluctuations, recognition of which allows prediction of the vertical and lateral distribution of reservoir facies.

The Three Forks consists of six facies groups: terrestrial paleosols, sabkha, subaerial gravity flow, intertidal, peritidal, and subtidal. Of these, only the sabkha, gravity-flow and peritidal deposits are common and present everywhere in the basin. Controlled by climate and sea-level changes, two different proximal to distal facies transects characterize the Three Forks sedimentary system. During arid times little sediment is derived from the cratonal source areas, and a wide sabkha develops, locally with intertidal algal mats that grade laterally into peritidal mixed carbonate-siliciclastic sediments and farther seaward into subtidal storm deposits. Its humid counterpart shows the same peri- and subtidal facies, but its landward portion consists of a subaerial plain receiving abundant debris flows from the hinterland, substituting for the sabkha; paleosols characterize local patches of non-deposition.

Sequence stratigraphic correlation of the succession shows an overall deepening of the environment reflected in backstepping parasequences. The non-reservoir sabkha facies is overlain by intercalated peritidal reservoir and continental non-reservoir deposits, arranged in a cyclic fashion. The top of the Three Forks succession is formed by peritidal reservoir facies in the outer parts of the basin, and subtidal non-reservoir facies in its center.

References

- LeFever, J.A., 1991, History of oil production from the Bakken Formation, North Dakota, *in* W. Hansen, Geology and Horizontal Drilling of the Bakken Formation: Montana Geological Society, 198 p.
- LeFever, J.A., 2008, Isopachs of the Three Forks Formation: Geologic Investigations No. 64, North Dakota Geological Survey, Bismark, North Dakota, Web accessed 3 May 2011, https://www.dmr.nd.gov/ndgs/Publication_List/pdf/geoinv/GI_64.pdf.

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Motivation

- ★ Develop a detailed depositional model for the Three Forks Formation in order to understand and predict sediment distribution patterns in this sedimentary system
- ★ Present a sequence stratigraphic model to predict reservoir geometries and their distribution
- ★ Determine how climate changes influence sedimentation throughout the Three Forks Formation in North Dakota and Montana

Three Forks Formation Facts

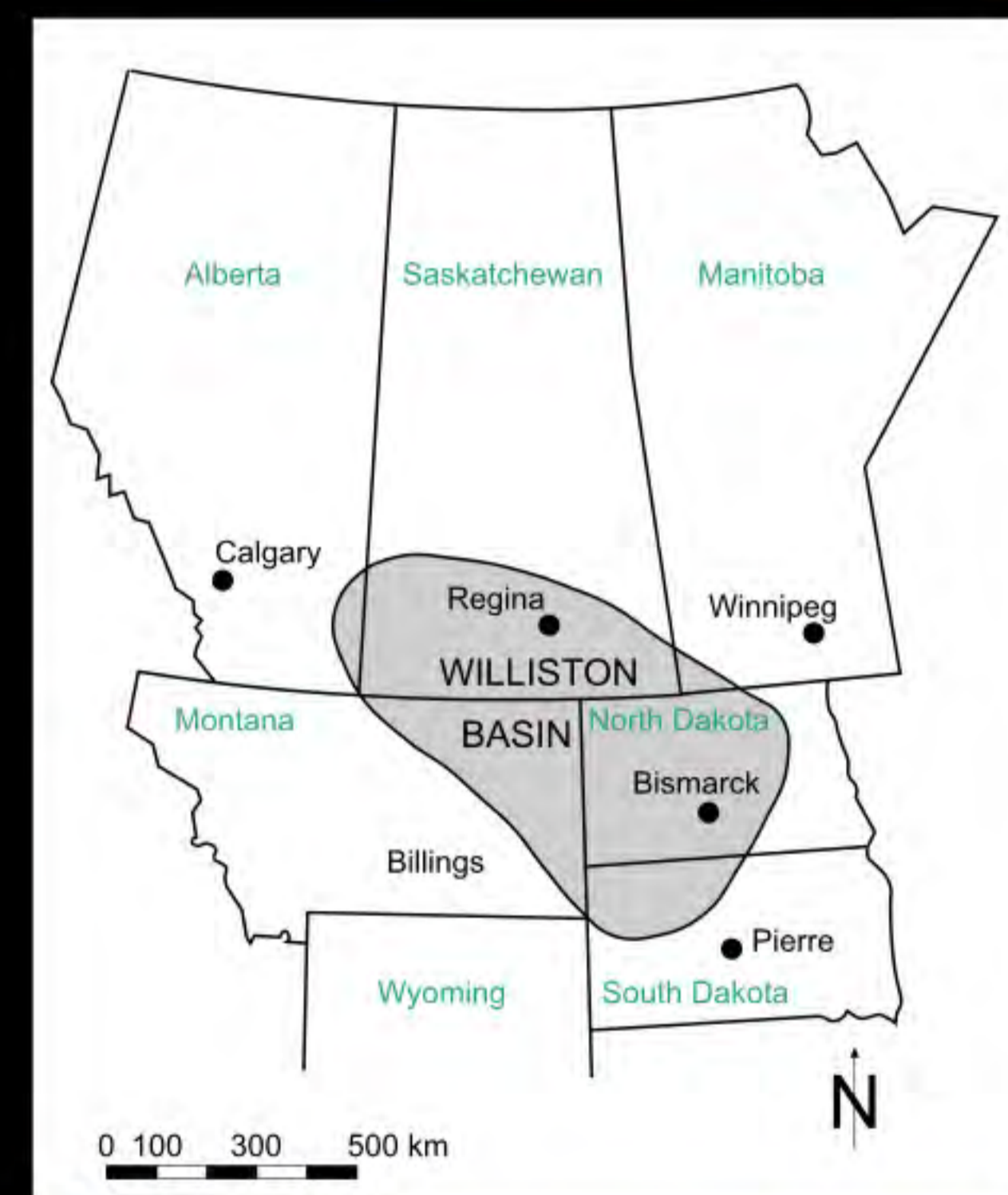


Fig. 1: Location of Williston Basin (shaded gray) in mostly North Dakota and Montana in the U.S. and in Saskatchewan, Manitoba and Alberta in Canada; modified from LeFever (1991)

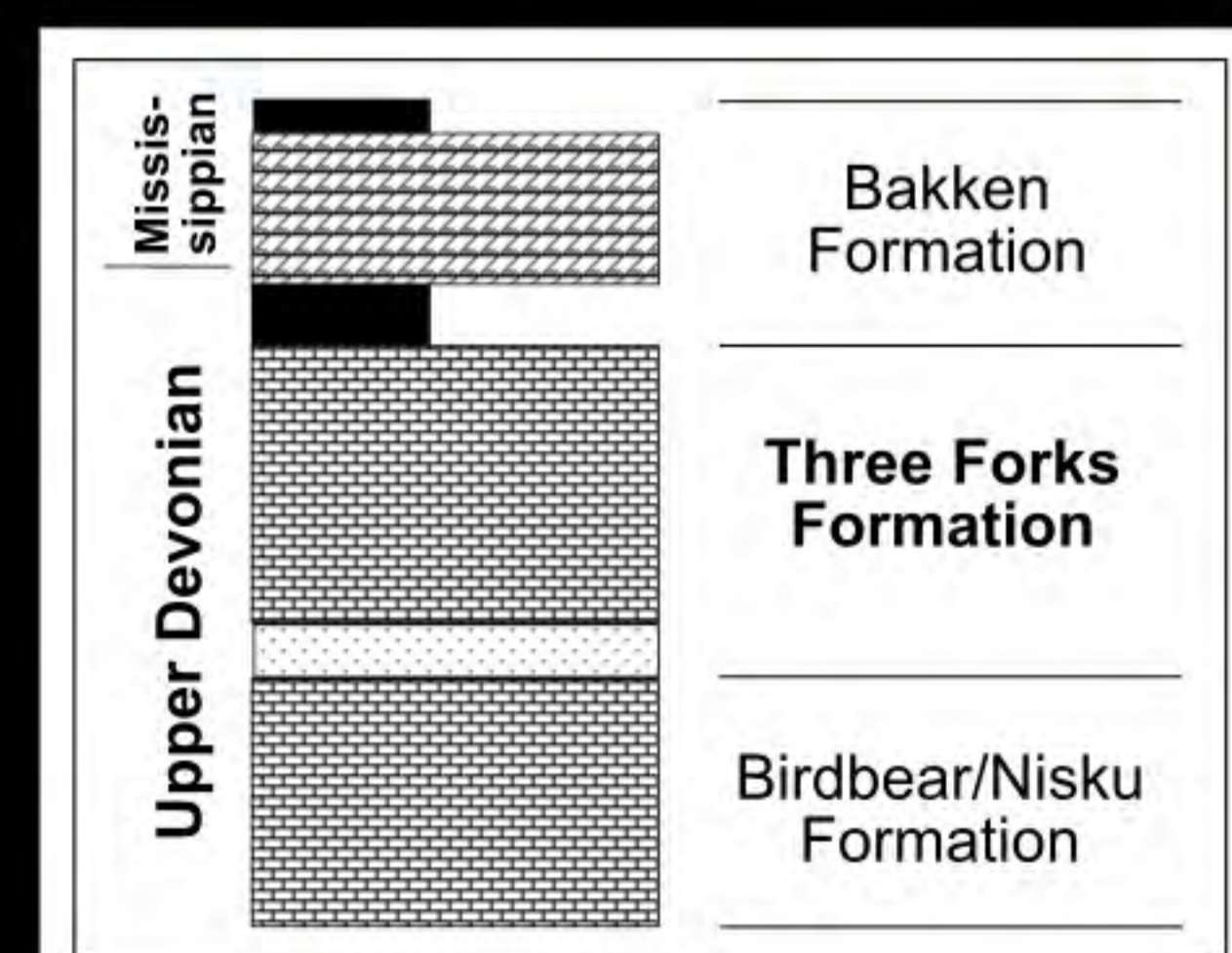


Fig. 2: Generalized stratigraphy of the Three Forks Formation and adjacent units. The Three Forks Formation is Late Devonian and reaches a maximum thickness of 270 ft (82 m; LeFever 2008). It is underlain by the Nisku/Birdbeak Formation, and overlain by the Bakken Formation (lower Bakken shale). The lower Bakken shale is considered the main source rock for the oil presently found within the Three Forks system.

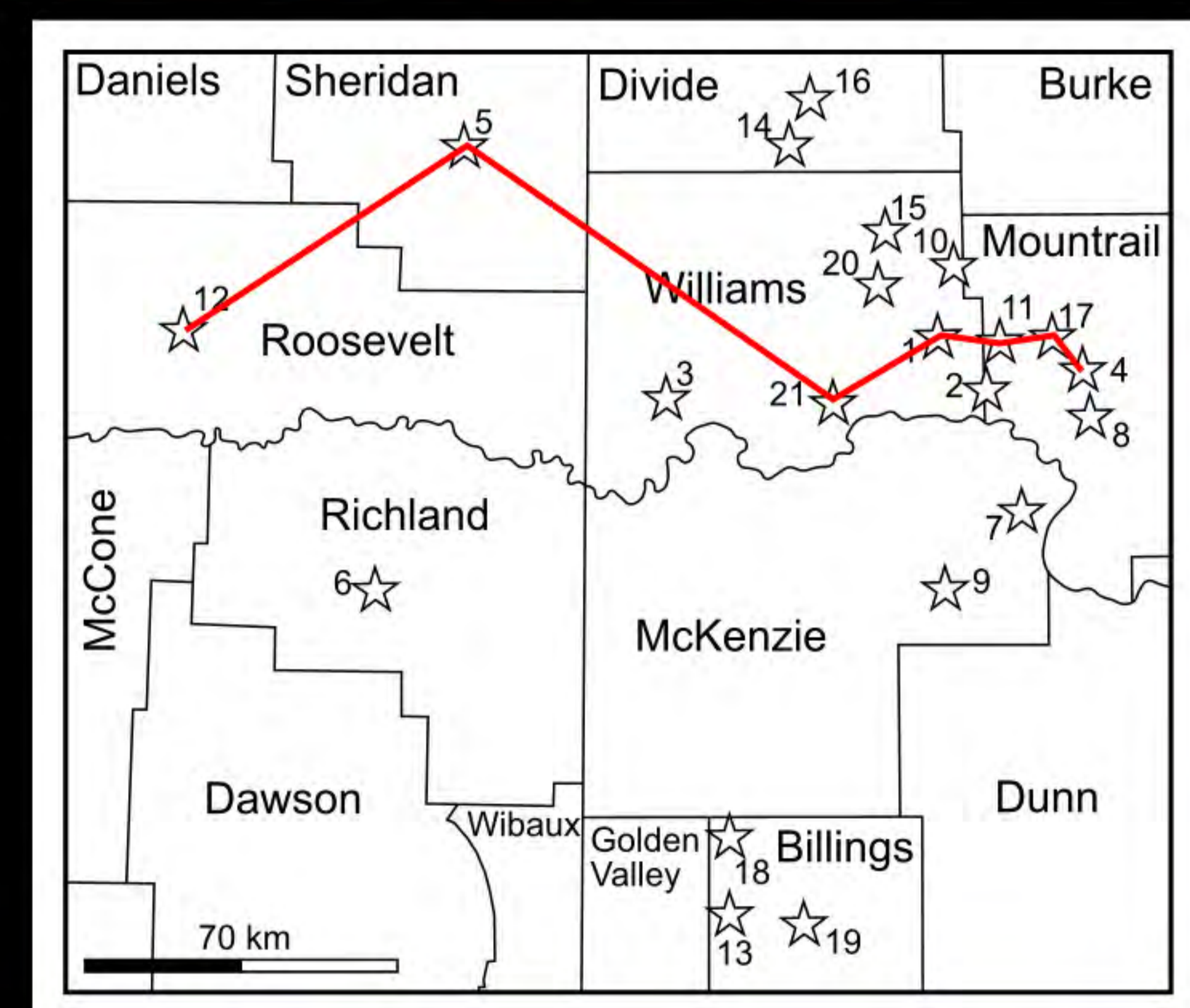


Fig. 3: Map of North Dakota, US, with the position of the investigated drill cores: (1) Amerada Hess 36-31H, (2) Amerada Hess Sara Barstad 6-44H, (3) Brigham Olson 10-15-1H, (4) Brigham Andersen 28-33H, (5) Brigham Richardson 30 No. 1, (6) Cenergy Inc. 1-4 Williams, (7) Duncan Rose #1, (8) Fidelity Deadwood 43-28H, (9) Gofor Oil Inc. Catherine E. Peck 2, (10) Hess Bakken 12-07H, (11) Hess E-R 156R-943328 H-1, (12) HNG Oil Company 1 Tribal, (13) Maxus Energy Short Fee 31-3, (14) Petro Hunt LLC Willard Johnston Trust 24B-2-1H, (15) Pogo Producing Company Pegasus 2-17H, (16) Samson Resources Norstog 14-23-161, (17) Shell Texel #21-35, (18) Tenneco Oil 1-15 Graham, (19) Tenneco Oil 3-17 TOC MEE USA, (20) Texaco Inc Clarence Peterson NCT-1, (21) Texaco LJ Hovde 1; red line shows location of cores incorporated into the cross section displayed to the right (Fig. 14).

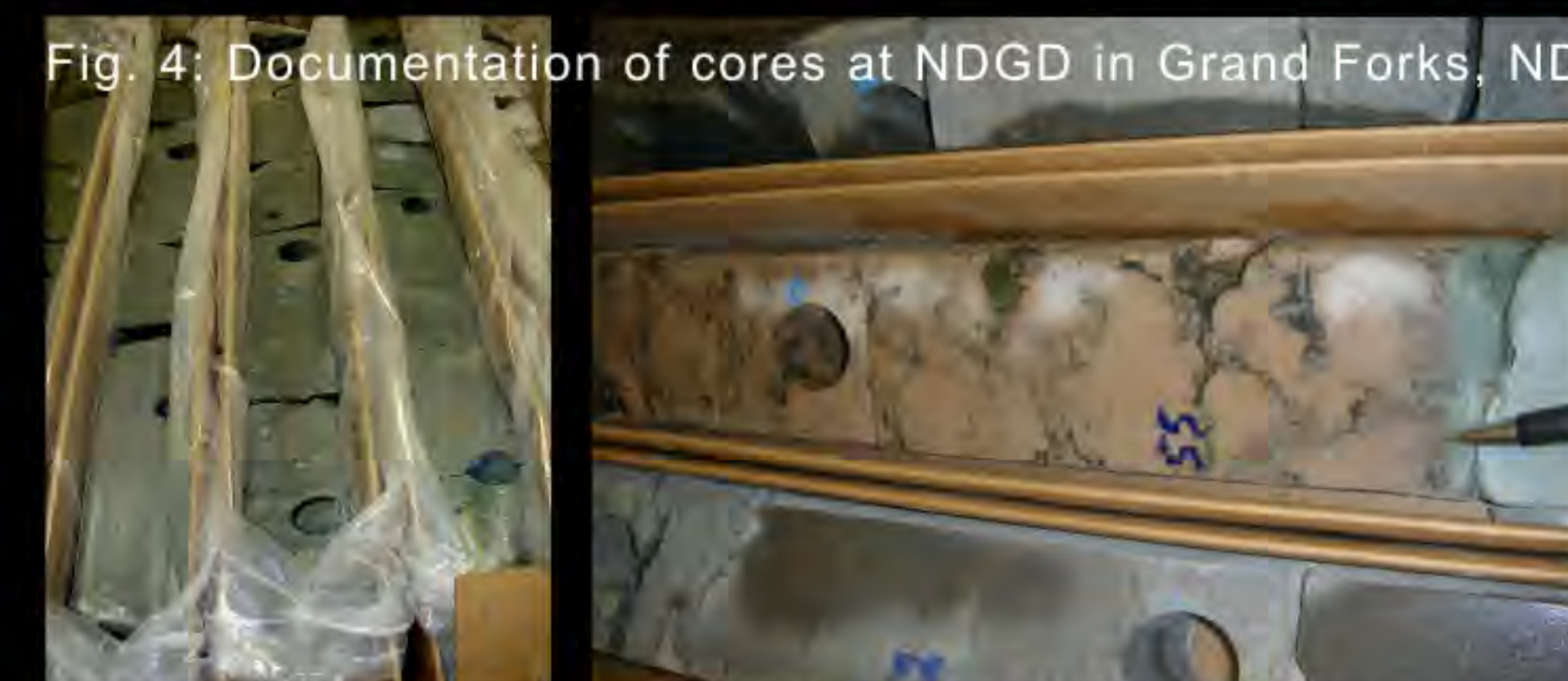


Fig. 4: Documentation of cores at NDGD in Grand Forks, ND

Six Three Forks Facies Associations

Facies association 1: Terrestrial paleosol



Petro Hunt Willard Johnston Trust 24 B-2-1H, 9220 ft

A-horizon?
E-horizon
B-horizon

E-horizon

B-horizon

- ★ Clay-, mudstone and siltstone with local iron staining, only locally occurring
- ★ Paleosol consisting of several well defined horizons with soil structures, some of them showing peds and cutans (B-horizon)

Facies association 2: Sabkha



Maxus Energy Short Fee 31-3, 10636 ft

- ★ Red carbonate and siliciclastic siltstones, mudstones, and gypsum nodules + beds, some mud-dominated conglomerates; some syndimentary deformation
- ★ Gypsum indicates arid conditions, red color of sediment characteristic for terrestrial/subaerially exposed setting; sabkha, occasionally flooded

Facies association 3: Debris/mud flows



Brigham Andersen 28-33H, 10208 ft

Brigham Richardson 30 No. 1, 8422 ft

- ★ Mostly matrix-supported, some clast-supported conglomerates; matrix red or green, clay-rich; clasts angular and subrounded dolomites and mudstones
- ★ Debris- and mud-flow deposits, reflect reworking of previously deposited peritidal sediments; deposited in subaerial environment

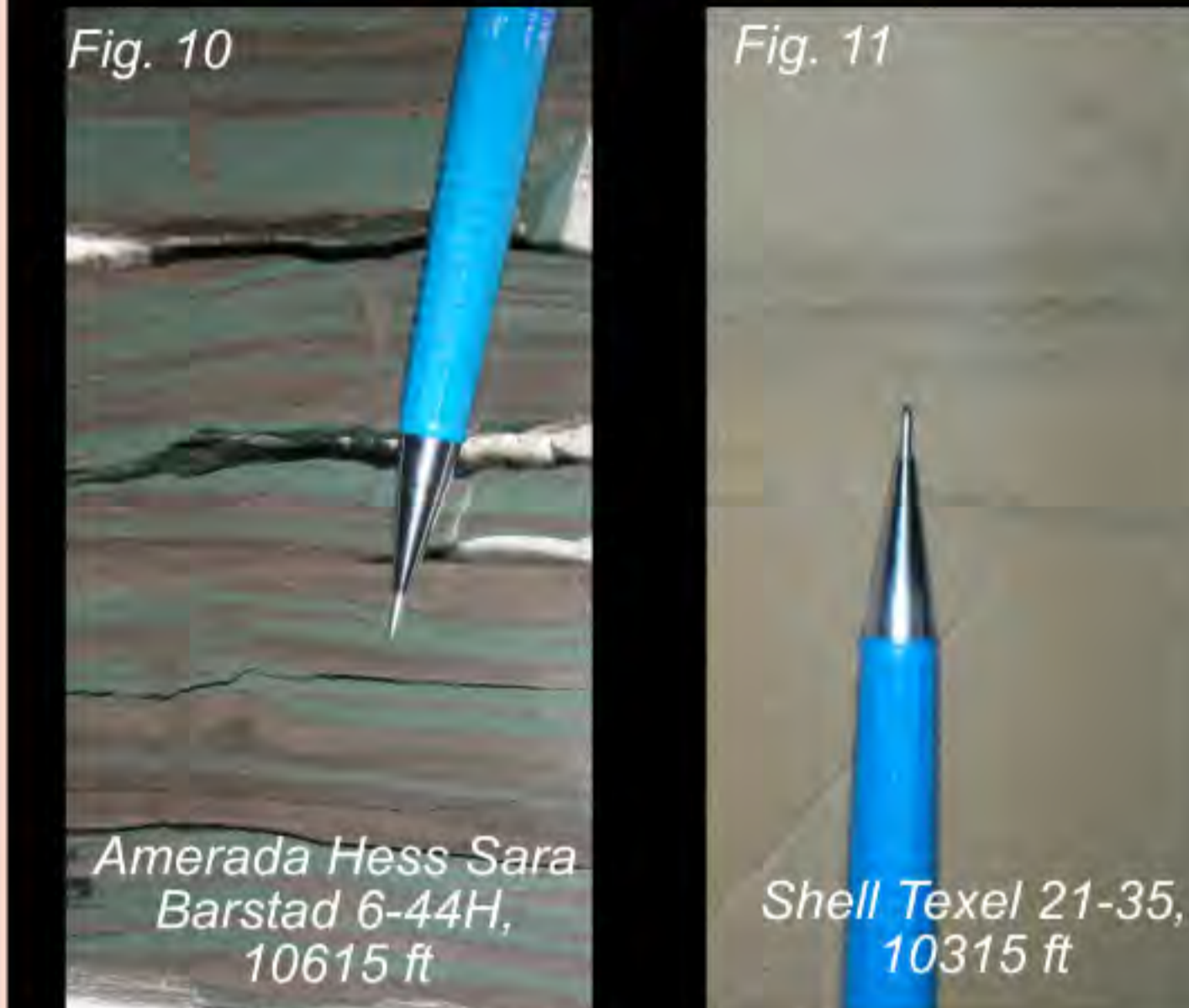
Facies association 4: Intertidal facies



Gofor Oil Catherine E. Peck 2, 10819 ft

- ★ Millimeter-thick irregular dolomitic microbial laminae (1), interbedded with laminae rich in organic material (2) with anhydrite nodules (3)
- ★ Intertidal setting on seaward margin of sabkha, characteristic of microbial mats; later subaerial exposure allowed for anhydrite nodule growth

Facies association 5: Peritidal facies

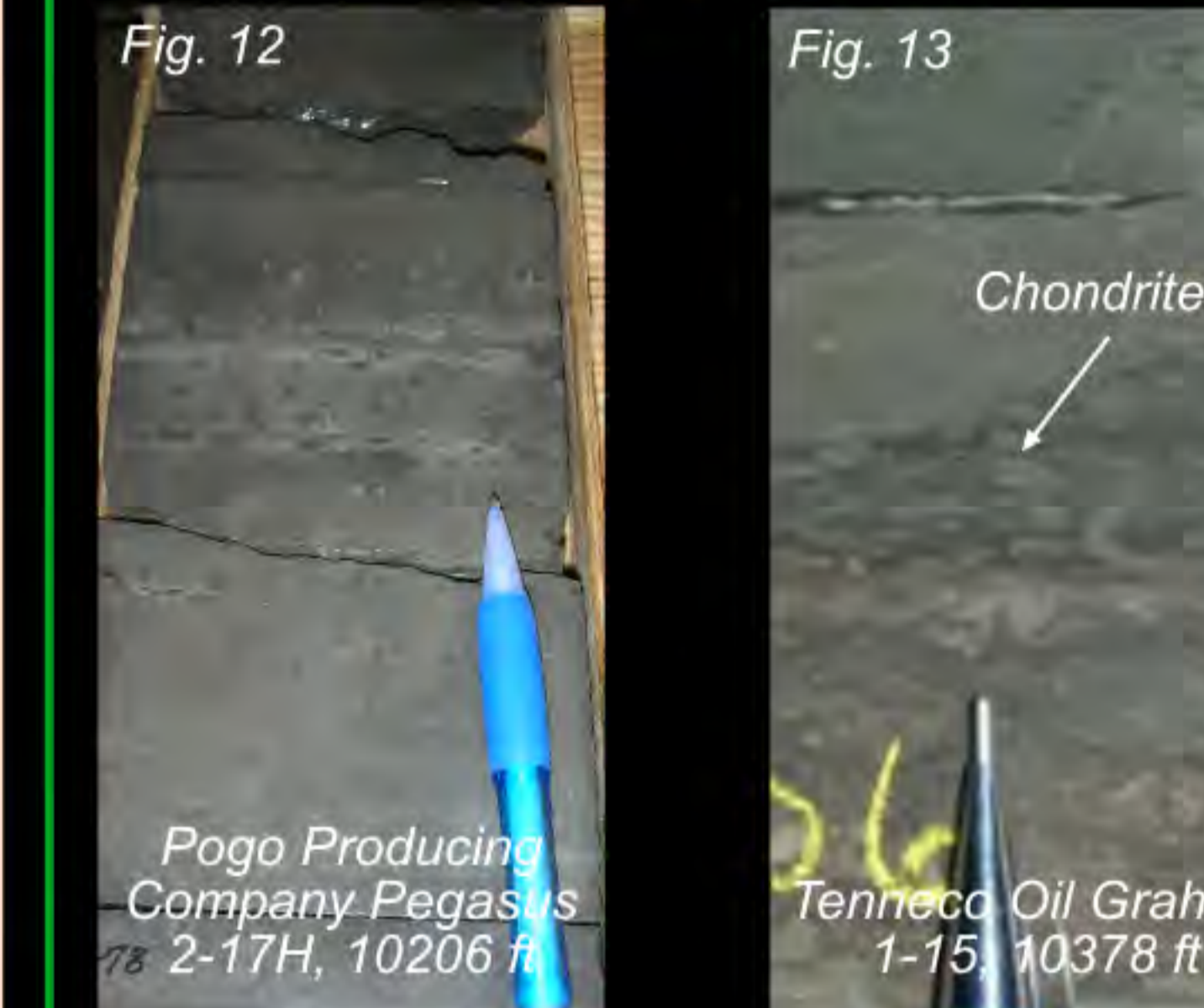


Amerada Hess Sara Barstad 6-44H, 10615 ft

Shell Texel 21-35, 10315 ft

- ★ Intercalated dolomitic siltstones and siliciclastic mudstones; clays green, dolomites tan to yellow, dolomites show variety of sedimentary structures
- ★ Facies reflects highly varying energy conditions likely in tidal to shallow subtidal environment

Facies association 6: Subtidal facies



Pogo Producing Company Pegasus 2-17H, 10206 ft

Tenneco Oil Graham 1-15, 10378 ft

- ★ Mostly greenish highly bioturbated mudstones with intercalated cm-sized sandstone beds; in places Chondrites
- ★ Deep shelf environment, facies deposited below normal, but above storm wave base; sandstones represent storms, mudstones fairweather sedimentation

Reservoir Facies

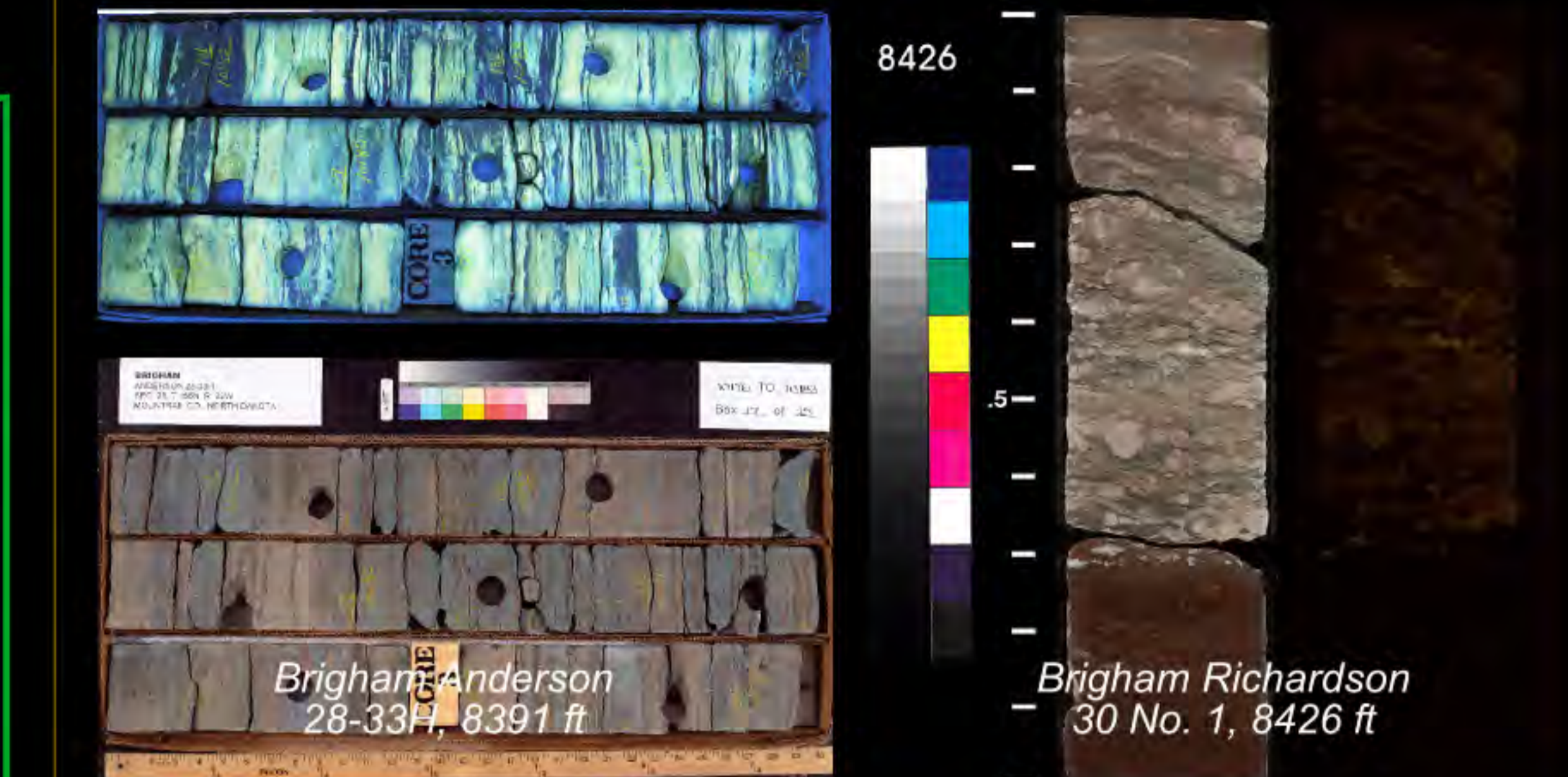


Fig. 15: Photos of Brigham Anderson Fig. 16: Photos of Brigham core, dolomitic siltstones with intercalated Richardson core, matrix-supported siliciclastic mudstones (facies association conglomerates (facies association 3 5 - peritidal facies); above under UV light, - sediment gravity flows).

Reservoir facies

- ★ Dolomitic siltstones from the peritidal facies association 5
- ★ Non-reservoir facies
- ★ All other facies as they are too mud-rich, including debris flow units (facies association 3), and sands in subtidal storm deposits (facies association 6)

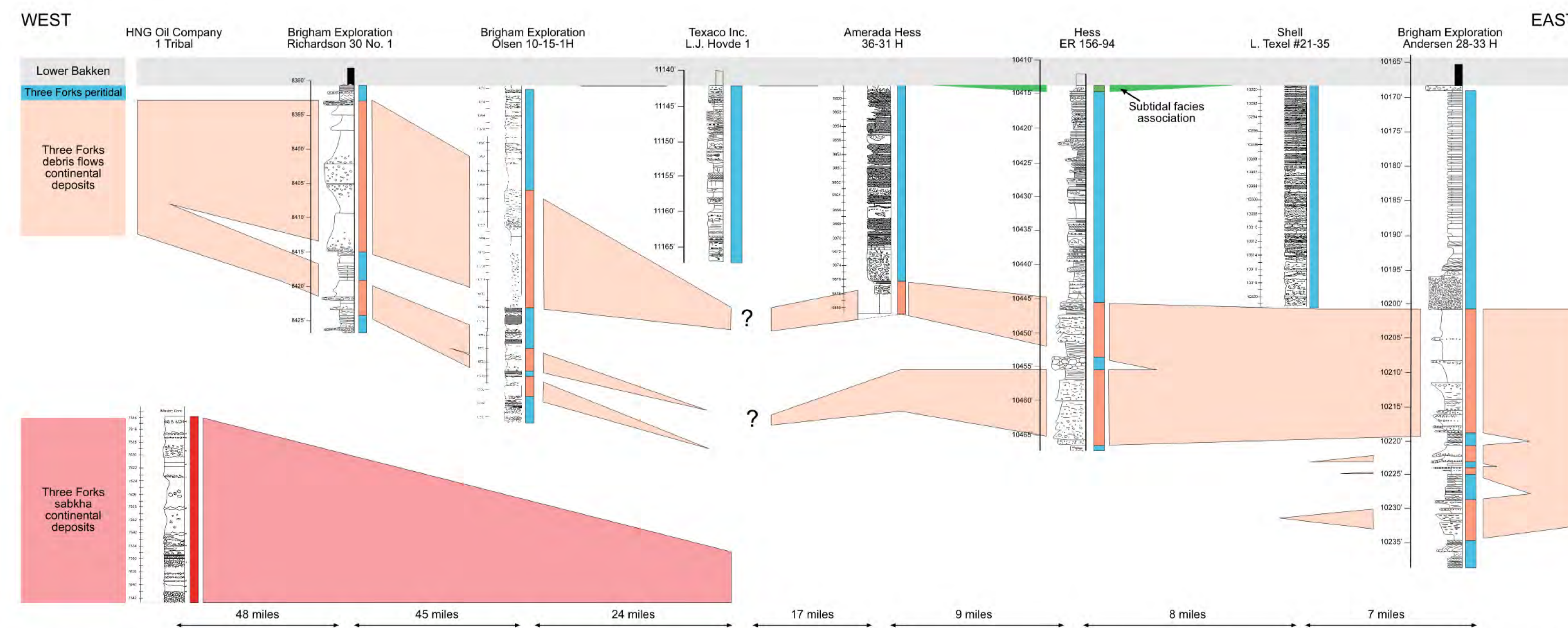


Fig. 14: STRATIGRAPHY

- ★ General succession of sabkha deposits (lower Three Forks) at base grading into intercalated peritidal and debris/mud flow deposits on top (middle Three Forks); upper Three Forks Formation is represented by massive peritidal deposits, locally overlain by subtidal units that define the basin center and the area of highest subsidence during Three Forks times.

- ★ Succession reflects initial arid conditions represented by sabkha deposits; this changes into humid conditions indicated by abundant debris flows with intercalated peritidal deposits. Late stage Three Forks deposition changes back to arid conditions with little sediment input from the margins and the development of "clean" dolomite siltstones.
- ★ Sea level shows overall transgression and final regression at top of Three Forks Formation. Internally, several small-scale trends are recorded: progradation of middle Three Forks cyclic peritidal-debris flow complex into basin center; subsequent transgression of upper Three Forks sea and deposition of thick peritidal reservoir rocks and locally subtidal sediments. Exposure led to development of paleosols (humid) and local microbial mats (dry) at the top of the Three Forks Formation.

Climate Control on Three Forks Deposition

ARID CLIMATE:

- ★ Little siliciclastic sediment input from hinterland in the form of debris/mud flows (facies association 3) because of minor precipitation; consequently few intercalated conglomerates
- ★ Dry conditions: gypsum/anhydrite indicative; sabkha facies belt only developed during arid climates; also developed preferentially during early phase of Three Forks evolution
- ★ Relatively thick peritidal reservoirs developed during arid climate as shallow-marine carbonate precipitation is not episodically interrupted by influx of massive debris flows

HUMID CLIMATE:

- ★ Abundant debris/mud flows (facies association 3) dominate terrestrial/supratidal portion of ramp during humid conditions, no sabkha (facies association 2) was developed
- ★ Paleosols formed in areas that did not receive deposition from debris flows (facies association 3)
- ★ Peritidal facies belt similar as during arid conditions, but succession not as thick
- ★ Did the debris flows fill up accommodation space? Reservoir less dissected during arid conditions

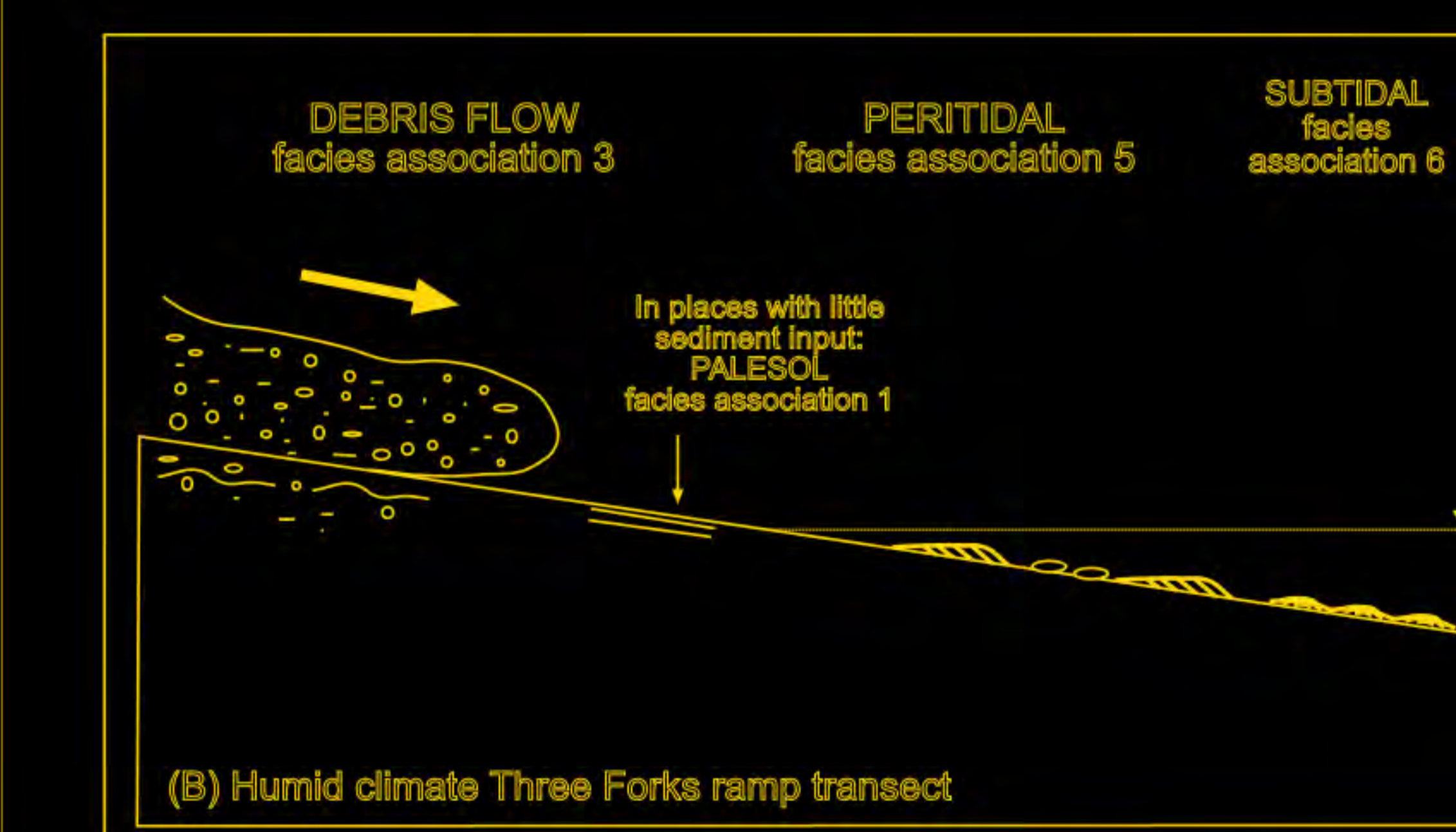
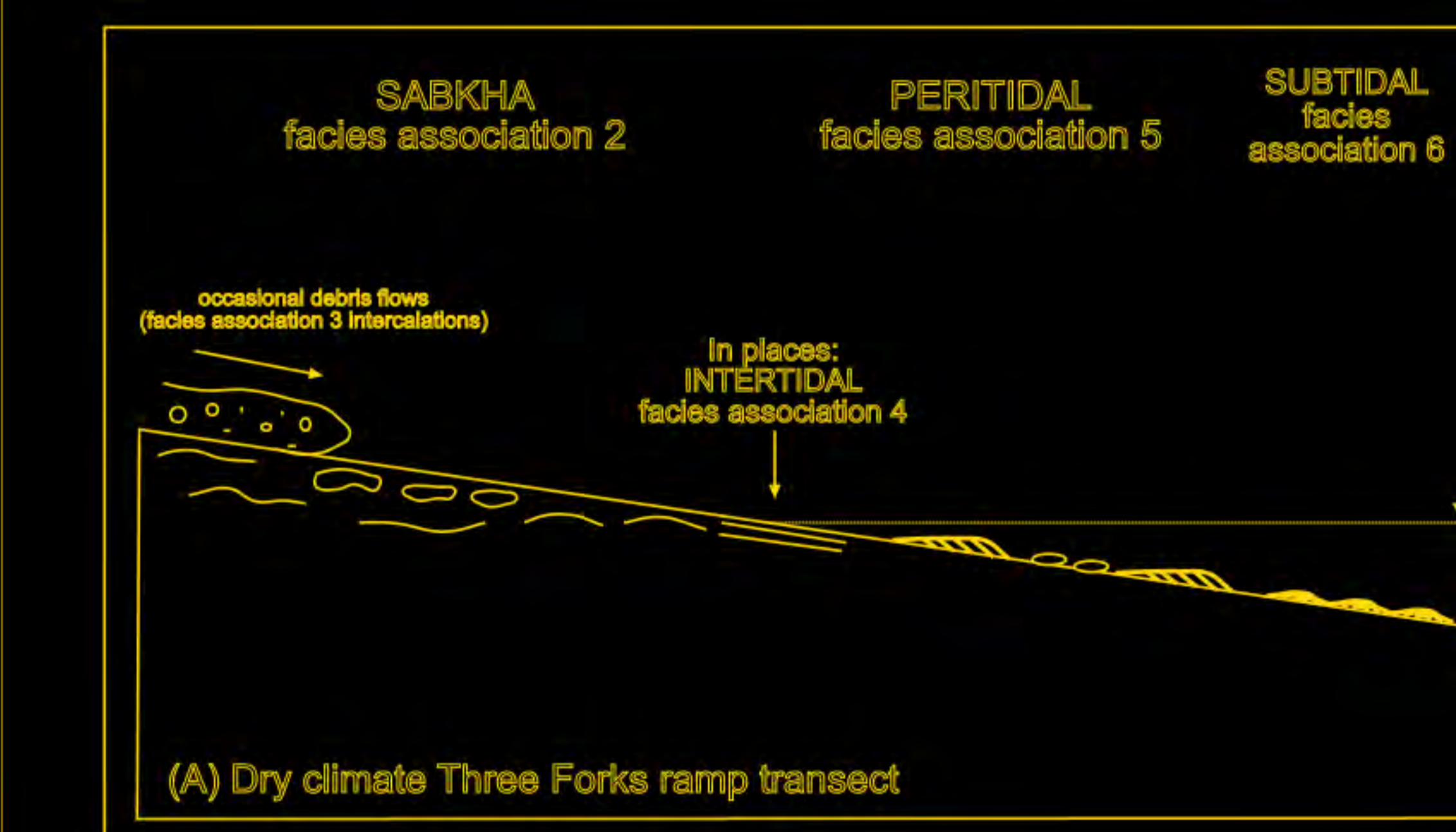


Fig. 17: Depositional transect across the Three Forks ramp during (A) arid conditions, characterized by relatively few subaerial gravity-flow deposits, and a sabkha landward of the peri- to intertidal zone; (B) humid conditions where subaerial debris-flow deposits (facies association 3) dominate the subaerial portion of the ramp, and no sabkha is developed. In contrast, paleosols occur in places.

References:

LeFever, J.A. (1991): History of oil production from the Bakken Formation, North Dakota. In: Hansen, W., Geology and horizontal drilling of the Bakken Formation. Montana Geological Society, 198 pp.
LeFever, J.A. (2008): Isopachs of the Three Forks Formation; https://www.dmr.nd.gov/ndgs/Publication_List/pdf/geoinv/GI_64.pdf