PSIndicators of Paleoseismicity in the Lacustrine Sediments of the Eocene Green River Formation, Wyoming, Colorado and Utah (USA)*

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Abstract

The carbonate-rich sediments of the Eocene Green River Formation (53–43 Ma) were deposited in a complex lake system in present-day Wyoming, Colorado, and Utah during the Laramide orogeny. Although syndepositional tectonic activity has been inferred previously for this interval, sedimentary deformation features linked to ancient earthquakes have never previously been studied. Stratigraphic intervals with synsedimentary deformation features were studied at several locations in all the sub-basins to provide information on the paleotectonic history of the area. Laterally extensive deformed horizons are common in laminated deposits of Fossil Basin (WY), and include folds, water-escape structures, dikes, microfaults, and chaotically brecciated intervals that preserved flow structures. These indicate hydrofracturing, dewatering, and the liquified state of sediments during deformation. Sediments deposited in sublittoral environments of the Bridger Basin (WY), at the boundary between the Tipton Shale and Wilkins Peak members, also show evidence of synsedimentary deformation. These features, some traceable laterally for tens of kilometers, imply tectonically influenced changes in sedimentary processes during that time. Pervasive deformation features are also present in the Mahogany Oil Shale Zone in the Piceance Creek and Uinta basins (CO, UT). Behavior ranges from brittle (fragmented laminites and faulted beds) to plastic (convolution, folds), to cm- to m-scale cracks filled with injected sediment. Deformation styles were controlled by the rheological properties of the host sediment. Grain size and morphology, abundance of organic matter (which influences ductility), and degree of diagenesis (compaction, cementation) all, in turn, influenced the deformation structures. All these structures resulted from increased pore pressures from cyclic loading, and vertical and horizontal stresses induced by ground motion. Masstransport deposits, triggered by seismic shaking, contain chaotic deformation features. Typically, undeformed strata separate the deformed horizons; this indicates that brief (tectonically-driven) events affected only near-surface sediments that were rheologically susceptible to syndepositional deformation. In many examples, the deformed horizons are overlain by beds showing contrasting lithology and/or degrees of bioturbation. This implies that many abrupt changes in the Green River Formation were tectonically, rather than climatically, driven.

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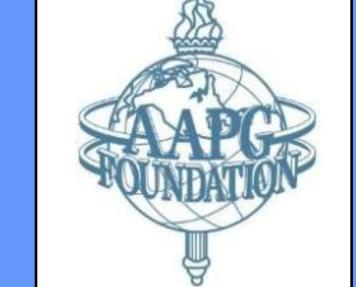
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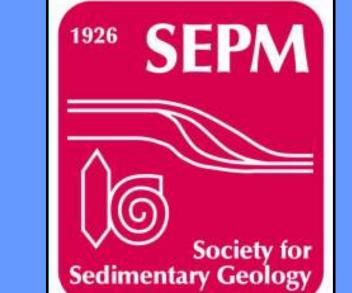


Fig. 1. Simplified Geological Map of the Green River Basins of SW Wyoming,

. Introduction and basic observations

- The heterolithic nature of lacustrine sediments gives them a high susceptibility to deformation owing to their variable rheological properties, and deposition in an overall quiet-water environment eliminates other trigger agents and increases the potential for preservation (Renaut & Gierlowski-Kordesch, 2010).

- Lacustrine sediments of the Green River Formation were deposited in interconnected foreland basins associated with ranges of the Rocky Mountains during the early and middle Eocene (53-45 Ma) during the time of the Laramide Orogeny, and comprise of siliciclastic, evaporitic, and carbonate sediments up to 2 km thick, in Wyoming, Colorado and Utah (Bradley, 1964; Dickinson et al., 1988; Roehler 1993; Smith et al., 2008).

- Despite the known syndepositional tectonic activity along the structures in and around these basins and the large number of geological studies devoted to the stratigraphy, deformation features related to seismic events have not previously

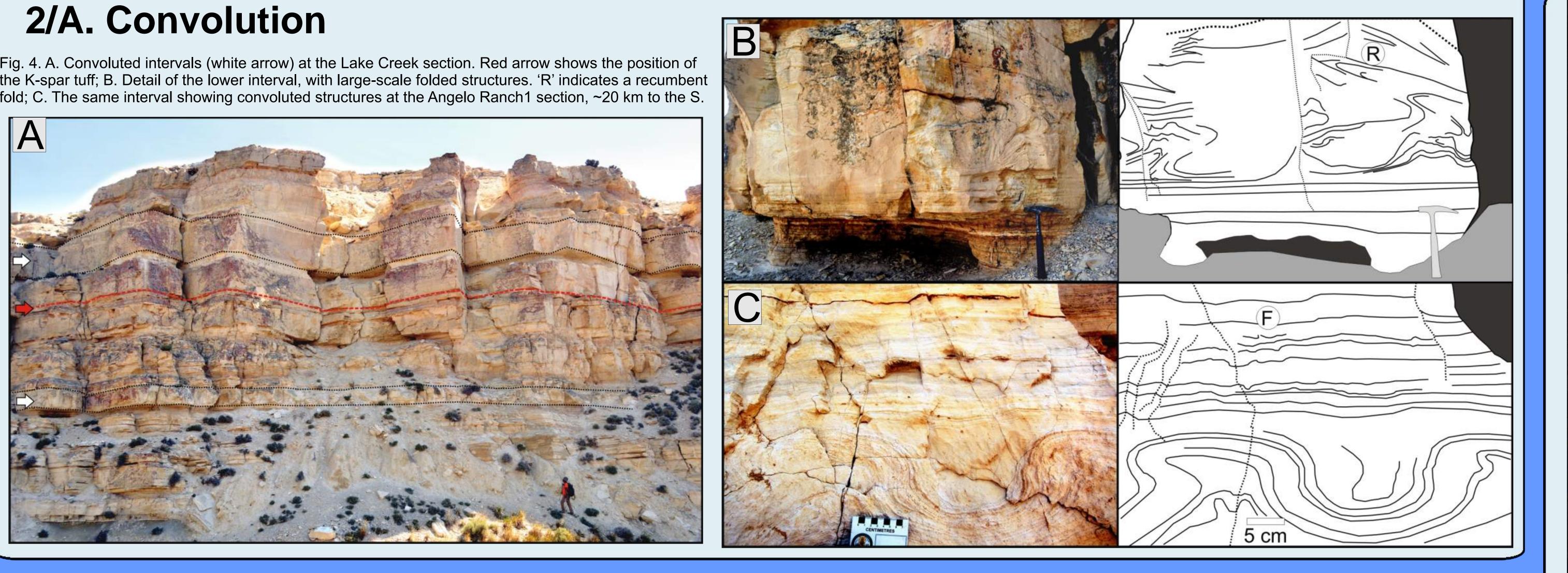
Several, laterally extensive deformed horizons were identified on outcrops and cores in all the sub-basins, in a variety of depositional settings.

- Deformed layers are bound above and below by undeformed beds of similar facies with horizontal bedding-plane surfaces, which imply short-lived, recurring events that affected only sediments with a susceptible rheological state at the time.

Tgf Fossil Butte Member (GRF) Twb Bullpen Member (WF)

Tgr Road Hollow Member (GRF) Tga Angelo Member (GRF)

The style of deformation in profundal deposits was governed by the rheological state of the sediment, while the degree of ductility in profundal deposits was controlled by the amount of organic matter and the diagenetic state.



2/B. Complex Brittle-Ductile Deformation



liquidization of the sediment.

2/C. Sedimentary Dikes - Sedimentary dikes are the most common features in Fossil Basin. with carbonate mud. silt. or sand and/or brecciated material. - Dikes formed by segregation during seismic shaking and dewatering

2/D. Synsedimentary Microfaults



2/E. Fluid Escape

2/F. Mass-Transport Deposits - Laminated lacustrine deposits of the Fossil Basin are commonly interbedded

with laterally extensive, brecciated beds.

The beds are generally matrix supported, polymictic (but monomictic layers

mudstone, chert, tuff, and locally siliciclastic sediments.

- Clasts with preferential orientation, following curvilinear lines, form 'flow structures', which indicates a plastic state and transportation.

The upper boundary of the beds is normally flat, while the lower boundary is irregular as the result of loading or scour and the underlying succession

commonly shows deformation (Fig. 9A-C). Some brecciated intervals show a coarsening-upward trend (Fig. 9D). - Most intervals can be traced laterally for several tens of meters along the outcrops or can be correlated for several km.

(> 15 cm) clasts on the top. The layer is capped by deformed

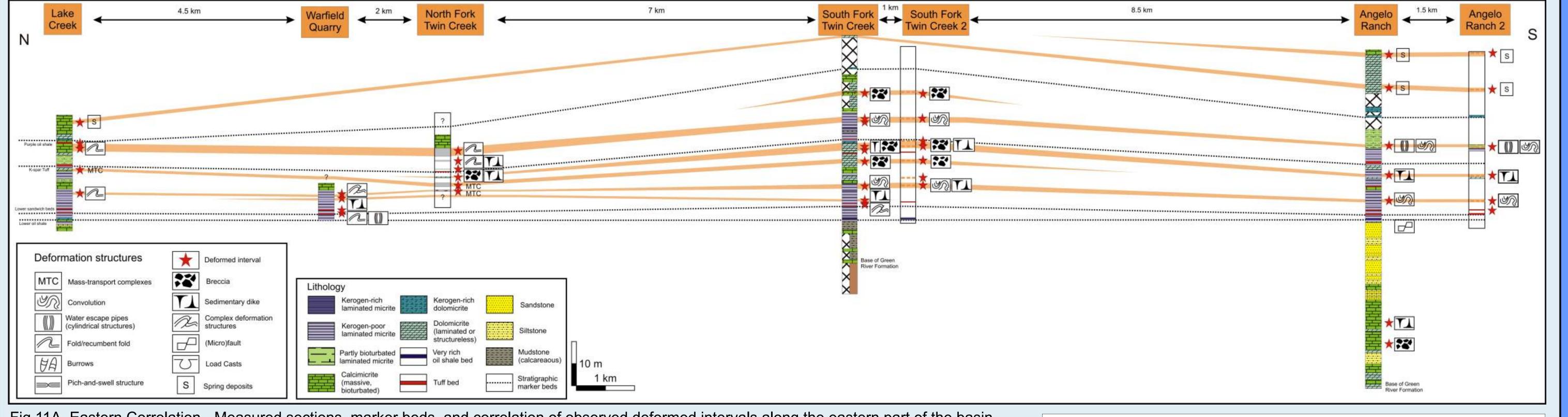
2/G. Oil Shale Breccias

- Monomictic brecciated oil shales occur in laterally extensive horizons, in most cases, over- and underlain by undeformed parallel laminated sediments. These intervals show highly contorted lamination, characterized by

pronounced sheared fabric, and flat base and top. characeristic slump features, were observed (e.g., unidirectional folding,

erosive base, aligned clasts - i.e., 'flow structures'). and the distance of transportation is short (cf. Dyni and Hawkins, 1981

2/H. Correlation of Deformation Features in Fossil Basin (WY)



brittle-ductile features.

- Deformation occurs dominantly in parallel laminated open lacustrine deposits with variable organic content. Correlation is aided by the presence of numerous stratigraphic marker beds (Fig. 11A, B).

- Deformed intervals can be traced for longer distances (up to 25 km) within the central part of the

Sediments deposited in the central areas (parallel laminated micrites) show the dominance of ductile or

Organic-poor and poorly laminated marginal lake deposits contain mainly brittle features (e.g., breccias) Laterally restricted features point to rheologically controlled deformation (as a result of lateral facies

- Extensive deformed intervals are interpreted to be the result of tectonic movements along the nearby Absaroka and Hogsback thrusts (~ 51-52 Ma).

2. Fossil Basin (WY)

- The Eocene lacustrine deposits of the Fossil Basin in SW Wyoming are up to 120 m thick (Buchheim et al., 2011).

Tänavsuu-Milkeviciene and Sarg, 2011), with the studied intervals.

Uinta Uplift/ Axial Basin Arch

Cherokee Ridge

- The main lithofacies include nearshore and deltaic siliciclastic claystone, siltstone and sandstone, and nearshore to offshore lime mudstone consisting of kerogen-poor bioturbated micrite, relatively deep-water kerogen-poor or kerogen-rich laminated micrite or dolomicrite ("oil shale") and massive dolomicrite. - As a result of the deposition in a small and relatively shallow lake the thickness and facies of the Green River Formation change rapidly within short distances.

- The depositional slope on the Fossil Basin was as low as 40cm/km or 0.023° (Buchheim, 1994).

- Laterally extensive deformation features were also described by others (e.g., Buchheim et al., 2011); however they were not linked to tectonic events.

- In this study only the upper 50-60 m, the balanced-fill Fossil Butte and the underfilled Angelo Member were studied in detail..

main lithofacies of the Green River Formation in Fossil Basin (modified after Buchheim et al., 20

laminated calci-micrite, siltstone and sandstone

Stratigraphy

Sevier Fold And Thrust Belt (W)/ Wind River

(WQ); B. Fluid escape pipe with a central tube (AR1). Pipes

- The boundary of the Tipton Shale and Wilkins Peak Members is marked by a sudden change in lithology from oil shaledominant lacustrine rocks of the Tipton Shale Member to the

organic-poor and evaporative Wilkins Peak Member. - The transition is sharp (1-2 m) and easily identifiable across

the study area.

- This sudden facies change was a response to the evolution of Eocene Lake Gosiute, from the balanced-filled (Tipton Shale) to underfilled lacustrine conditions (Wilkins

Peak Member) (Carroll & Bohacs, 1999). These changes in the lacustrine sedimentation were (partially) induced by structural movements (Pietras & Carroll,

The origin of laterally extensive sedimentary deformation features has been investigated based on centimetre to decimetre-scale visual description of outcrops and cores. - The base of the Wilkins Peak Member contains at least 5 well defined deformed intervals in two coarsening-upward cycles of sublittoral sandy calcareous siltstone/silty mudstone

- Each interval could be traced for more than 20 km in the northern part of the study area.

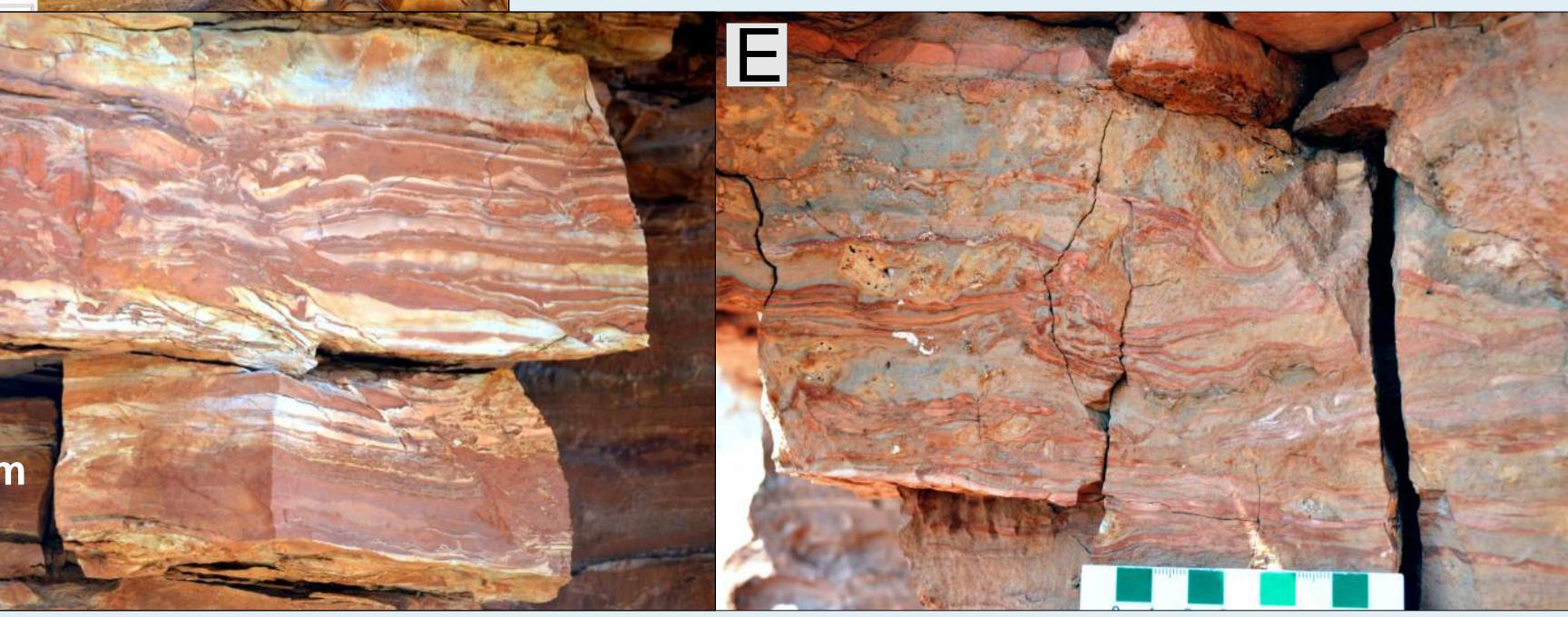
3/A 'Northern' Deformation Features

Wyoming, with the studied locations of outcrops and cores.

- Deformation structures include various types of folds, balland-pillow structures, microfaults, breccias and sedimentary dikes, but most commonly deformation is represented by composite structures.

 Coarsening-upward sedimentary cycles with similar depositional environment higher in the sections show no deformation, which indicates an allokinetic trigger.

 Further to the north, at the White Mountain area, deformation structures could not be observed as a result of facies changes nto recessive sediments with a lack of good exposure. Deformation (e.g., recumbent folded oil shale beds) were also found in oil shale, approximately 2 m below the boundary.



upper left & lower right), slight folding and sedimentary injections (on the left); E. Convolution and sedimentary injection in calcareaous sandstones interlaminated with silt and mud (Sage Creek section)

3/B 'Southern' Deformation Features (Red Creek Area)

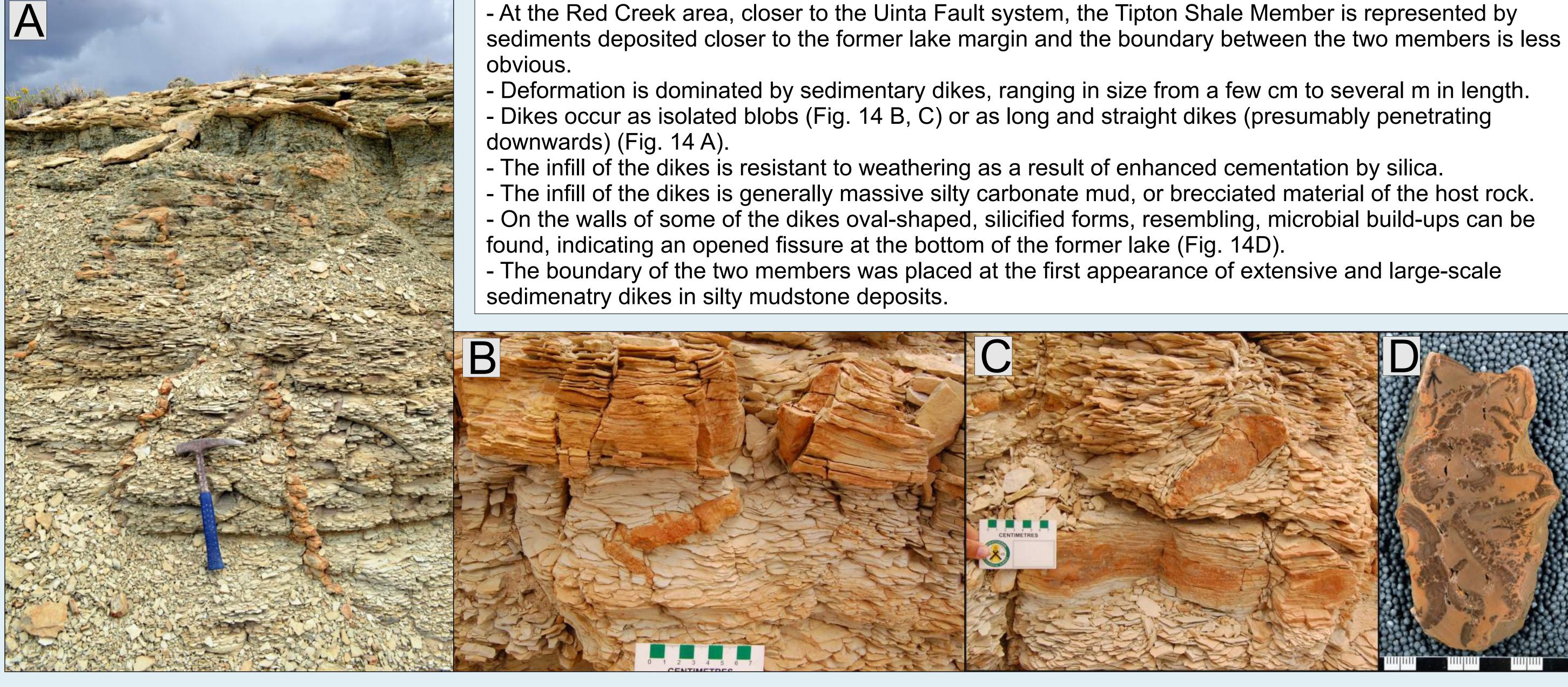
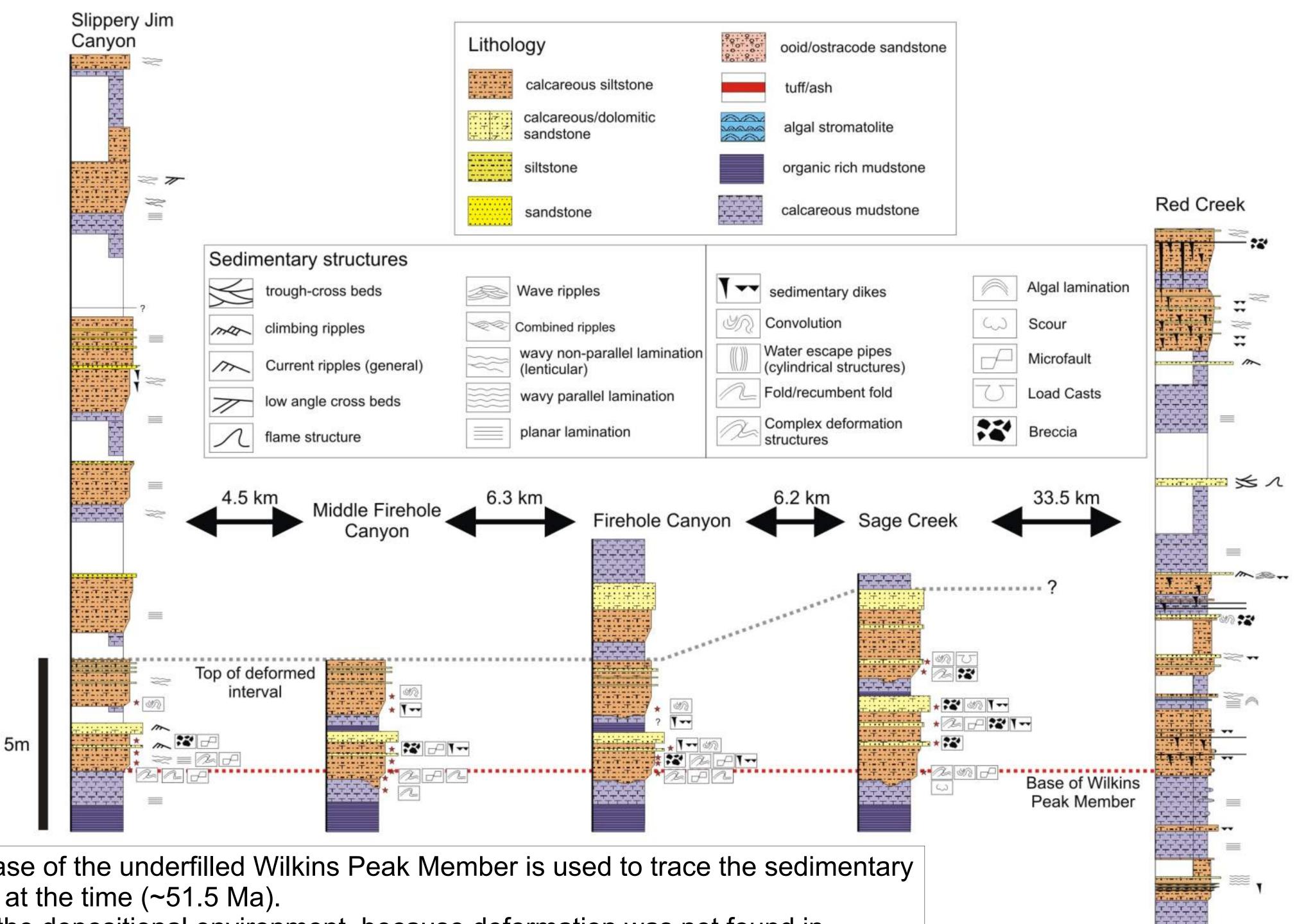


Fig. 14. Sedimentary dikes at Red Creek section: A. Long and straight sedimentary dike with homogeneous silty mudstone infill; B. Isolated crack filled with brecciated material; C. Large isolated crack filled with silicified brecciated material (Red Creek). Note the smaller horizontal sill on the left; D. Cut surface of dike showed on 'C' containing brecciated rim overgrown by microbial-like structures.

3/C Correlation



- Deformation features at the base of the underfilled Wilkins Peak Member is used to trace the sedimentary record of structural movements at the time (~51.5 Ma).

- Deformation is not specific to the depositional environment, because deformation was not found in sedimentary cycles stratigraphically higher, with deposits identical to the ones hosting the deformation structures.

- Consequently, based on their characteristics and laterally extensive nature, these indicate structural movement along the nearby uplifts and related fault systems (Rock Springs Uplift, Uinta Fault System). - As these features also mark the boundary of two distinct stages in the evolution of Lake Gosuite (the boundary of the balance-filled Tipton Shale Member and the overlying, underfilled Wilkins Peak Member), they also indicate tectonically driven changes in the lake sedimentation (cf. Pietras & Carroll, 2006).

4. Washakie Basin (WY) - Laney Member

- Sedimentary dikes identified in the Laney Member of the Washakie Basin are up to 1.5 n long and several cm wide.

- They are filled with homogeneous mudstone or a mixture of fragmented material of mud, silt, sand, massive or laminated chert, fragments of lacustrine sedimentary rocks and tuff material. - The crack-fill is generally silicified, and a

central conduit can be observed, filled with massive or laminated chert/calcite (Fig. 17B). Cracks show moderate sinuosity, branching (Fig. 16A), multiple fillings, brecciated internal structure (Fig. 16A), and their overall width decreases downward and/or upward in the

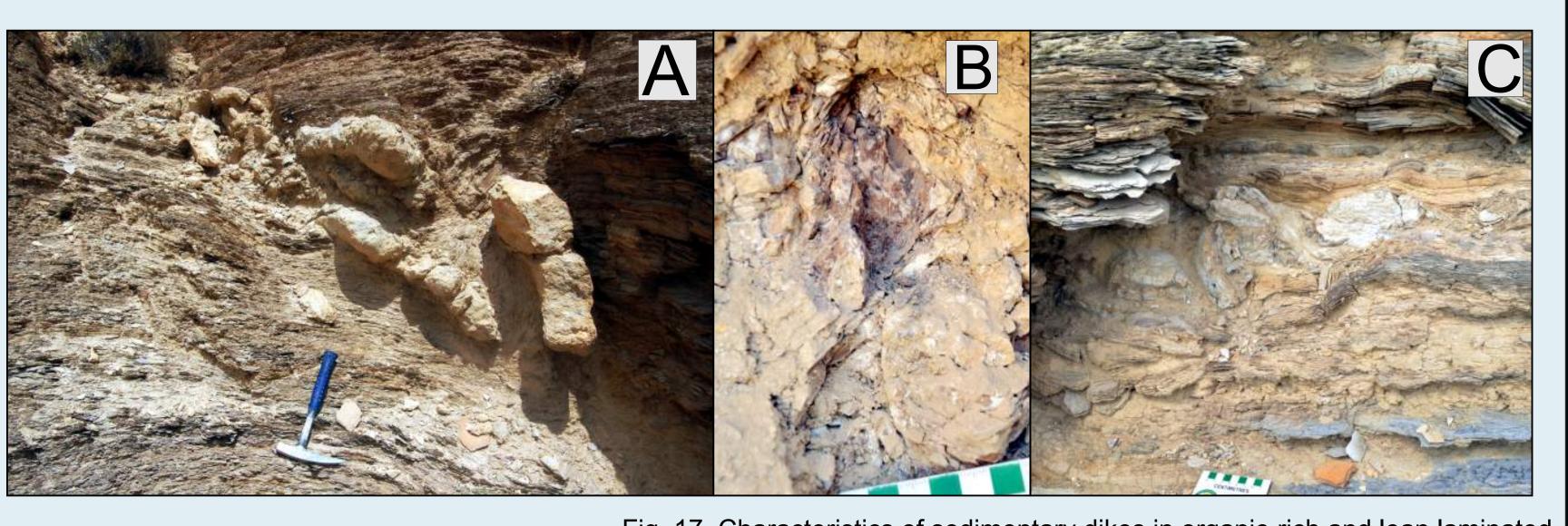
laminated oil-shales or micritic mudstones. - In many cases the cracks are represented by isolated bulbs or horizontal sills without a defined source (Fig. 16B, 17C).

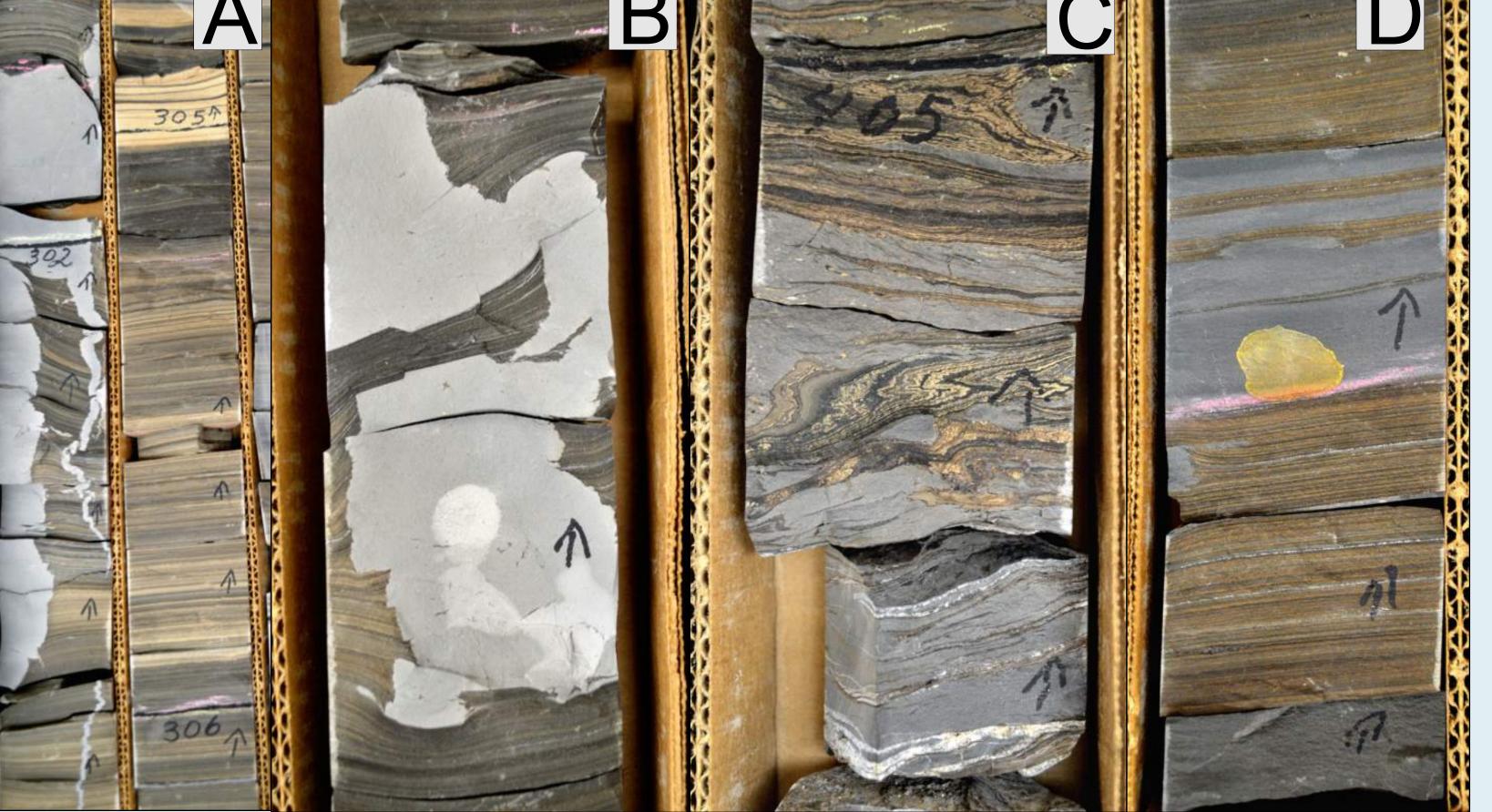
- Dikes are more frequent, and larger in size a the base of a regional marker bed, the Buff Marker Bed (Fig. 17A).

- In cores dikes are generally filled with massive silty mud.



Sample with multiple filling indicating more than one fluidization event (TD); B. Dike filled with carbonate mud and silt. Note the thin analcime-tuff layer with long cracks (SB)





enetrating downwards filled with massive silty mud; B. Complex sedimentary injection feature; C. Soft-sediment deformed shale and massive silty mud; D. Massive silty mudstone bed showing isolated sedimentary dike and upward-protruding top

- Rhodes et al. (2007) interpreted these cracks nt the base of the Buff Marker Bed as the result of desiccation that occurred after a regional tectonic event which caused the modification of the regional drainage system. However, the morphology and the infill of the cracks (with a central conduit) indicate fluid migration and sediment remobilization.

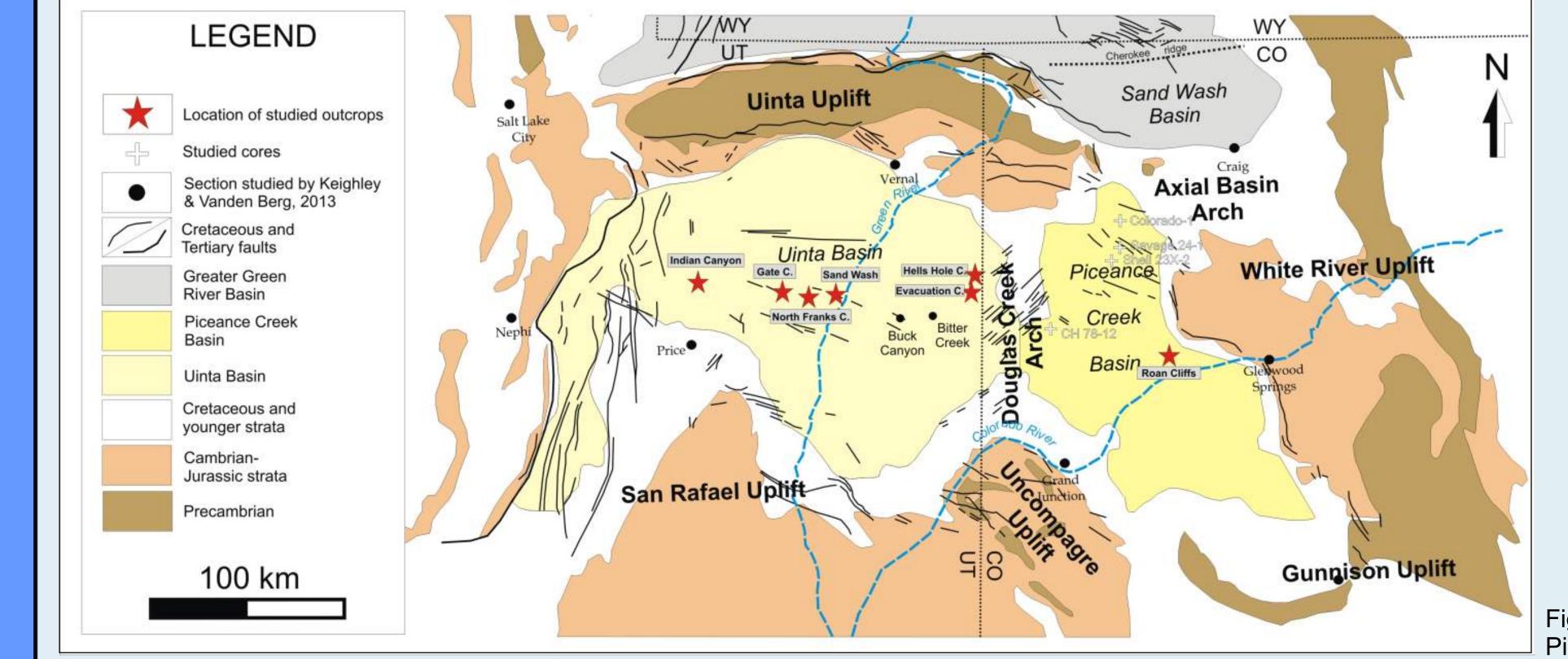
- The morphological characteristics of the dikes related to the Buff Marker Bed are similar to the ones, found in several other stratigraphic levels in the Laney Member; this suggests a common, seismic origin.

Sedimentary dikes and other deformation structures identified in cores were previously not recognized, or misinterpreted (for example as burrow structures, scour features or rip-up

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Panel - 2

5. Mahogany Oil Shale Zone - Uinta Basin (UT)



- Pervasive deformation features were investigated across the Uinta and Piceance Creek basins in the Mahogany Oil Shale Zone (MOSZ), a 20-30-m thick extensive stratigraphic marker, zone, which contains several organic rich shale beds. - Deformation structures have been identified both in cores

and outcrops. - Deformation style ranges from brittle (fragmented laminites and faulted beds) to plastic (convolution, folding), with

sedimentary injection into cm- to m-scale dikes. - The style of deformation was governed by the rheological properties of the sediment.

- Their great lateral extent and confinement to a thin (20-30 m), well-defined stratigraphic level indicate a regional tectonic event, which caused dewatering, hydrofracturing and slope instability/ slumping at different parts of the basin.

Fig 19. Studied locations of the Mahogany Oil Shale Zone and major fault zones of the Uinta and Piceance Creek basins (NE Utah and NW Colorado).

5/A. Indian Canyon (UT)

Fig. 21. Sedimentary injections in sublittoral silty lime mudstones showing multiple fluidization events and hydrofracturing, Indian Canyon. B. Fragmentation and upward bending of the sediments indicate upward fluid movement.



beds showed N/NNE movement/compression.



Fig 20. Outcrop of the MOSZ at Indian Canyon along Hwy 191. Two prominen deformation zones are marked with red boxes.

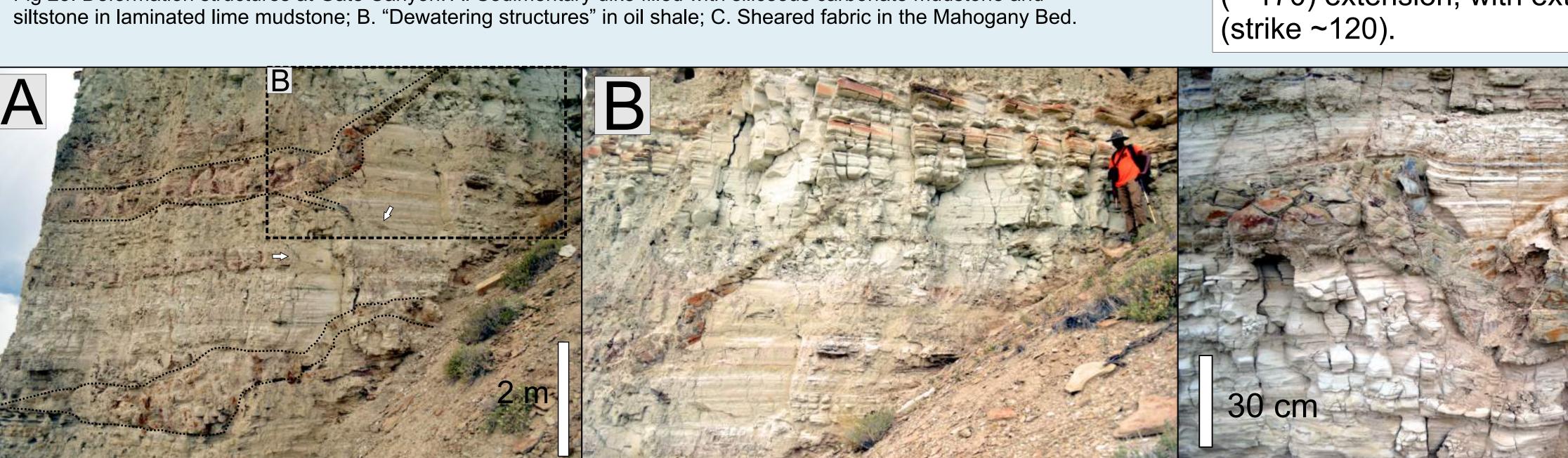
5/B. Gate Canyon and North Franks Canyon (UT)

Deformation features are characterized by horizons with mud-filled carbonate injection ("dewatering structures") in the oil- shales (Fig. 23B). 0.1-2m long cracks filled with silicified carbonate mud

Gate Canyon

and silt also occur (Fig. 23A). - Sheared oil shale (the Mahogany bed), showing en-echelon fabric, shear-related propagation folds, kink and sheath folds, shear duplexes and thrusting (Fig. 23C). - Small scale oriented cracks and the shear fabric indicate top to left (North) shear/compression and perpendicular

(~ 170) extension, with extensional joints (strike ~120).



North Franks Canyon

- Deformation structures are dominated by remobilized non-calcareous/silicified mudstones at multiple detachment surfaces, forming large- and small-scale dikes and sills 0-3 m below the Mahogany Bed (Fig. 24).

Sheared layers within the interval indicate N-ward displacement, while small duplexes within the dikes show S-ward movement.

N-S-oriented joints and oriented small-scale "shrinkage-cracks" or "syneresis cracks" in silty mudstone deposits in the succession indicate E-W extension.

- At Sand Wash the Mahogany Oil Shale Zone hosts a 4-10-m thick chaotic interval with complex deformation features, showing characteristics of a

mass transport complex (MTC). - The interval has a sharp, erosional lower boundary on the top of horizontally bedded lake sediments, with smaller scale deformations and

silicified sedimentary injections (up to 3 m long). - The source of these irregular dikes, either the base of the MTC or horizons within the slightly deformed lake sediments. At many places a distinct, oil-rich shale bed forms the basal boundary (e.g., 2), which is in turn brecciated or disrupted by the MTC.

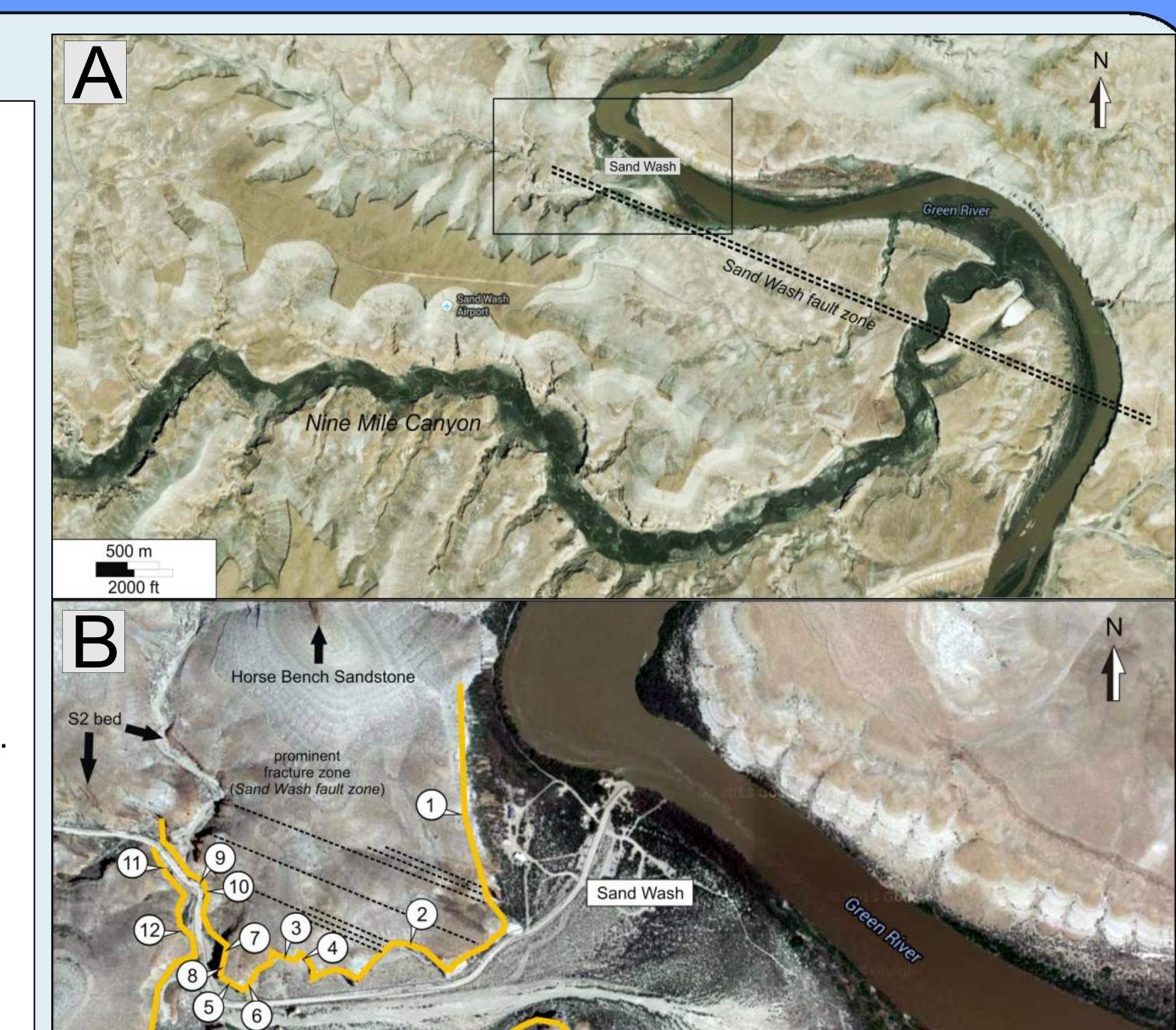
- Internally the MTC shows two distinct lithofacies: (a) sandy-silty matrix, with sand-/silt-/mudstone and oil shale clasts, or (b) massive/laminated, blocky brown-dark brown siliceous mudstone with clasts of oil shale. In both cases chaotic deformation, sheared fabric, or large-scale recumbent folded intervals are general.

- Large, sometimes tilted rafts of brecciated oil shale can be found at the top of the MTC. This upper oil shale is considered to be the Mahogany Bed. - In places it seems continuous and intact; however, even at those places it shows brecciation and small-scale disruption. Locally it is overlain by irregular, lens-shaped lacustrine succession and/or orange tuff layer (e.g., 3), mixed with organic-rich and lean oil shale and tuffaceous sediments, showing plastic deformation and brecciation.

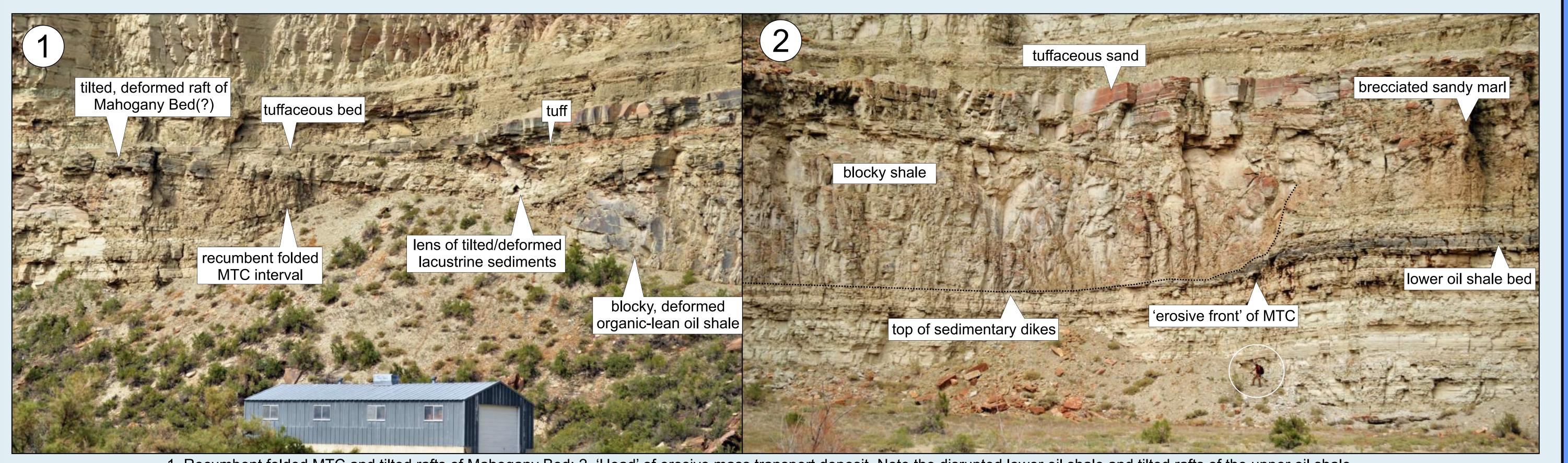
- This upper succession is overlain by undeformed (ledge-forming) wavybedded tuffaceous sand- and siltstone.

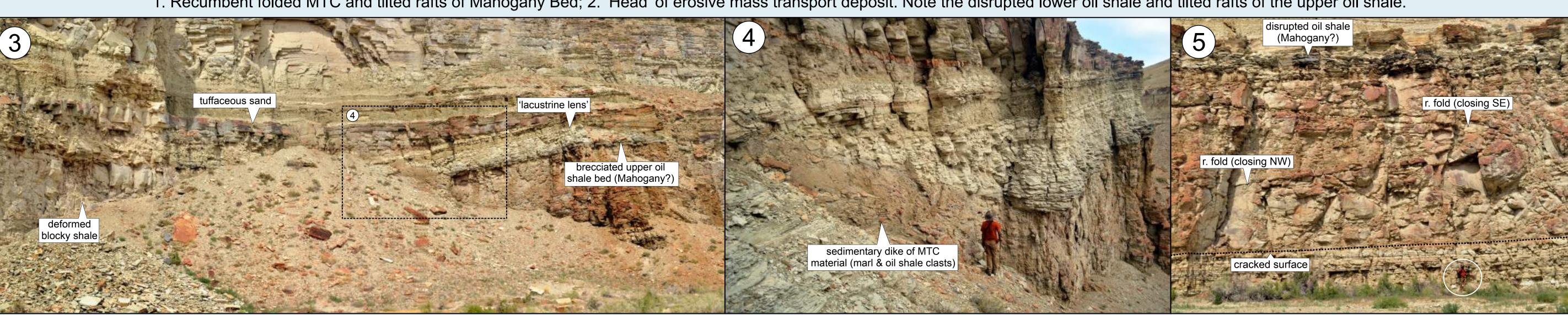
- The MTC indicates a large-scale slumping event and the instability of profundal to sublittoral sediments.

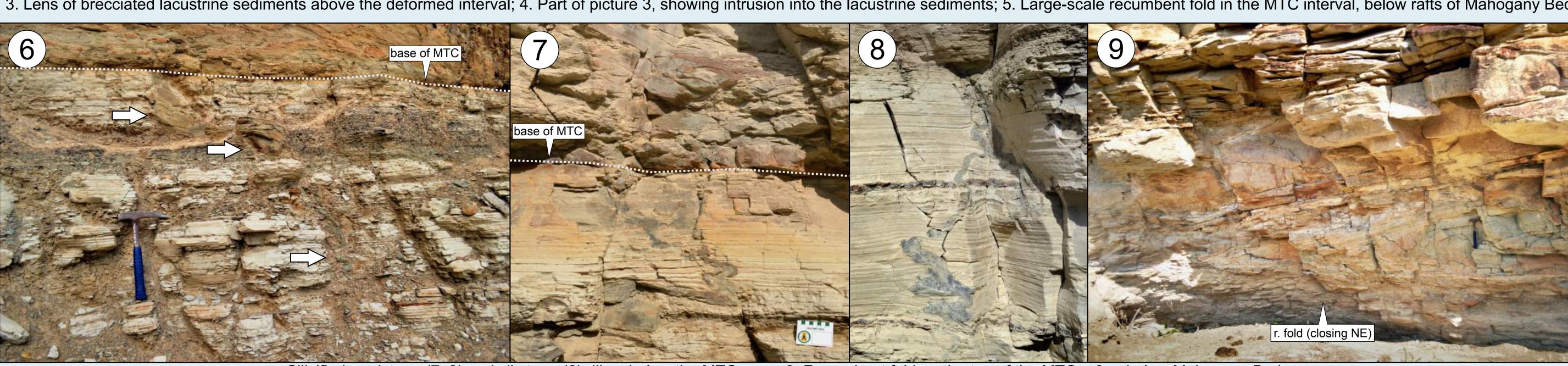
> Fig. 25. Location of the studied area, northeast of Nine Mile Canyon and the location of photos presented below.

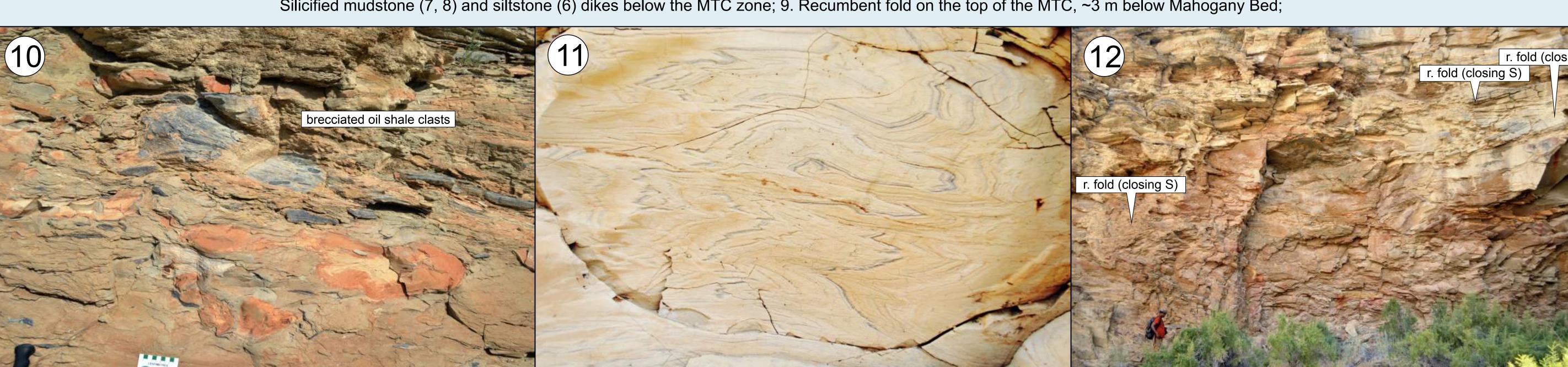


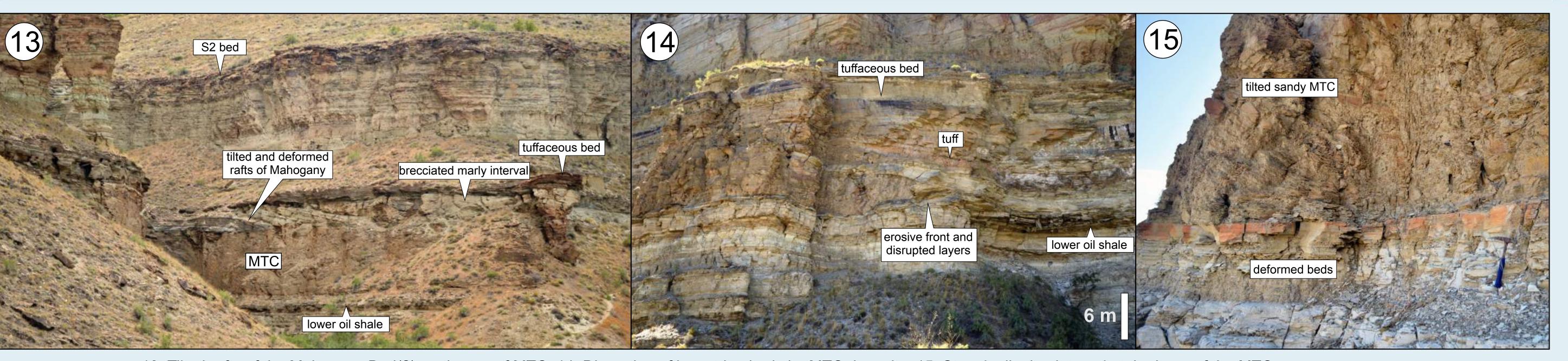










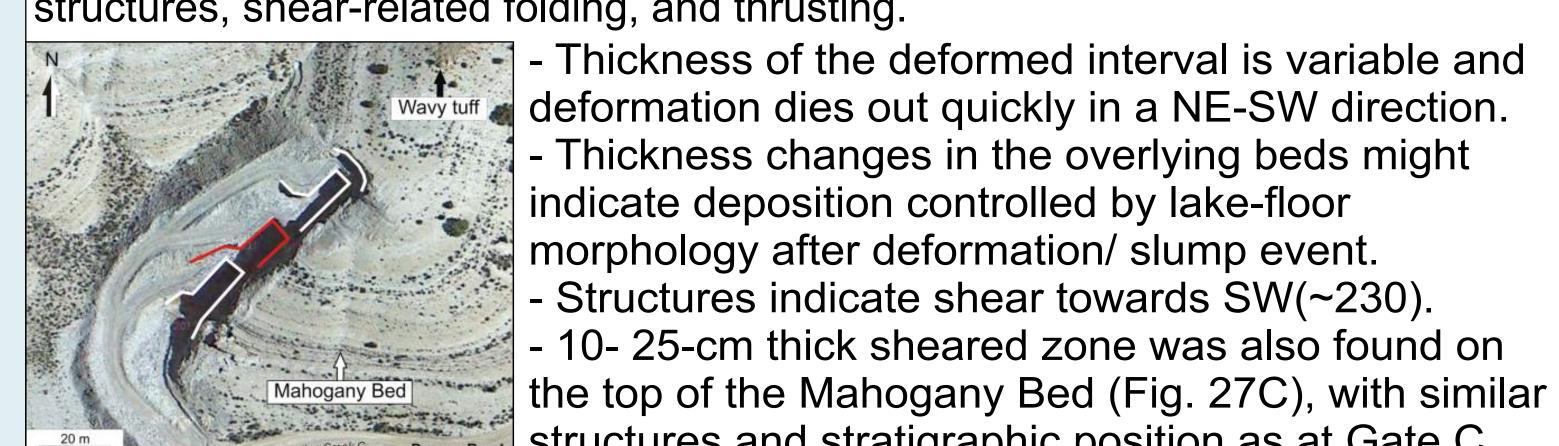


5/D. Eastern Utah (Evacuation Creek Canyon; Hells Hole Canyon)

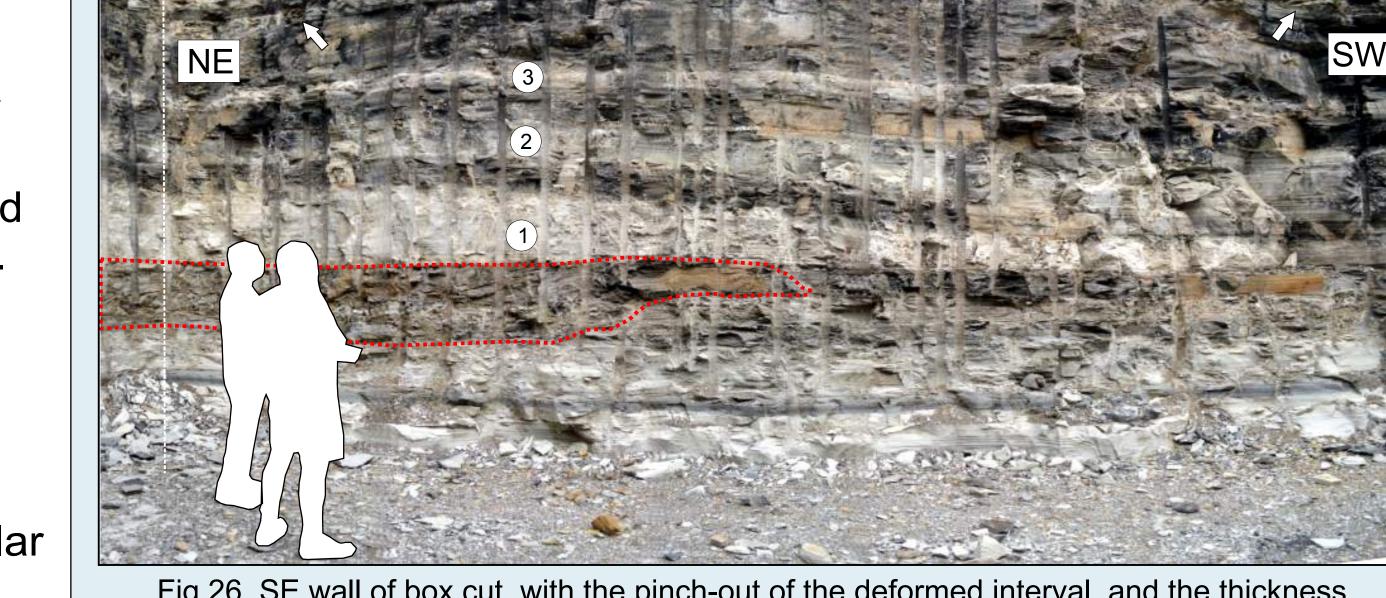
Evacuation Creek Canyon

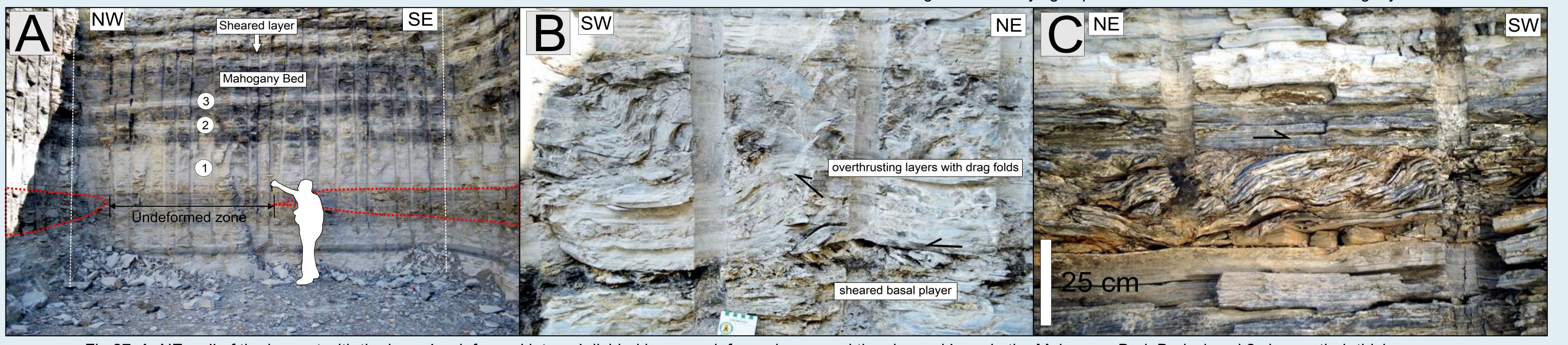
- Study of MOSZ in the box cut of the Enefit American Oil

- ~1.5 m below the Mahogany Bed, an irregular horizon, with en-echelon shear structures, shear-related folding, and thrusting.



 Thickness changes in the overlying beds might Structures indicate shear towards SW(~230). 10- 25-cm thick sheared zone was also found on he top of the Mahogany Bed (Fig. 27C), with similar





Hells Hole Canyon

Several well defined, horizontally persistent and traceable brecciated and/or plastically deformed horizons.

Deformed horizons over- and underlain by non-/ or less deformed, laminated lake deposits.

Injection features occur in the vicinity of a ~15-cm thick tuff, containing

- Injection features, the brecciation and the presence of lithoclasts indicate dewatering of a fluid-saturated, reworked tuff material. Sheath folds show WSW (~245) compression.



at the base and top of a tuff layer (Mahogany Marker?). Note the mixing of the oil shale and tuff material on the top of the tuff.

5/E. Piceance Creek Basin (CO)

- Contorted "breccias", disrupted bedding or "blebby" oil shale beds ranging from a few centimetres to 11-m thick, are common features near the depocentre of the Piceance Creek basin.

Johnson (1981) and Tänavsuu-Milkeviciene & Sarg (2012) identified and correlated soft-sediment deformed (slumped) or brecciated individual oil shale beds over several square kilometers in the northern, tectonically active part of the basin, along with other deformation structures, such as "dewatering" structures and intraformational conglomerate beds.

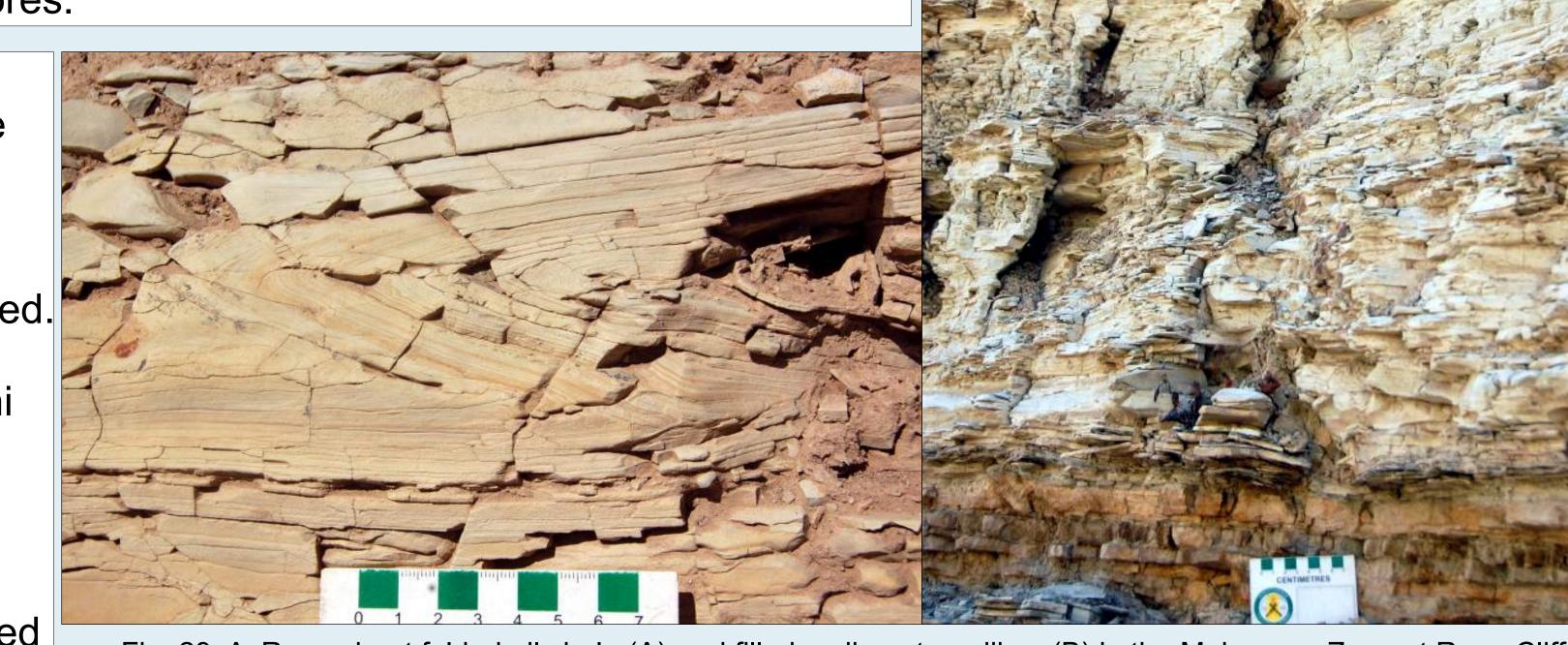
Deformed beds have sharp upper/lower boundaries and are over- and underlain by undeformed sediments. Such features have been studied at the Roan Cliffs and in cores.

- Brecciated beds contain faulted, folded, tilted or imbricated clasts of laminated oil shales (intraclasts) or massive mudstone or siliciclastic clasts, which are floating in the matrix.

Sheared fabric is common, and beds can be associated with sedimentary dikes above or below. Grading is not apparent and the clasts are randomly distributed.

The origin of these sediments were interpreted as slumps, slides, debris-flows and higher-energy turbidity currents by Dyni & Hawkins (1981), Johnson (1981), Johnson et al. (2010), and Tänavsuu-Milkeviciene & Sarg (2012) In most cases, specific trigger mechanism was not defined.

Due to their lateral extent and the deposition in a low-energy environment such features are interpreted as seismically induced



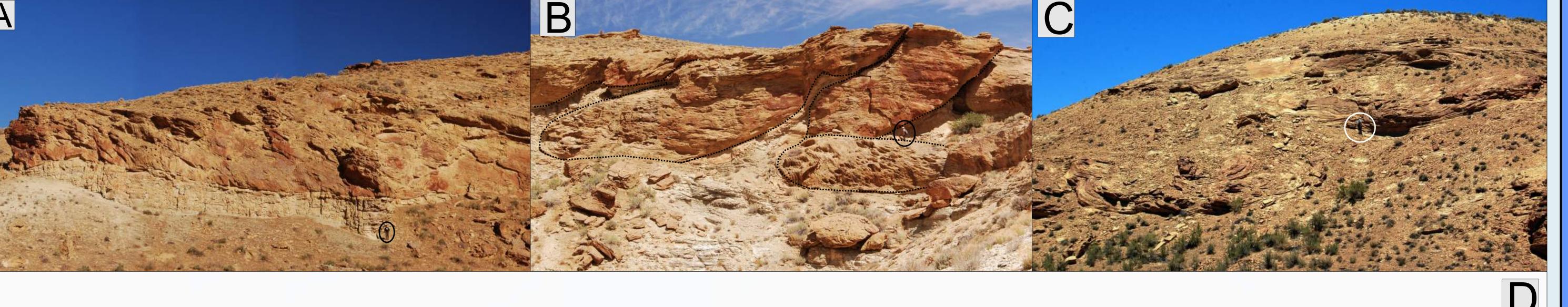
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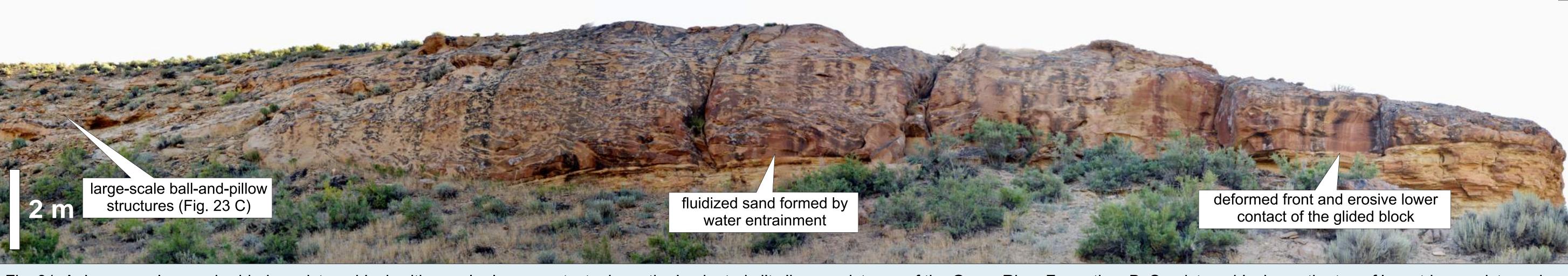
6. Deformed contact between the Uinta and Green River Formations in E-Uinta Basin

Large-scale sandstone blocks, foundered into deformed or undeformed lacustrine sediments in the eastern Uinta Basin, form an irregular upper boundary of the Green River Formation (Fig. 31). The sand blocks are intact or plastically deformed, with sharp, erosive

In places the blocks are separated by large diapirs of lacustrine sediments. At other places the boundary marked by large-scale liquidization (ball-andpillow) structures (Fig. 31 C) and hydroplaning (Fig. 31 D). Deformation/shear structures indicate a S-ward displacement of the exotic

sandstone blocks due to seismicity along the Douglas Creek Arch.





The lower blocks show plastic deformation and bending of the original bedding. The upper blocks are imbricated and divided by dome-like intrusions of the sandy lime mudstone or by shear planes; C. Large-scale ball-and-pillow structures, near Watson; D. Outcrop shows the hydroplaning and fluidization of semilithified, glided sandstone block.

7. Conclusions

lower boundary (e.g., Fig. 31A).

Pervasive horizons of seismically induced deformation structures were identified in the lacustrine sediments of the Eocene Green River Formation

Deformation is represented by brittle and plastic behavior, as well as sediment injection and mass transport.

The deformed layers in the profundal setting are confined by undeformed beds which implies sporadic short-lived events that affected only near-surface sediments with susceptible rheological state at the time.

Based on (1) the tectonic setting of the lacustrine basins; (2) the sedimentary environment and sedimentological characteristics of the successions in which the deformed layers occur; (3) their lateral extent and proximity to known active fault systems during the time of the deposition of host sediments; and (4) their recurrence at different stratigraphic levels, intervals showing large-scale sedimentary deformation structures are the result of in-situ loss of shear

strength (without or without the role of gravity), formed by increased pore pressure and vertical or horizontal stress induced by seismic activity. Features previously described as the result of desiccation are reinterpreted as seismically induced sedimentary deformation and/or fluid flow.

- Silicified sedimentary injection features ("dewatering structures") indicate segregation of fine grained sediments, dewatering and remobilization. These features also acted as conduits of silica-rich brines.

Mass transport complexes formed due to seismicity induced instability of the sediments on a flat or very gently dipping depositional slope (Buchheim, 1994; Dyni, 1981).

Features in the MOSZ indicate a basin-wide tectonic event.

These features can provide information about the location and timing of the tectonic **movements** in the lake sub-basins. Clearly, synsedimentary deformation is an important but hitherto neglected aspect of the petroleum geology of the Green River Formation.

> Fig. 32. Proposed concept illustrating the origin of mass movement deposits and other sedimentary deformation features, triggered by earthquakes (depositional model modified after Tänavsuu- Milkeviciene and Sarg. 2012)

änavsuu-Milkeviciene, K. and Sarg, F. J., 2011. Evolution of the Green River Formation, Piceance Creek Basin - Implications for Eocene lake history, Colorado, Utah and Wyoming. 31st Oil Shale Symposium, Poster presentation

änavsuu-Milkeviciene, K. and Sarg, F. J., 2012. Evolution of an organic-rich lake basin – stratigraphy, climate and tectonics: Piceance Creek basin, Eocene Green River Formation. Sedimentology, 59, p. 1735 – 1768

FA92: Oil shale breccias FA10: Siliciclastic turbidites FA4: Delta deposits FA8: Laminated oil shale

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