PALEOSEISMIC INDICATORS IN THE LACUSTRINE GREEN RIVER FORMATION (EOCENE, USA) - CHARACTERISTICS AND IMPLICATIONS

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1. Introduction and basic observations

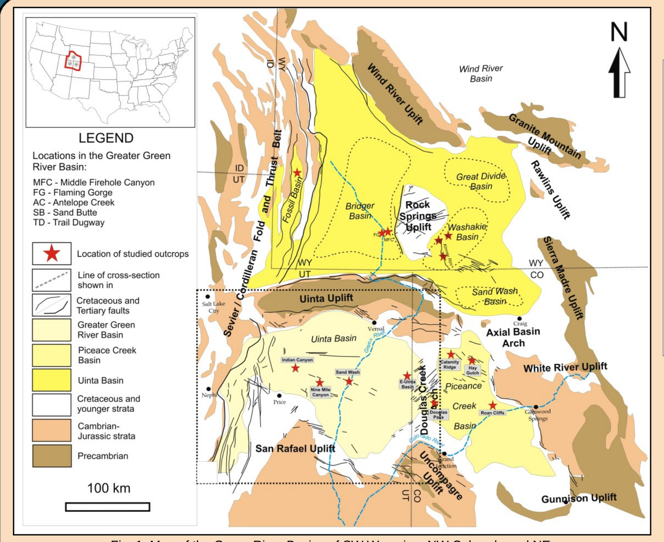


Fig. 1. Map of the Green River Basins of SW Wyoming, NW Colorado and NE Utah (modified after Smith et al., 2008), showing the study sites

Lacustrine sediments of the Green River Formation were deposited in interconnected foreland basins along the Front Range 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 almost 2 km thick, in Wyoming, Colorado and Utah (Bradley, 1964; Dickinson et al., 1988; Roehler 1993; Smith et al., 2008). These sediments host several, laterally extensive deformed horizons, which were identified on outcrops. Deformed layers are found above and below by undeformed beds of similar facies with horizontal bedding plane surfaces, which imply short-lived, recurring events that effected only sediments with a susceptible rheological state at the time. The presence of the undeformed beds is useful to discard possible autokinetic trigger mechanisms, such as internal and ordinary sedimentary and/or erosive processes. The style of deformation 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. The variation in size, morphology and areal extent of the deformation features can be explained by the thickness changes and/or lateral facies variations.

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 definitely to seismic events have not previously been identified.

Sediments deposited in lacustrine environments are regarded as particularly suitable deposits for the analysis of soft-sediment deformation features induced by shaking during ancient earthquakes (seismites - Seilacher, 1984) (Rodríguez-Pascua et al., 2000; Moretti & Sabato, 2007). Their heterolithic nature 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). Soft- sediment deformation features induced by earthquakes are indicative of synsedimentary tectonism. As a result these features can provide information about the location, timing, and intensity of the movements of structural elements in the study area (e.g. Weidlich & Bernecker, 2004; El Taki & Pratt, 2012).

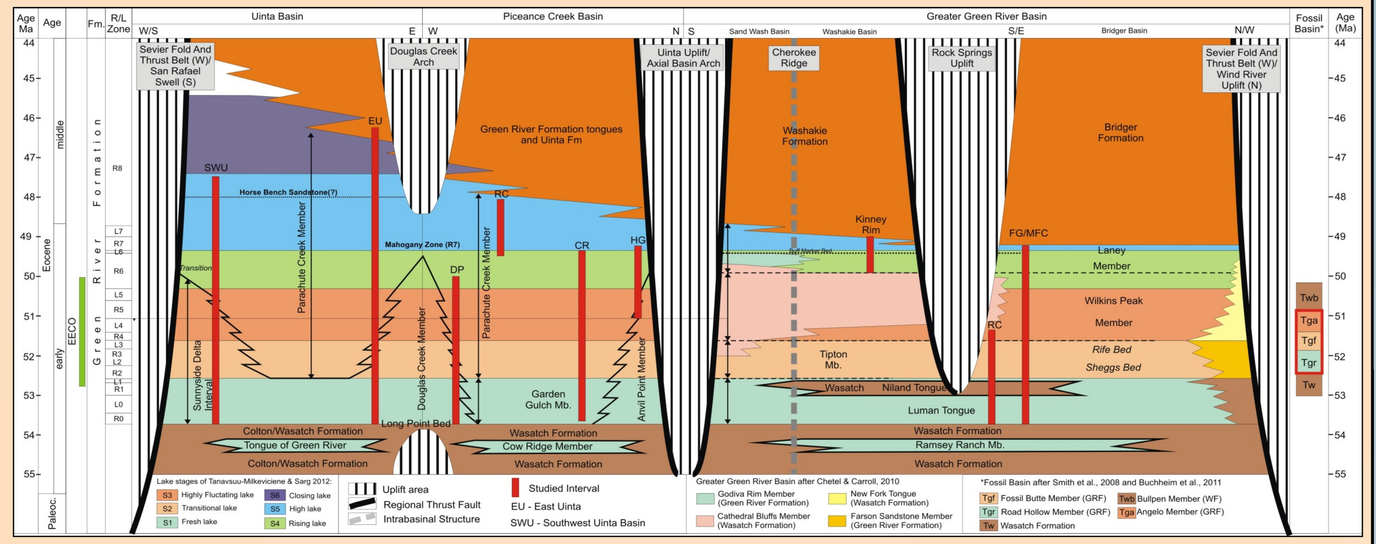


Fig. 2. Main structural elements, simplified stratigraphy and correlation of the Greater Green River, Piceance Creek and Uinta basins (modified after Smith et al., 2008; Chetel & Carroll, 2010; Tänavsuu-Milkeviciene and Sarg, 2011), with the studied intervals

2. Fossil Basin (WY)

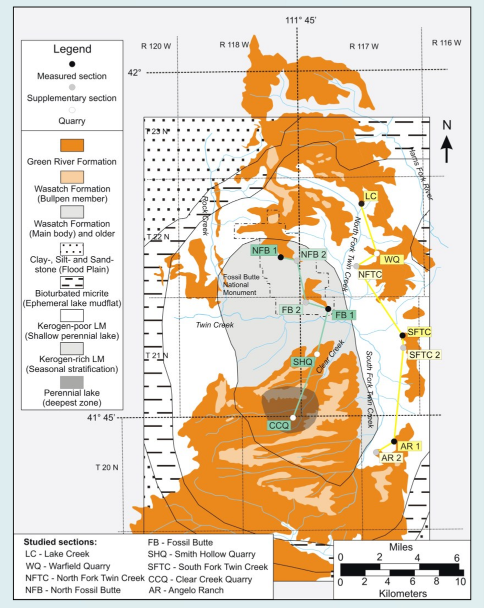


Fig 3. Studied locations and paleoenvironments of Fossil Lake during the lower part of the Fossil Butte Member (after Buchheim & Eugster, 1998)

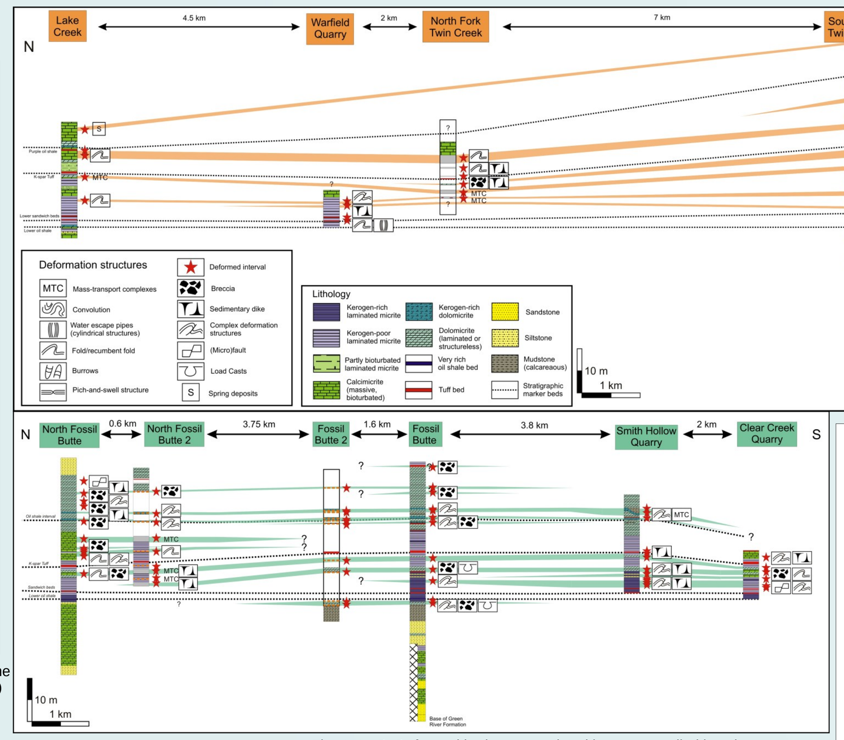


Fig. 4. A - B. Deformed horizons correlated between studied locations showed on Fig 3 (stratigraphic sections N-Fossil Butte, Fossil Butte, Clear Creek Quarry, Angelo Ranch, and Lake Creek after Buchheim & Eugster, 1998; Buchheim et al., 2011). Note: distance between 'North Fossil Butte' and 'North Fossil Butte 2' locations is not to scale.

The lacustrine deposits of the Fossil Basin in SW Wyoming offer a great opportunity to study and correlate deformed horizons within longer distances (up to 25 km). The thickness of lacustrine sediments deposited in the Fossil Lake is up to 120 m. As a result of the deposition in a small and relatively shallow lake, the thickness and depositional facies of the Green River Formation change rapidly within short distances. These facies transitions are better exposed and easier to study than in other basins of the Green River Formation. Correlation of extensive deformed intervals is aimed by the presence of numerous stratigraphic marker beds. Laterally extensive deformation features were also described by several authors (e.g. Buchheim et al., 2011), however they were not linked to tectonic events.

Extensive deformed intervals are interpreted to be the result of tectonic movements along the nearby Absaroka and Hogsback thrusts.

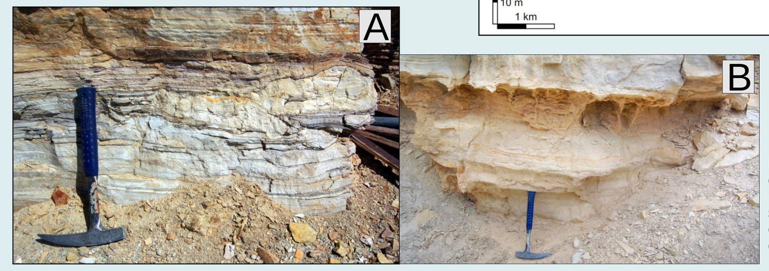


Fig 5. Sedimentary injection features in profundal laminated carbonate mudstone deposits. A. Bulbous dike filled with carbonate mud in organic rich oil shale, formed by segregation during seismic shaking and dewatering; B. Sedimentary dikes filled with calcareous silt and sand are penetrating downward from an irregular discontinuity surface.

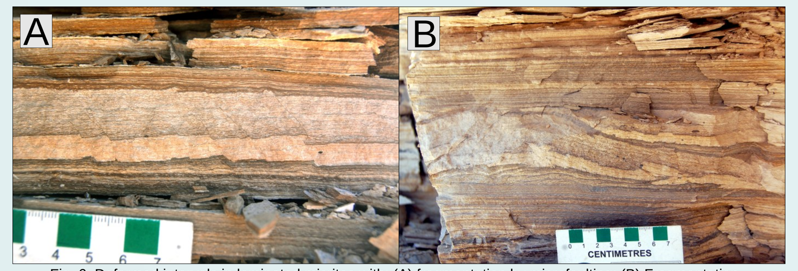


Fig. 6. Deformed intervals in laminated micrites with: (A) fragmentation by microfaulting; (B) fragmentation and folding. Sharp, erosive top indicating deformation after shallow burial. Fossil Basin, Wyoming.

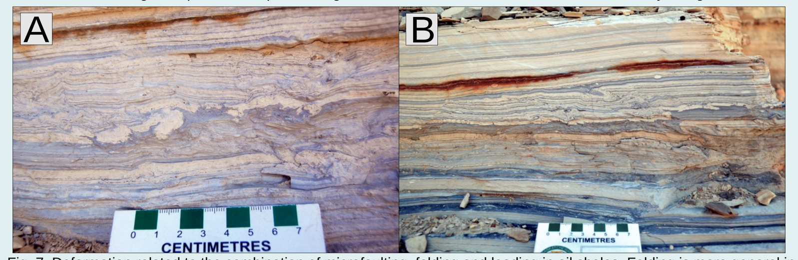


Fig. 7. Deformation related to the combination of microfaulting, folding and loading in oil shales. Folding is more general in the blue, organic-rich intervals, with continous lamination, while the white, organic-lean parts show fragmentation, thrusting. A. Organic lean interval also shows loading into a massive, structureless part indicating liquidization of the sediment.

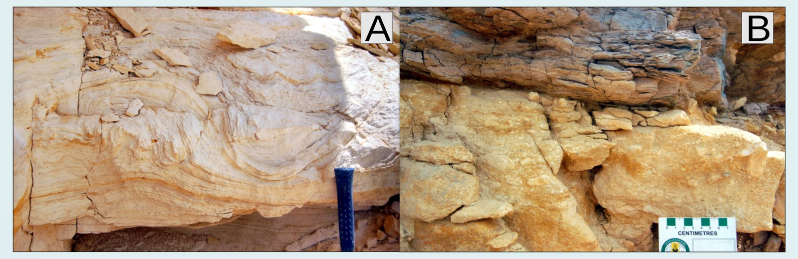


Fig. 8. A. Convoluted profundal laminated lime mudstone (micrite). B. Inverse graded brecciated lime mudstone bed (mass transport deposit) with large (> 15 cm) clasts on the top. The layer is capped by deformed organic rich oil shale bed.

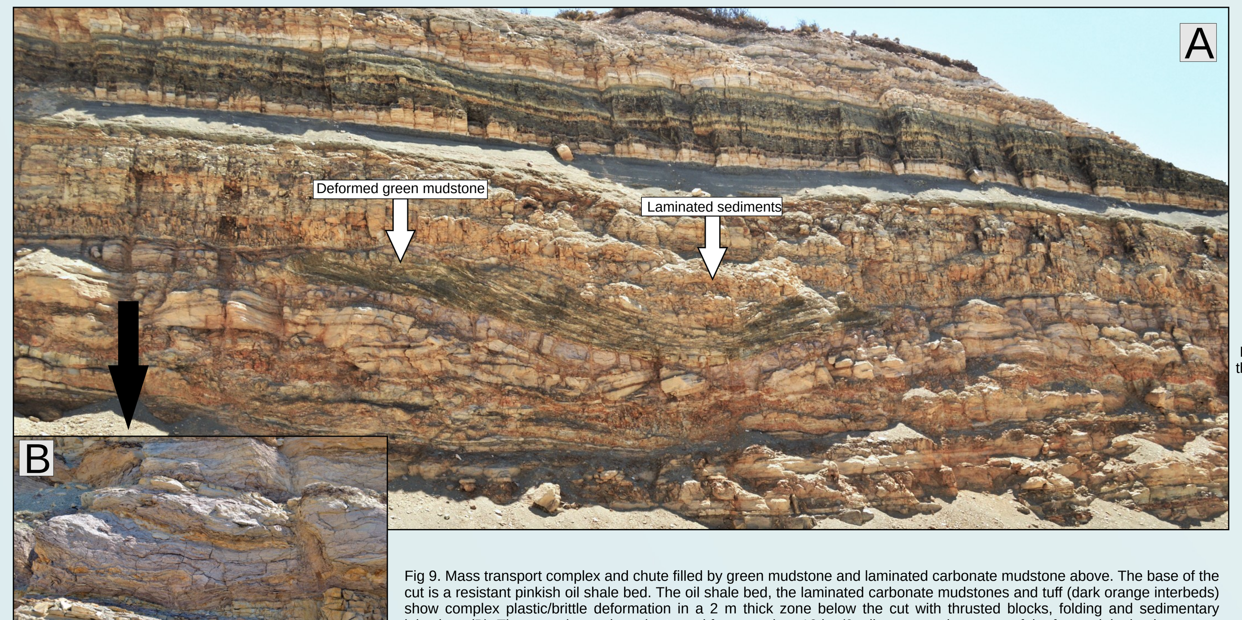


Fig 9. Mass transport complex and chute filled by green mudstone and laminated carbonate mudstone above. The base of the cut is a resistant pinkish oil shale bed. The oil shale bed, the laminated carbonate mudstones and tuff (dark orange interbeds) show complex plastic/brittle deformation in a 2 m thick zone below the cut with thrusted blocks, folding and sedimentary injections (B). The same interval can be traced for more than 10 km/6 miles across the centre of the former lake basin.

3. Tipton Shale - Wilkins Peak Member boundary (Bridger Basin)

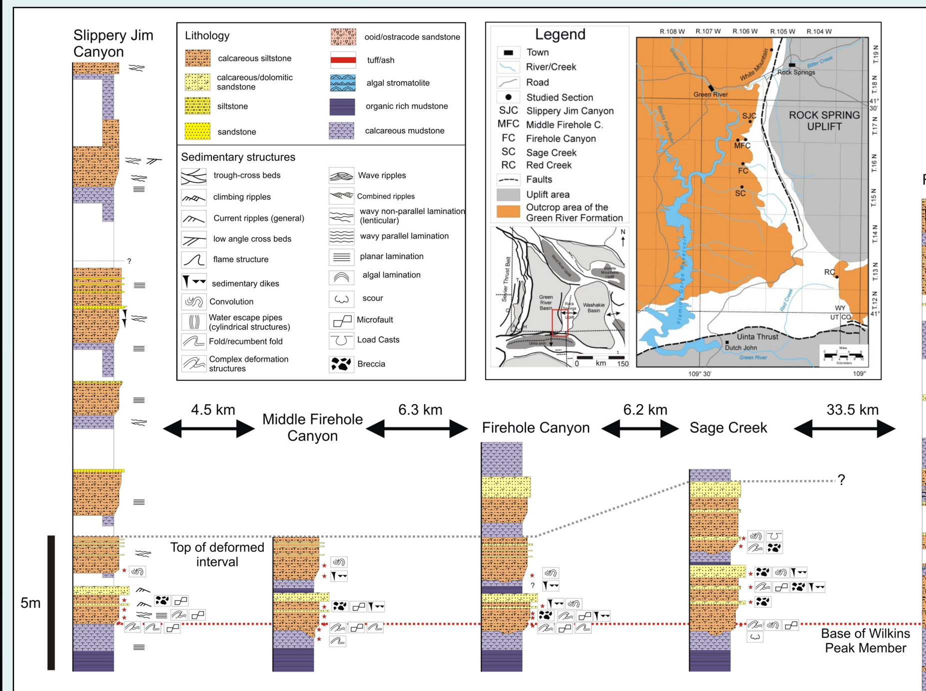


Fig. 10. Studied locations, Eocene faults and measured stratigraphic sections from the eastern margin of the Bridger Basin, WY.

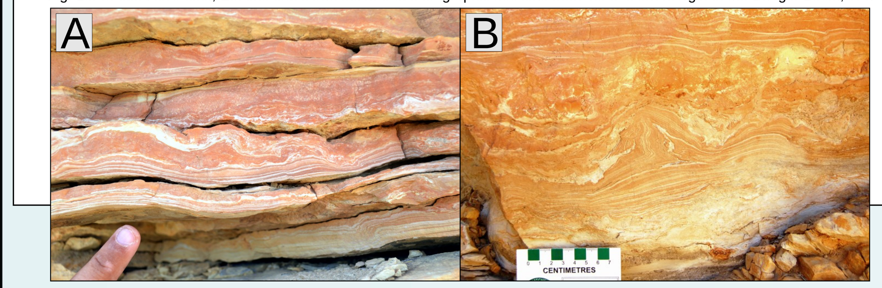


Fig 11. Lowermost deformed interval at Slipper Jim Canyon with plastic features indicating liquefaction and microfault. B. Lowermost deformed interval at Middle Firehole Canyon, showing complex deformation (fault related folds) in a mixed layer.

- The boundary of the Tipton Shale and Wilkins Peak Member contains at least 5 well defined deformed interval in two coarsening upward cycles of sublittoral sandy calcareous siltstone/ silty mudstone deposits.
- Each interval could be traced for more than 20 km. In general the lower 3 deformed intervals show mainly plastic or brittle-plastic deformation. Upsection the brittle behaviour is dominant.
- Coarsening upward sedimentary cycles with similar depositional environment higher in the sections showed no deformation, which indicates an allokinetic trigger.
- Further to the north, on White Mountain, deformation structures could not be observed as a result of facies changes into recessive sediments with a lack of good exposure.
- At the Red Creek area, closer to the Uinta Fault system, the Tipton Shale Member is represented by sediments deposited closer to the former lake margin and the boundary between the two members less obvious. The boundary was indicated by the first appearance of extensive and large-scale sedimentary dikes in silty mudstone deposits.

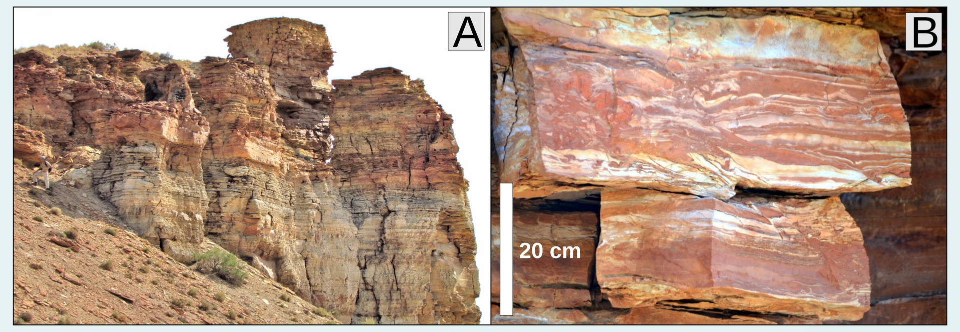


Fig. 12. A. Outcrop of the Tipton Shale-Wilkins Peak boundary at Firehole Canyon, with two coarsening upward cycles (indicated); B. Brittle-ductile deformation in the second deformed interval, with thrusts, brecciation (upper left & lower right), slight folding and sedimentary injections (on the left)

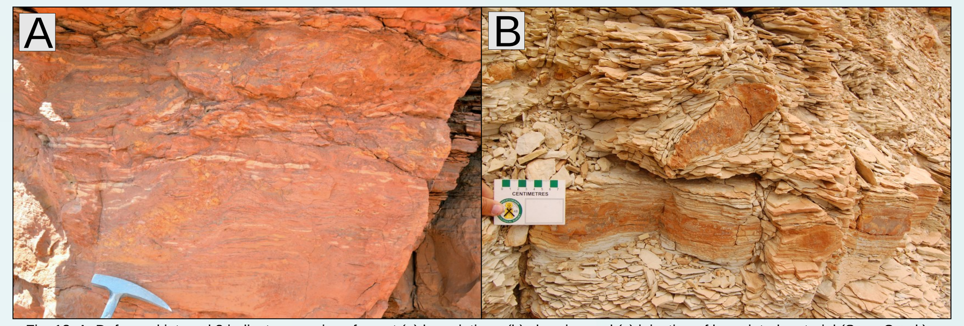


Fig. 13. A. Deformed interval 3 indicates a series of event (a) brecciation - (b) shearing and (c) injection of brecciated material (Sage Creek); B. Large isolated crack filled with silicified brecciated material (Red Creek). Note the smaller horizontal sill on the left.

4. Washakie Basin (WY) - Laney Member

- Sedimentary dikes identified in the Laney Member of the Washakie Basin are up to 1,5 m long and several cm wide, filled with homogeneous mudstone or a mixture of fragmented material of mud, silt, sand, massive or laminated chert, and fragments of lacustrine sedimentary rocks and tuff material.
- The crack-fill is generally silicified, and many times a central conduit can be observed, filled with massive or laminated chert/calcite.
- The source of the crack fill is frequently a brecciated/rip-up layer or massive silty mudstone.
- Cracks show moderate sinuosity, branching, multiple fillings, brecciated internal structure, and their overall width decreasing downward and/or upward in laminated oil-shales or micritic mudstones.
- In many cases the cracks are represented by isolated bulbs or horizontal sills.

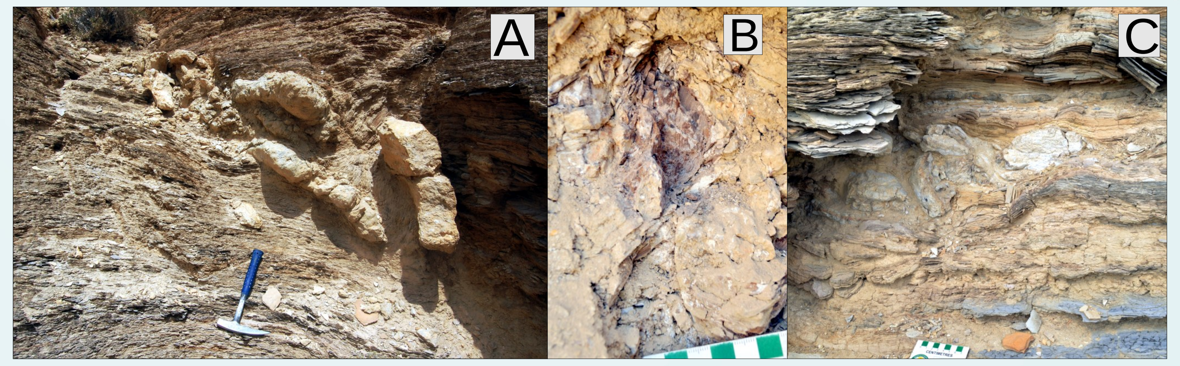


Fig. 14. Characteristics of sedimentary dikes in organic rich and lean laminated lime mudstone deposits of the Laney Member, Washakie Basin: A. Dike at the base of the Buff Marker Bed filled with fragmented material showing multiple filling (AC); B. Dike with a central conduit filled with laminated chert (SB); C. Weathered dike (sill) indicates intrastratal, horizontal injection (SB)

- Rhodes et al. (2007) interpreted these cracks as the result of desiccation that occured 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.
- Cracks are more frequent and larger in size at the base of a regional marker bed, the Buff Marker Bed. Their morphological characteristics are similar to the ones, found in several other stratigraphic levels in the Laney Member, which suggests a common, tectonic origin.

Fig. 15. Characteristics of sedimentary dikes in laminated lime mudstone deposits of the Laney Member, Washakie Basin, Wyoming: A. 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 at its base (SB).

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

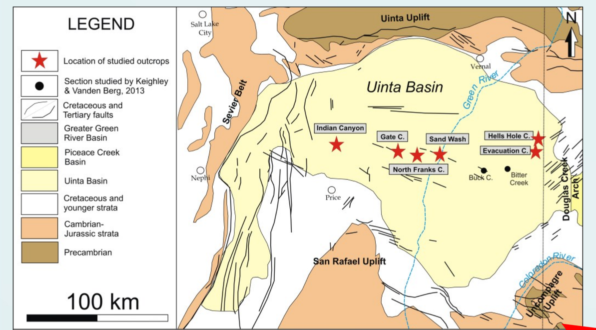


Fig 16. Studied locations of the Mahogany Oil Shale Zone and major fault zones of the Uinta Basin.

- Pervasive deformation features were investigated across the Uinta Basin in the Mahogany Oil Shale Zone (MOSZ), an extensive stratigraphic marker in the Piceance Creek and Uinta basins (CO, UT), which contains several organic rich shale beds.
- Deformation style ranges from brittle (fragmented/faulted beds) to plastic (convolution/folding), to 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 indicates a regional tectonic event, which caused dewatering, hydrofracturing and slope instability/slumping at different parts of the basin.

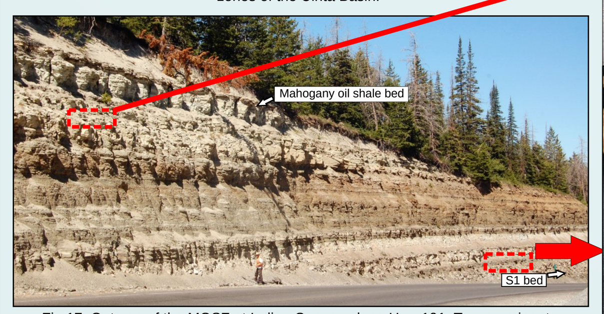


Fig 17. Outcrop of the MOSZ at Indian Canyon along Hwy 191. Two prominent deformation zones are marked with red.

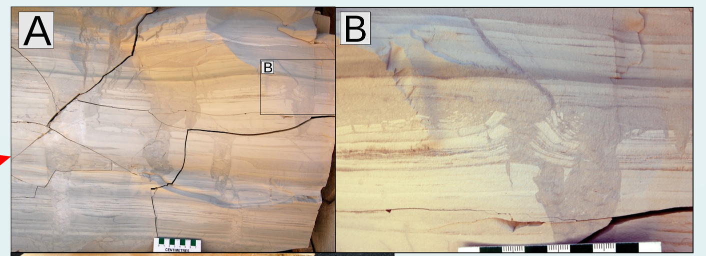


Fig. 18. Sedimentary injections in subtidal silty lime mudstones showing multiple fluidization events and hydrofracturing, Indian Canyon. B. Fragmentation and upward bending of the sediments indicate upward fluid movement

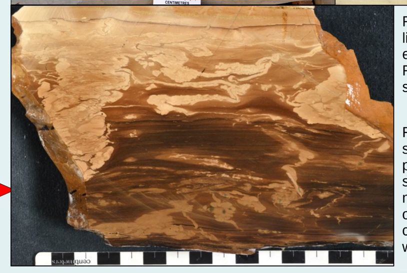


Fig. 19. Sedimentary injections ("dewatering structures"), filled with carbonate mud, in profundal rich oil shales; Indian Canyon. The source is an organic-poor, massive carbonate mudstone layer. Injections form bulbous oriented dikes and irregular sills. In many cases these structures are isolated without a well defined source.

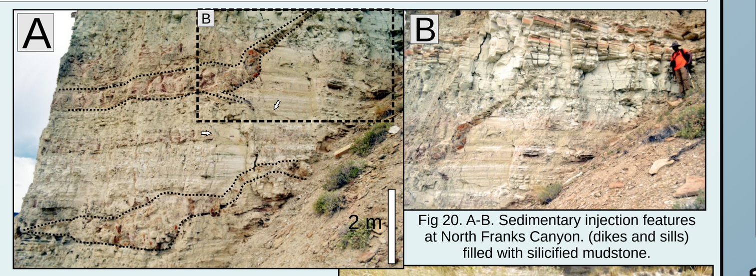


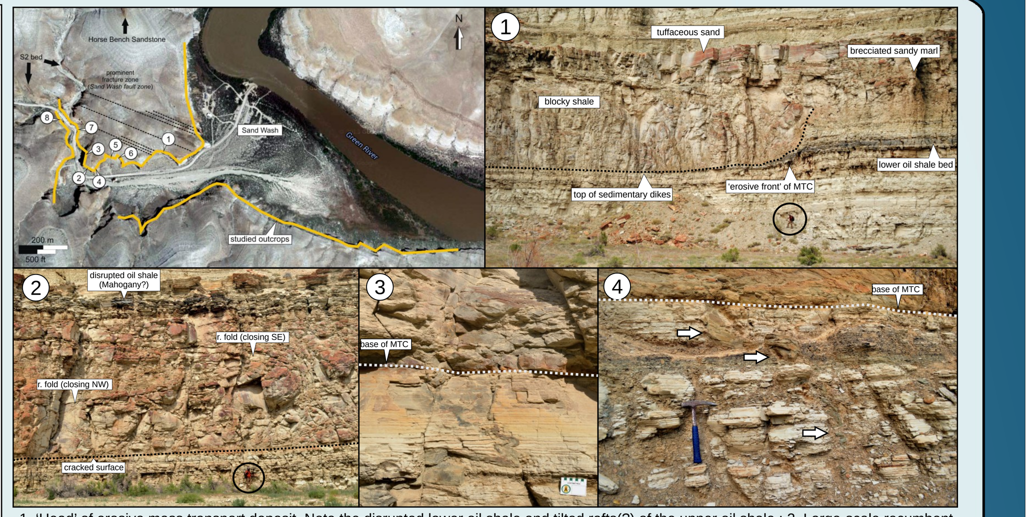
Fig. 20. A-B. Sedimentary injection features at North Franks Canyon. (dikes and sills) filled with silicified mudstone.

Stress indicators:
- **Indian Canyon**: joints - E-W extension; N/NNE compression/shear.
- **Gate Canyon**: N-ward shear; ext. tow. ~170 and ~120 striking joints
- **North Franks C.**: E-W extension; shear movement towards N & S

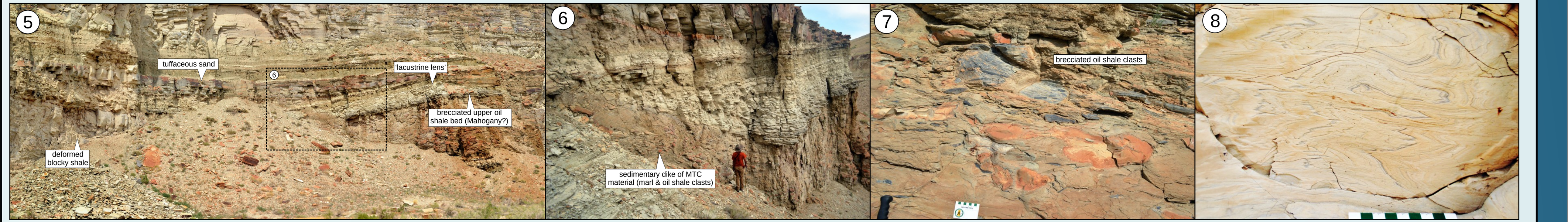
Fig 21. Sheared fabric in the Mahogany Bed at Gate Canyon, showing en-echelon fabric; shear related propagation folds, kink and sheat folds, shear duplexes and thrusting.

Sand Wash

- At Sand Wash the Mahogany Oil Shale Zone hosts a 4-10m 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 dikes either the base of the MTC, or horizons within the deformed lake sediments
- At many places a distinct, rich oil shale bed forms the basal boundary (e.g. 1), 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, 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 continous and intact, however even at those places it shows brecciation and small-scale disruption.
- Locally the upper oil shale bed is overlain by irregular, lens shaped lacustrine succession and/or orange tuff layer, mixed with organic-rich and lean oil shale and tuffaceous sediments, showing brittle-plastic deformation.
- This upper lacustrine succession is overlain by an undeformed (ledge-forming) wavy-bedded tuffaceous sand- and siltstone.
- The MTC indicates a large-scale slumping event and the instability of profundal to sublittoral sediments, which might have related to tectonic activity along the Sand Wash Fault Zone.



1. 'Head' of erosive mass transport deposit. Note the disrupted lower oil shale and tilted rafts(?) of the upper oil shale.; 2. Large-scale recumbent fold in the MTC interval, below rafts of Mahogany Bed?; Silicified mudstone (3) and siltstone (4) dikes below the MTC zone



5. Lens of brecciated lacustrine sediments above the deformed interval; 6. Part of picture 5, showing intrusion into the lacustrine sediments; 7. Oil shale clasts in the silty/marly matrix of the MTC with injection features and brecciation; 8. Deformed oil shale clasts in the MTC.

Evacuation Creek

- 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, folding, and thrusting.
- Deformation dies out quickly within a NE- SW direction.
- Structures indicate shear/slump towards SW (~230)
- 10- 25 cm thick sheared zone was also found on the top of the Mahogany Bed (Fig. C), with similar structures and stratigraphic position as at Gate Canyon 100 km W

Hells Hole Canyon

- Several well defined, and traceable brecciated and/or plastically deformed horizons
- Sheat folds with clear indication of the stress field showed shear/compression to WSW (~245)

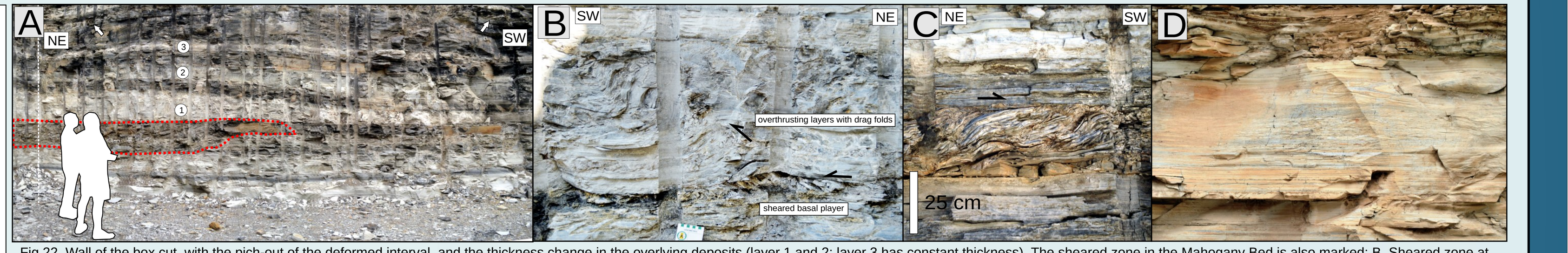
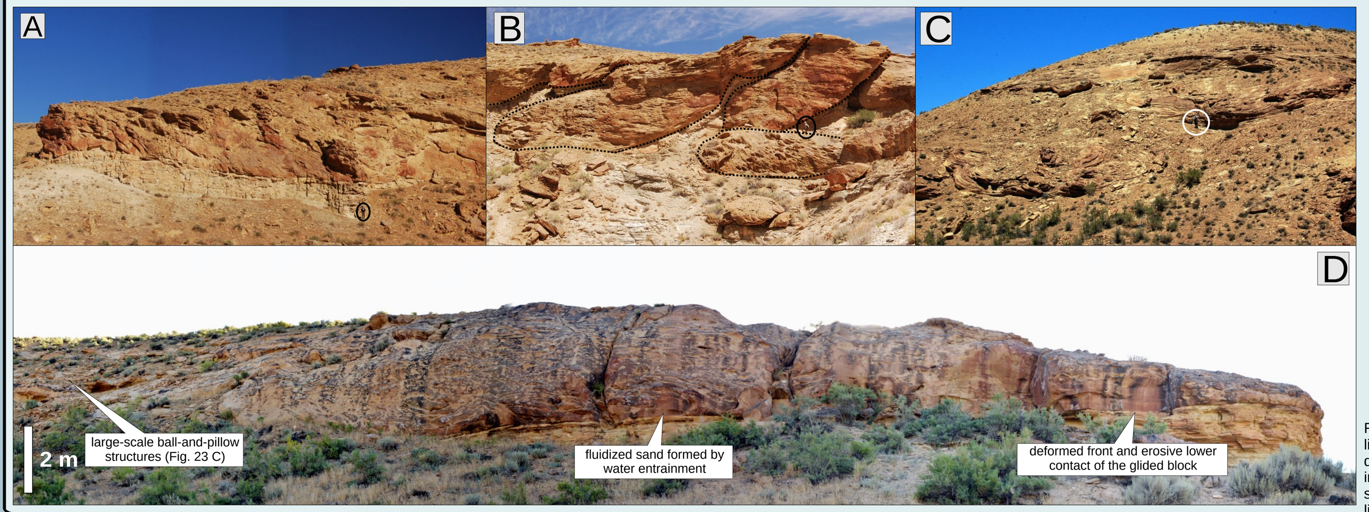


Fig 22. Wall of the box cut, with the pich-out of the deformed interval, and the thickness change in the overlying deposits (layer 1 and 2; layer 3 has constant thickness). The sheared zone in the Mahogany Bed is also marked; B. Sheared zone at the base of the deformed interval, with thrust related folding above; C. En-echelon structure in the sheared layer of the Mahogany Bed. D. Brecciated oil shale bed (40 cm thick) with recombent folded intraclast(?) at the top at Hells Hole Canyon

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. 23 A-D)
- The sand blocks are intact or plastically deformed, with sharp, erosive lower boundary (e.g. Fig. 23 A)
- In places the blocks are separated by large diapirs of lacustrine sediments (Fig. 23 B)
- At other places the boundary marked by large-scale liquidization (ball-and-pillow) structures (Fig.23 C) and hydroplaning (Fig.23 D)
- Deformation/shear structures indicate a S-ward displacement of the exotic sandstone blocks
- Seismicity along the Douglas Creek Arch and related fault systems might have caused emplacement of (semi)lithified deltaic sand bodies on the N/NE
- Similar features are also present in northern Colorado (at the base of Uinta rocks), and in Wyoming (base of Sand Butte Bed in the eastern Bridger/Green River Basin)

Fig. 23. A. Large-scale crossbedded sandstone block with angular lower contact, above the laminated silty lime mudstones of the Green River Formation; B. Sandstone blocks on the top of lacustrine mudstone deposits. 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-scaleball-and-pillow structures, near Watson; D. Outcrop shows the hydroplaning and fluidization of semi-lithified glided sandstone block.

7. Conclusions

- Pervasive horizons of seismically induced deformation structures were identified in the profundal lacustrine sediments of the Eocene Green River Formation, USA.
- Deformation is represented by brittle and plastic behaviour, as well as sediment injection and mass transport.
- The deformed layers 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; (4) their recurrence at different stratigraphic levels, intervals showing large-scale sedimentary deformation structures are interpreted as result of in-situ loss of shear strength, 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 of the sediment. 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 gently dipping slope. Oversteepening, loading and slumping of the sedimentary slope are also possible triggers of mass movements. However, the morphology of the slope existing in the basins during the time of deposition was unknown and information on the slope gradient in the basin center varies in the literature (0.2 to 0.6 m/km to 1-2° (17-35 m/km); e.g. Dyni, 1981).
- Features in the MOSZ indicate a basin-wide tectonic event in both the Piceance Creek and Uinta Basin.

As soft-sediment deformation features induced by earthquakes are indicative of synsedimentary tectonism, these deposits can **provide information about the location and timing of the tectonic movements along nearby fault systems** in the lake sub-basins. Small-and large-scale deformation features and deformed oil shale intervals may have significant effects on the horizontal and vertical permeability and connectivity of the oil shale beds. Moreover, large scale clastic dikes may affect local and regional hydrology of an area. Clearly, synsedimentary deformation is an important but hitherto neglected aspect of the sedimentary and petroleum geology of the Green River Formation.

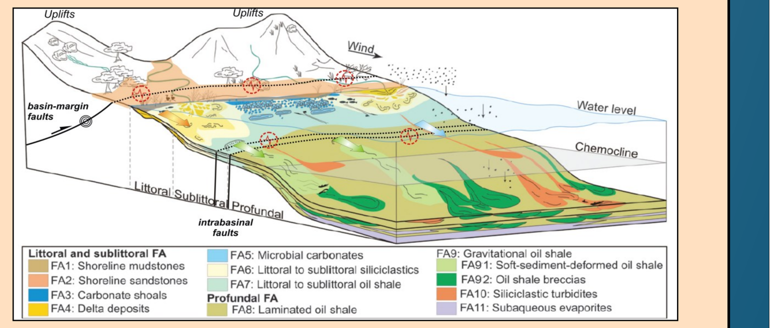


Fig. 24 Proposed concept illustrating the origin of mass movement deposits and other sedimentary deformation features, triggered by earthquakes (depositional model modified after Tänavsuu- Milkeviciene and Sarg, 2012)

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