Stratigraphy, Exploration and EOR potential of the Tensleep/Casper Formations, SE Wyoming

Steven G. Fryberger, Nick Jones, Matthew Johnson and Curtis Chopping

Enhanced Oil Recovery Institute, University of Wyoming. 2016

Summary

There are two main themes of this poster.

The first theme is to provide an update on the stratigraphy and sedimentology of the Tensleep/Casper Formation of Southeast Wyoming (and parts of Northern Colorado), and oil production from these rocks. We incorporate new measured sections, stratigraphic analysis and petrographic work undertaken by the authors. To this end we created a new database in ArcGis (geographic information software) of tops and other information that updates the historical well database of the Wyoming Oil and Gas Commission archived in Casper. This new database has been used to create Common Risk Segment (CRS) maps of the Upper Tensleep oil play in Southeast Wyoming. These CRS maps indicate trends in Tensleep reservoir, charge and trap that are useful in planning further exploration. It is possible that use of advanced seismic techniques applied over the complex structural terrains in the identified high potential areas of SE Wyoming will produce new leads and ultimately, new discoveries.

The second theme of this poster is to describe the occurrence in outcrop and core, of various flow units and discontinuities produced by reservoir heterogeneity associated with depositional facies in the Tensleep. We have created simple models of the mechanics of the impact of eolian primary strata, mainly ripple and avalanche strata, on recovery factors in eolian reservoirs. Ultimately we plan to improve our models, undertake experimental work and based on our data develop engineering formulas that allow more reliable estimates of recovery factors. These will take into account the impact of primary strata anisotropy, and crossbed dip direction. We continue to compile data on the abundance and arrangement of primary eolian strata – as well as small scale flow units- in outcrops and core in the Tensleep. This descriptive work is a necessary step in order to control digital flow models run in Petrel, Eclipse or other software, or to develop new software that will improve estimates of recovery factors. The history of Wyoming includes much down-spacing of oil fields to produce bypassed reserves; and implicitly to correct originally over-optimistic estimates of recovery factors that stipulated widely spaced wells and inappropriate EOR (usually waterflood) designs.

Eolian petroleum reservoirs are of course, not unique to Wyoming although this state has an abundance of them; for example the Tensleep, Leo, Minnelusa Casper, Leo, Nugget and Sundance Formations. Eolian reservoirs worldwide commonly provide long-lived, high-volume production of both oil and gas, and importantly for Wyoming, provide new ideas from around the world that can be applied to similar reservoirs in Wyoming. As with any geological rock unit, each oil/gas field has production characteristics peculiar to its geological history. However, certain common factors link most eolian reservoirs. Cross-stratification due to bedform migration can create preferred sweep directions and thus impact recovery factors. Moreover, stacking of sand seas or bedforms through geological time will create distinctive flow units in subsurface petroleum reservoirs. We hope our work will enable these general observations to be evaluated quantitatively.

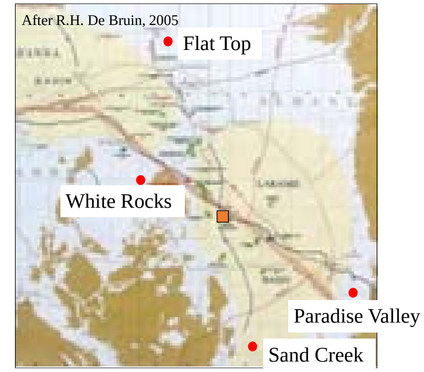
Conclusions: Tensleep Stratigraphy Southeast Wyoming

- The Tensleep and Casper Formations comprise the same rocks in SE Wyoming.
- The Tensleep Formation can be divided into a mainly eolian Upper Tensleep member and a carbonate rich, paralic and eolian Lower Tensleep Member.
- The Upper and Lower Tensleep of this study probably correlate to the Hyatt Ranch (Upper Tensleep) and Medicine Lodge (Lower Tensleep) Members of the Big Horn Basin, although that is not confirmed by this study.
- The Upper Tensleep is mainly Permian, the Lower Tensleep is Pre-Permian. Lithological change between Upper and Lower Tensleep was probably driven by climate changes from Upper Carboniferous time into Permian times.
- The Upper and Lower Tensleep Members are recognized regionally in SE Wyoming.
- The "Fountain" inter-bedding with Tensleep occurs mainly in the Lower Tensleep, close to pre-Permian uplifts.
- Oil Production is mainly from the Upper Tensleep in structural traps.
- Shallow marine carbonates inter-tongue with the Upper Tensleep (Permian) occurs along the Laramie Range.

Conclusions: Petroleum exploration, production and sedimentology Southeast Wyoming

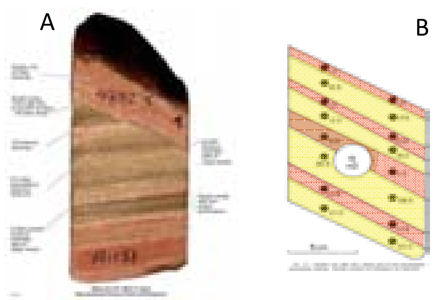
- Common Risk Segment analysis of SE Wyoming Tensleep oil shows, structure and reservoir quality has identified four regions near existing production that may still have opportunities for further exploration using improvements exploration technology.
- Oil production in SE Wyoming occurs in a variety of stages from primary through tertiary (EOR), as well as various states of IOR (mechanical upgrades). There may development opportunities in existing fields.
- The State of Wyoming well database is a valuable asset. EORI has used this trove create to a digital database of tops and other data that updates older (historical) tops in the State of Wyoming database, using modern stratigraphic concepts. This database will be made public, and may lower informational barriers to oil industry activity in Southeast Wyoming.
- Much oil in the Tensleep may be trapped in microscopic, or very small stratigraphic traps created by primary eolian strata and flow units derived from small dunes.
- EORI is working on ways to calculate oil trapped by eolian primary strata, and devise strategies to produce it. We are using t static and dynamic models, and rock experiments along with natural outcrops and field studies. We hope this will help to guide down-spacing and other strategies both old and new to improve recovery of oil from Wyoming fields.

The Permian Upper Tensleep Formation at Flat Top Anticline near Medicine Bow, Wyoming. Several measured sections here are being used to create a model of the outcrop as a petroleum reservoir. Our observations on heterogeneity are helped by the fact that the lower half of the outcrop is oil saturated, which makes variation in oil saturation visible. Unsaturated laminations and beds tend to be red or white, whereas oil saturated portions of the outcrop are brown beneath a thin "whitish" layer of degraded oil.

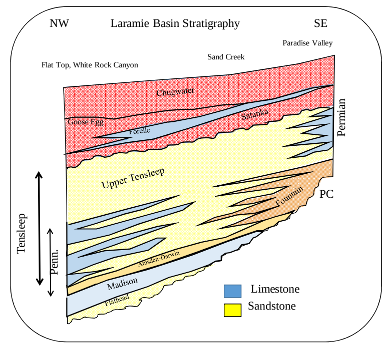


Laramie and Eastern Hanna Basin Oil Fields with location of key sections measured for this report. Red square marks Quealy Dome oil field.

Reservoir heterogeneity caused by eolian primary strata



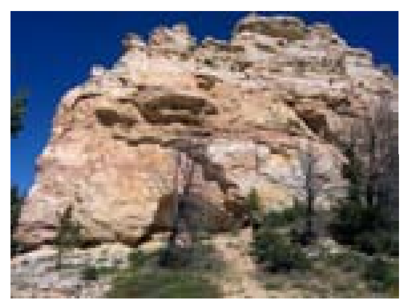
Much of the critical flow effects of eolian cross bedding and cross strata are due to strong differences in porosity and permeability between individual laminations, as illustrated in the two figures above. The isolation of permeable laminae by tight laminae may drastically reduce sweep efficiency in rocks that, on standard logs and core plugs, appear quite permeable. These microfabrics also, potentially, create anisotropic sweep tendencies in the rocks. A. On the left, brown laminae are oil saturated. White laminations have probably been reduced by the presence of oil, but are very low permeability. Red laminations have no oil. B. On the right we reproduce an excellent illustration from Weber (1987) showing the variability of permeability at laminar scales due to primary stratification.



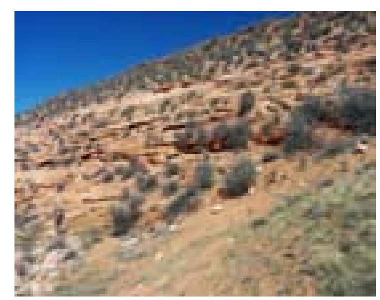
Schematic cross section showing the stratigraphy of a portion of the Permo-Pennsylvanian rocks of SE Wyoming. This section shows the interbedding of marine carbonates with the Upper Tensleep along the Laramie Range. Most common is the presence of carbonates in the Lower Tensleep farther west. Approximate locations of measured sections indicated above the diagram.

Tensleep (Casper) Formation at Sand Creek,, in the Southern Laramie Basin, Wyoming. View to the north.

The Ingleside Formation (Casper-Tensleep correlative) at Owl Canyon, Colorado. Two sections were measured in this area for comparison with nearby Wyoming outcrops. View to the east.



Complex stacking of genetic (crossbedded) units in the Tensleep Formation at White Rock Canyon near Arlington, Wyoming



Upper Tensleep (Casper) Formation at Paradise Valley, Laramie Basin, Wyoming. Exposure is on private land, one should seek permission before visiting this outcrop.

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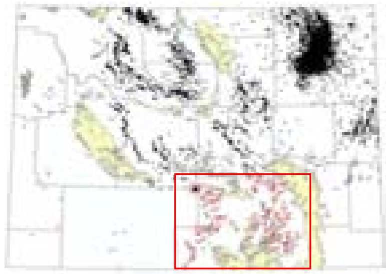
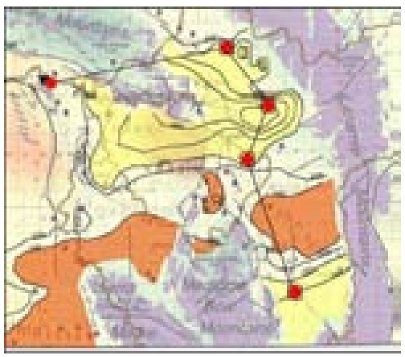
Cross section

Tensleep penetrations used for this study

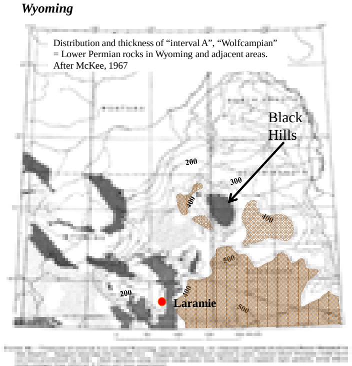


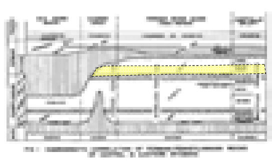
Index map of Wyoming and counties, showing State database of Tensleep Penetrations (Tensleep, Casper, Minnelusa). Our study area is shown by red box with Upper Tensleep Thickness posted. Not every Tensleep penetration was used in our regional study. Older wells with poor logs or little data were omitted, as well as dense grids intra-field wells such as those at Wertz and |Lost Soldier.



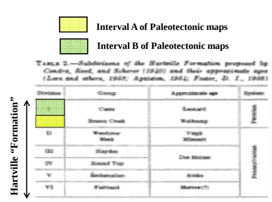
Index map of the cross section shown on the right. Base map is the basement map of Wyoming, and Upper Tensleep thickness.

Lower Permian (Wolfcampian) isopachs In Eastern Wyoming



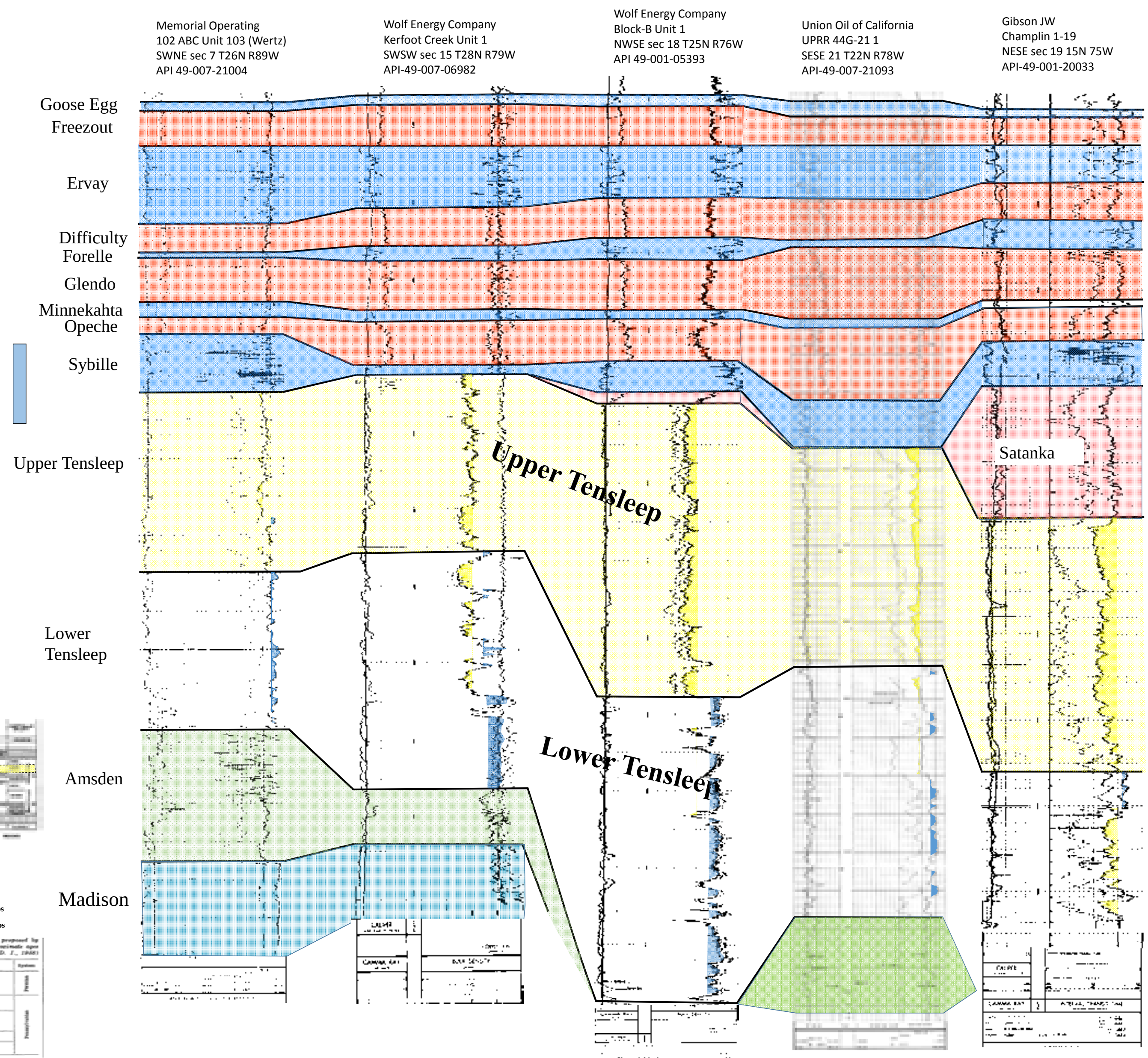


Regional unconformities in the Permo-Pennsylvanian rocks of Wyoming. After Foster, 1958



Subdivisions of the Hartville Formation, SE Wyoming. After McKee et al, 1967

Regional Tensleep Stratigraphic cross section



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Sand Creek, Wyoming Measured Section

The Sand Creek measured section was chosen at a locality that shows the transition upward from the red siltstones and arkosic fluvial sands of the fountain to the eolian dunes of the Casper (Tensleep). The section is relatively complete, lacking only the upper 50 feet or so of Casper below the Satanka red beds. There is a major change in wind direction from northward to south- and southeastward at unit 16. The section is a whole is a classic "cleaning upward" section, reflecting both the sorting of older fluvial sediments from the fountain, and in the end, the arrival of long-distance sand transported from the Permian sand sea to the north. To the north, at a nearby well, the (Penn) Fountain formation has thinned and disappeared. This is typical of the Fountain in the Laramie basin, that does not seem to extend very far northward or westward of the old Pennsylvanian age uplifts.

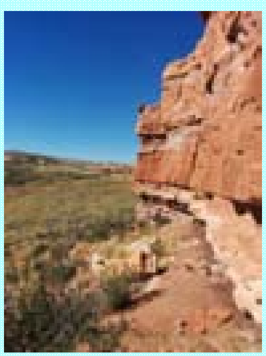
Fluvial and pond sediments

A carbonate pond deposit with wavy, irregular bedding. This is probably a local deposit within an arid dune field where fresh water table is close to the surface. Bioturbated but no direct evidence of evaporites. Found at about the level of sample 7C in the measured section.

An interdune carbonate pond deposit (arrow) in the upper part of the measured section, immediately below the sabkha shown on the cross section (near sample 11, blue colored unit). In this outcrop the carbonate depositing "ponds" was discontinuous laterally, extending perhaps 200 m. Note pinch out along bounding surface. Sabkha above (flat bedded unit) was more extensive, as visible in this view. Eolian dunes (white) cap the skyline.

A fluvial channel filled with sandy red mud, cut into fluvial sandstones, in Tensleep (Casper). Base of channel is marked by white arrow. This sort of stratigraphy is typical of the lower Tensleep

A soil horizon in flat bedded (fluvial?) sands; with rhizocretions, bioturbation from plants and some clastic dikes. White arrow marks where soil zone is overlain by eolian dunes.

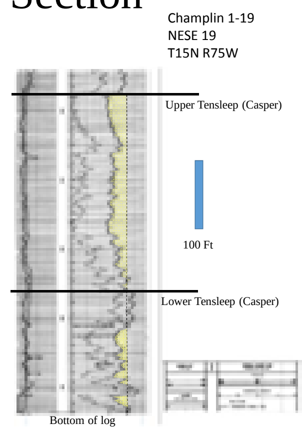


A view near the base of the measured section, showing mostly fluvial deposits of Upper Fountain-Lower Tensleep. View to the south.

Fluvial deposits consisting of coarse sandstone and conglomerate, with mud (rip up clasts). This muddy, arkosic section was formed by recycling older Pennsylvanian Fountain Formation lithologies and the Front Range granites.

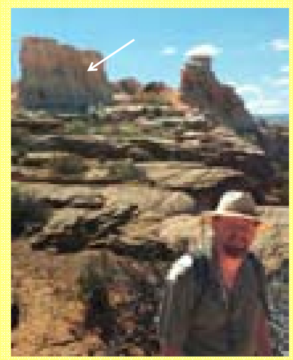
Eolian sediments

Eolian avalanche and ripple primary strata in the Upper Tensleep (Casper) Formation. Below, flat bedded ripple strata with pin-stripe laminations and inverse grading (arrow 1). Above the erosional bounding surface near notebook sand flow toes at base of a slipface (arrow 2) and avalanche strata with wavy pin stripe laminations that fade out along the stratum (arrow 3).

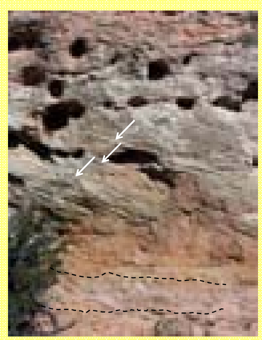


Sonic-GR log of the Upper Tensleep (Casper) in the Champlin 1-19 well (NESE sec 19, T15N R 75W) drilled north of the outcrops. A thick section of eolian dunes, very porous and permeable comprises the Upper Tensleep above the Lower Tensleep sand and carbonate section. In the short distance northward to this well, most of the fluvial recycling of Front Range PC rocks, and Fountain Formation has vanished. Thus, the Sand Canyon area provides a glimpse into thow the Tensleep sand sea interacted with the alluvial fans of the Fountain Formation.

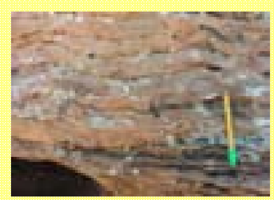
View of dome-like weathering pattern of white, quartzose eolian dunes in the uppermost part of the measured section.



Matt Johnson pauses for scale in this image of the upper part of the measured section. Arrow shows the reddish sabkha unit just above a carbonate pond deposit (blue on the measured section). Behind him the eolian cross beds from which sample SC-12 was taken.

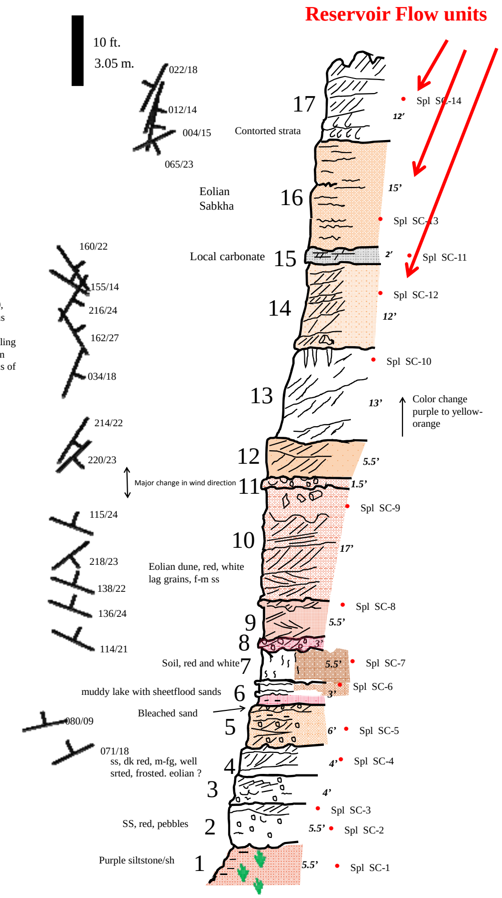


Several slightly disconformable sets of eolian avalanche strata in the Upper Tensleep (Casper) Formation in middle part of measured section. Arrows show approximate boundaries between sets. Such groups of strata can partition petroleum sweep into subtle compartments, even in avalanche strata which are commonly the most porous and permeable eolian facies. Below, pink mixed source eolian and fluvial stratification.

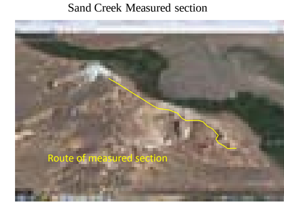


Detail view of eolian sabkha deposits in the upper part of the measured section. Such deposits form from the interaction windblown sand and a shallow water table that is moderately evaporitic. Salt crystal concentration causes expansion of surface layers and doming to form ridges, that are then filled by windblown sand, commonly through grainfall processes.

Measured section: Tensleep (Casper) Formation
Sand Creek, Albany County Wyoming
Fryberger, Jones, Johnson
Section complete except for upper 30 feet of Tensleep



Sand Creek Measured section



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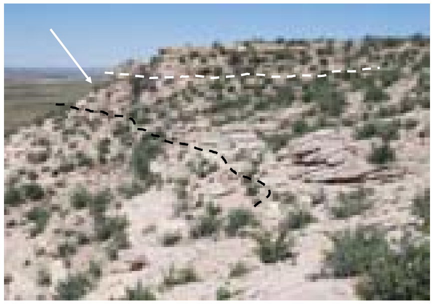
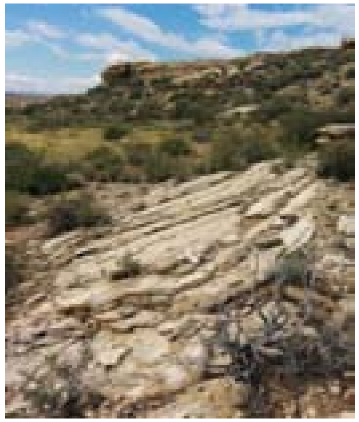
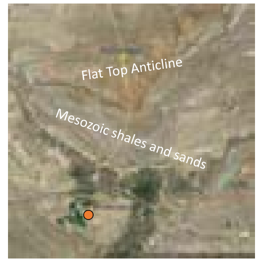
Tensleep Sandstone at Flat Top Anticline Carbon County, Wyoming (ft.)



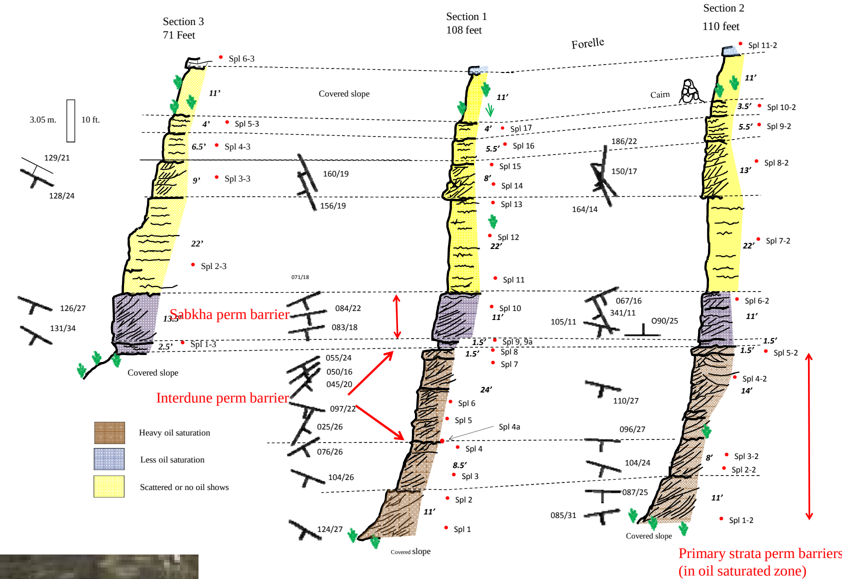
Eolian crossbedding in unit 11 (found in all three sections – arrow, dashed lines)). Unit consists of several sets of slipface deposits with interbedded ripple strata, in an approximate 60/40 APS/RPS ratio on measured section 1 (this image). Dip of cross strata is toward the southwest, view to west.

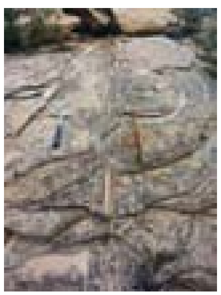


Eolian slipface deposits consisting of a mixture of avalanche and ripple strata, Unit 1, measured section 1. These sandstones are saturated with heavy, live oil. View is to the west, cross beds dip south, indicating wind from the north.



Satellite view of the Flat Top Anticline surrounded by exposures of Permo-Triassic red bed formations. East Allen Lake Oil field (red dot) in the Tensleep is just south of the town of Medicine Bow.

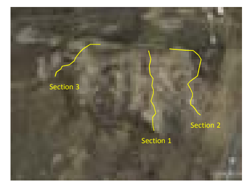




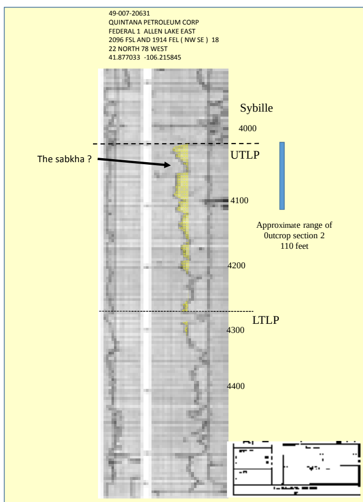
Cemented fractures typical of units 1 and 2. These bands of fractures would impede sweep of oil from left to right through this eolian reservoir. Eolian slipface deposits in this image are saturated with heavy oil. Dip of the crossbedding to toward the viewer.

Flat bedded ripple strata in Unit 2 measured section 1, showing fabric selective (white) cementation along boundaries between each ripple stratum White laminations are also known as pin-stripe laminations (Fryberger and Schenk, 1988). These fine layers cut this oil saturated sandstone into many small compartments.

Mixed ripple and avalanche strata in Unit 2 of the Flat Top measured section 1. Note that the black-brown oil saturated sand in the ripple strata is broken up into many compartments by the cemented pin-strip laminations from each stratum. This phenomenon creates microscopic barriers to flow in otherwise very porous and permeable oil reservoirs throughout the Tensleep sandstone in Wyoming.



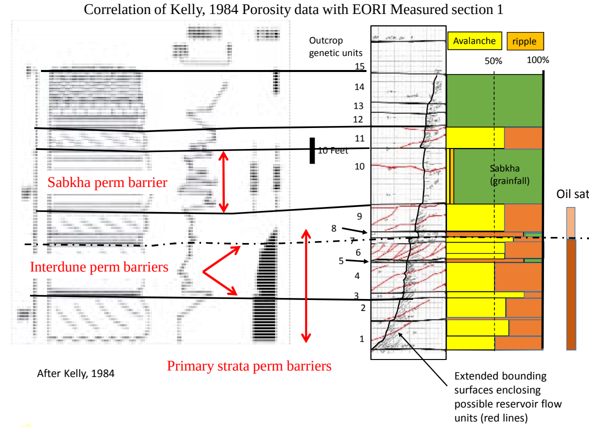
Light- colored exposures of the Upper Tensleep Formation in the core of the flat top anticline. Routes of measured sections are shown by yellow lines.

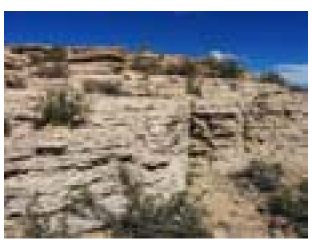


Density-GR log of the Federal 1 Allen Lake East well that penetrates both the Upper and Lower Tensleep at nearby Allen Lake East (Tensleep) oil field. The sabkha encountered at Flat Top Anticline may be present in this well (arrow).

Flat Top anticline

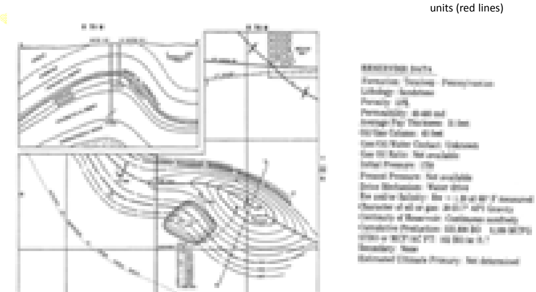
Correlation of Kelly, 1984 Porosity data with EORI Measured section 1





Eolian sabkha bedding consisting mainly of grainfall deposits in unit 10. Wavy beds are produced due to formation of salt ridges by precipitation of evaporites from near surface water table. This sequence records a long period of accretion, probably under conditions of rising water table. Such deposits may indicate proximity to the sea, which would supply halite, gypsum and anhydrite early cements through seepage-reflux.

Sandy dolomite/dolomitic sandstone in unit 14. Lithology is sabkha-like, with much more carbonate than unit 10, which is a sabkha created dominantly by eolian processes. Sedimentological origins of this dominantly carbonate body are more obscure. This may represent carbonate sedimentation in an evaporitic lake, or the salt ridges (wavy bedding) may indicate proximity to sea water. Although the overlying carbonates and red beds of the Goose Egg Formation have marine affinities, an unconformity separates this Upper Tensleep section from the Goose Egg. Thus, there may be no immediate connection to marine shorelines in the Upper Tensleep at Flat Top.



East Allen Lake Oil field structure

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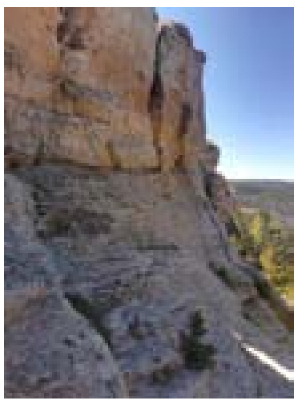
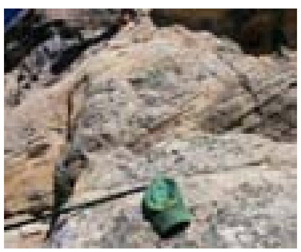
White Rock Canyon

The Upper Tensleep Sandstone at White Rock Canyon, east side of outcrop. Our 226 foot (partial) measured section began in the Upper Tensleep, which in this area is roughly 400 feet thick, based on well control. It was measured on the opposite (west) side of this cliff where access was easier. It begins about the middle of the Upper Tensleep and continues to the first carbonate in the Phosphoria (Goose Egg) Formation. See log this page for comparison. Note the variety of genetic units in terms of thickness, shape and crossbedding. This suggests that oil recovery factors from these genetic units would be equally diverse, mainly as a function of the arrangement of primary strata in each, as well as geometry, lithology etc.. Thrust fault zone of deformation shown by red lines.



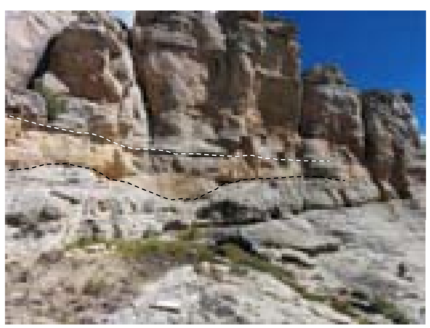
Upper part of the measured section consisting mainly of eolian dunes with some sabkha and relatively clean coarse fluvial sandstones.



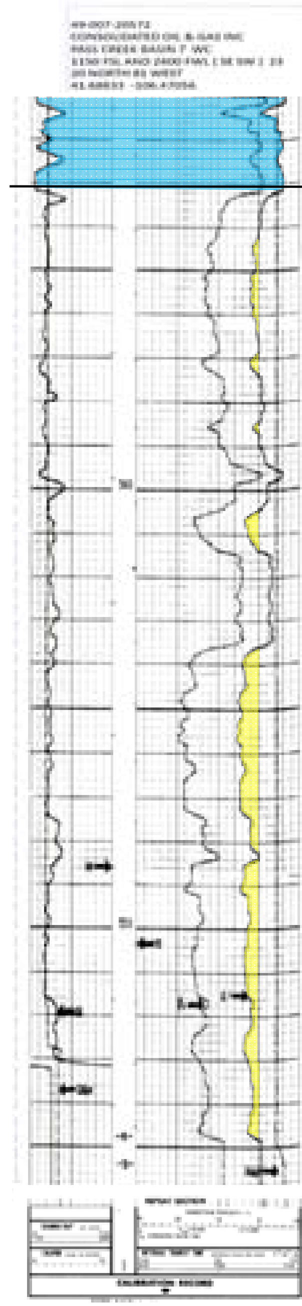
Eolian avalanche and ripple primary strata in unit 17. Close study of the image reveals that 80% of the outcrop is ripple strata, despite the relatively steep dips.

Fluvial red beds (conglomerate, sandstones, siltstones) in unit 7. These sediments represent Upper Fountain Formation tongues that have pinched out a short distance northward at Pass Creek oil field. They are the product of runoff into the Upper Tensleep dune field from an ancient uplift to the south.

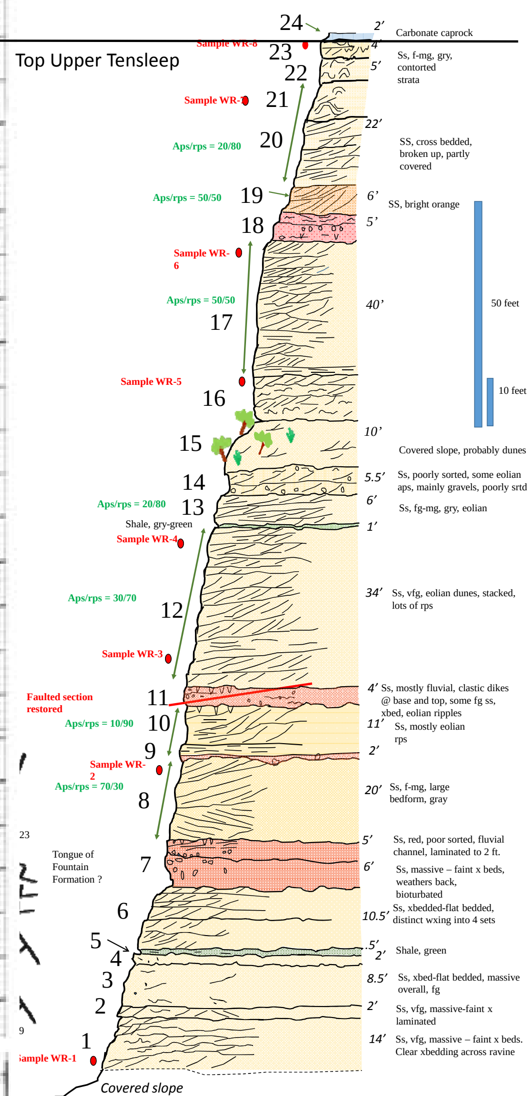
View of the outcrop from the east side reveals complexity of individual genetic units, most of which probably act as flow units in subsurface reservoirs. Red fluvial sand is indicated by arrow.



Fluvial channel with coarse reddish sand and irregular bedding (between dashed lines). It is enclosed by dune sands above and below. Unit 18. Steep cliff above goes to top of section units 19-23.



Tensleep Formation Measured Section (Partial)
White Rock Canyon
Carbon County, Wyoming
Sept 2, 2015
Fryberger and Jones
226 ft. Upper Tensleep



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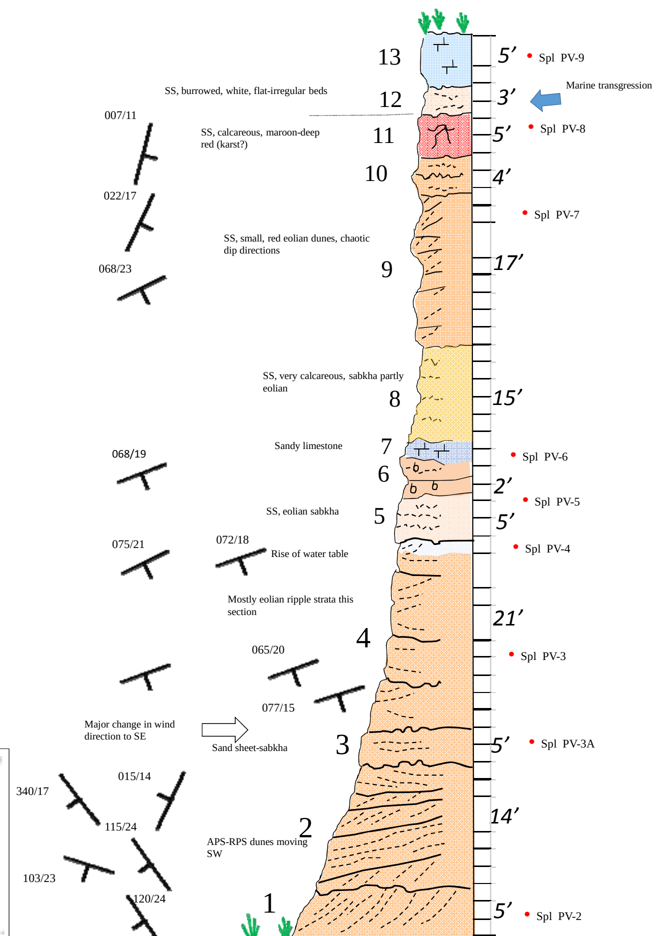
Paradise Valley Measured Section

Close up view of a set of avalanche strata on a dune slipface at the base of the measured section. This is Unit 1 of the measured section. Crossbedded unit above consists of stacked sets of strata of Unit 2, which overall has higher proportion of ripple primary strata to avalanche strata, perhaps because the preserved bedforms are smaller.

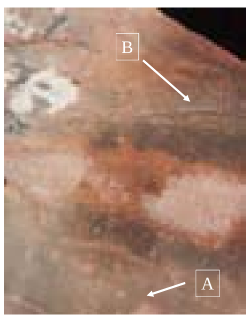
Lower part of the Paradise Valley measured section with dune bedforms, where Nick Jones is seated. Generally, bedforms become smaller up-section. This sequence (see measured section) would make a complex petroleum reservoir with numerous distinctive flow units – the best probably the dunes shown here at the base of the cliff below the dashed line.

Tensleep/Casper Formation
Paradise Valley,
Albany County Wyoming
Measured partial measured Section
101 Feet
(June 4 2015) Fryberger and Jones



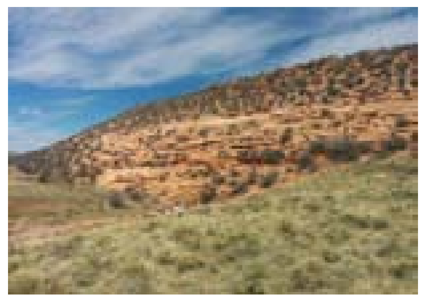
Base of section:
x 41.21526 Y -105.53116

Paradise Valley section is on private land. Please ask permission to access.

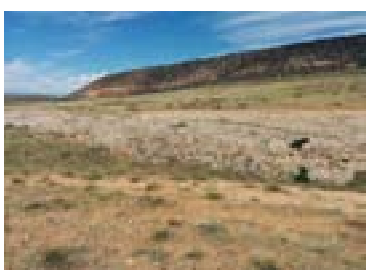


Small scale eolian sedimentary structures at Paradise Valley Casper (Tensleep) section. (A) Pin-stripe laminations typical of eolian ripple strata. (B) "Bagnold surface" consisting of a thin layer of coarse sand grains winnowed by the wind, typical of eolian deposits.

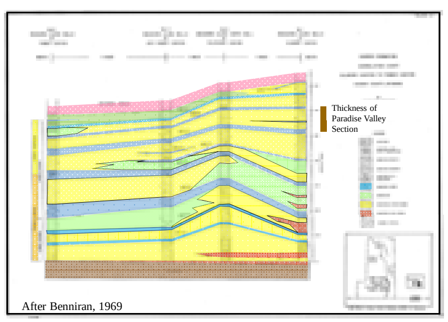
A monolayer of coarse sand grains (within white oval) typical of eolian sedimentation. Many of the coarse grains are light-colored.



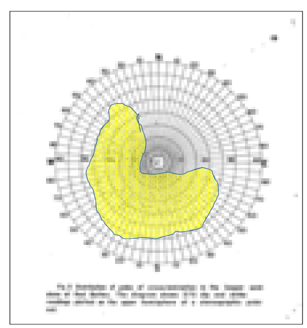
Measured section at Paradise Valley. It consists of an eolian sequence sandwiched between two marine carbonates. Base and top of the section are on marine limestones of the Tensleep (Casper). Dune sequence in this outcrop has largest dunes at base, smaller, more complex sets of dunes, sabkhas and marine shoreline deposits including carbonates higher up. Dashed white line shows base of sabkha (Unit 5)



The marine limestone that forms the base of the dominantly eolian rocks of the measured section in the background. This limestone contained shell fragments.



Stratigraphy of the Casper Formation near Laramie. Our measured section was in the upper, Permian part of the Formation about where the brown bar is positioned. This area along the Laramie Mountains is one of the few where marine carbonates inter-bed with the Upper Tensleep dunes. Carbonates in the Permian part of the Casper (Tensleep) are commonly thin, continental limestones, occasionally dolomitic with affinities to interdune lakes or ponds.



After W.H. Wilson, 1950 MS thesis Uwyo

Stratigraphy, Exploration and EOR potential of the Tensleep/Casper Formations, SE Wyoming

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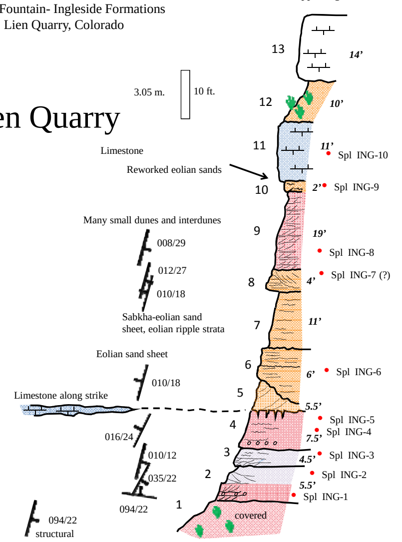
Upper Fountain-Ingleside Fm Lien Quarry and Owl Canyon Northern Colorado

Lien Quarry

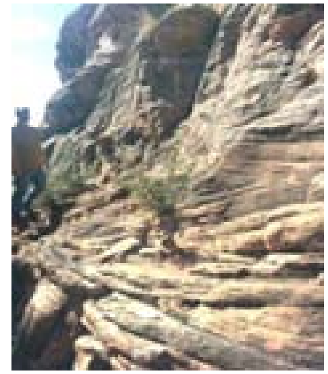


Overview of the Owl Canyon Upper Fountain-Ingleside Formations measured section. This section begins in the Upper Fountain fluvial conglomerates and arkosic sandstones. It continues into mixed eolian, fluvial and marine sediments of the Ingleside Formations (Virgil-Wolfcamp). A thin gray limestone visible in the photograph taken north of the measured section proper pinches out at the measured section , leaving only and erosional bounding surface (white arrow).

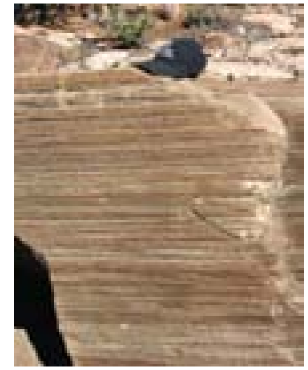
Route of measured section at Lein Quarry (partial section of Upper Fountain-Ingleside).

Contact of eolian dunes from unit 9 with marine limestone unit 11. A thin reworked eolian sand (unit 10, arrow) only a few inches thick (gray) records the reworking of the dune sands.

The clastic dikes shown here are all the remain of a thin limestone that occupies this disconformity at the top of Unit 4, 100 m further north along the outcrop (see measured section and photo above, left).

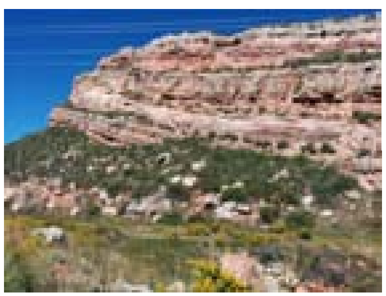


Unit 8 in the Lein Quarry measured section. It consists of crossbedded small eolian dunes.

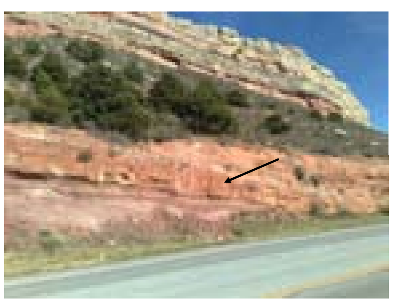


Flat-bedded eolian ripple strata in Unit 6 (sand sheet).

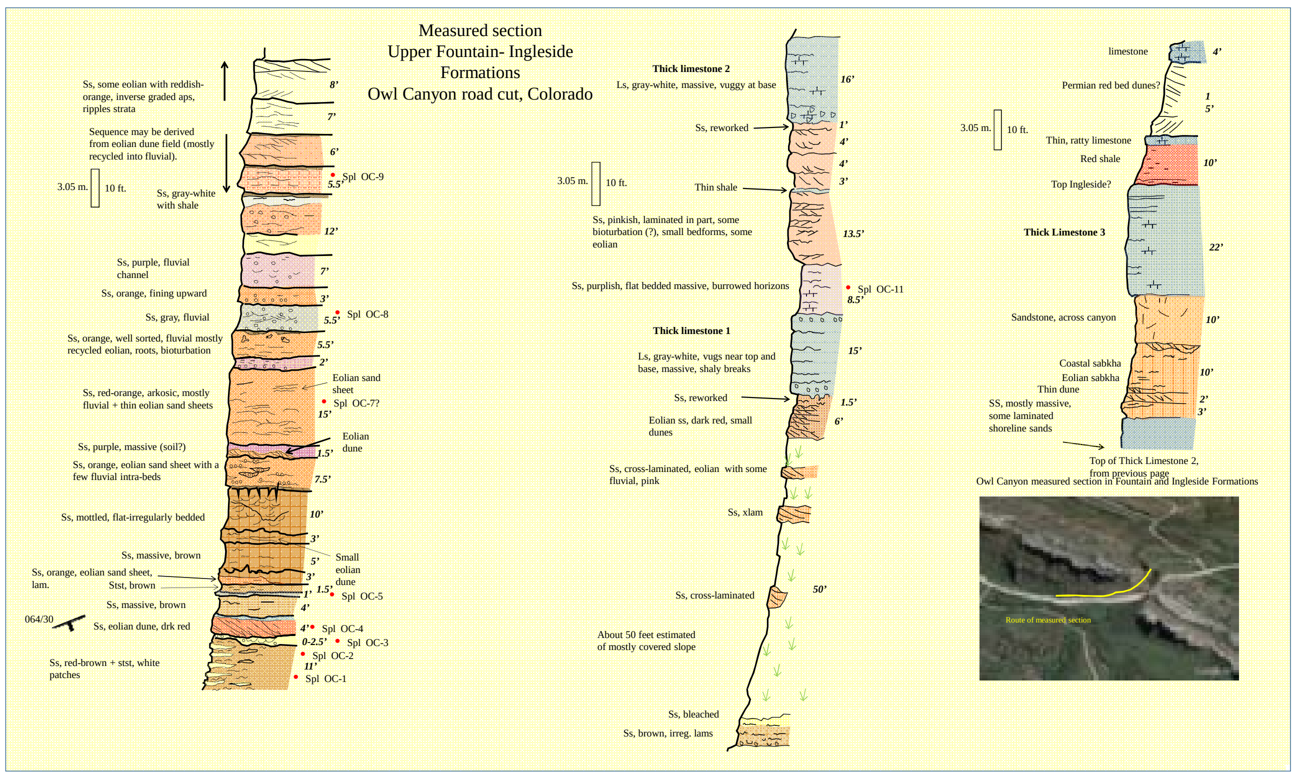
Fountain-Ingleside measured along highway 287



Upper part of the measured section (mainly Permian Upper Tensleep-Minnelusa correlative) in the Ingleside Formation at Owl Canyon road cut.. Gray, blocky weathering units are shallow marine limestones. Reddish and rounded-weathering units are mixed eolian-shoreline sandstones.



Our section (shown to the right on this page) begins in the Upper Fountain formation. Transition to Ingleside is in the vegetated slope. To our surprise we found some considerable eolian dune and sand sheet deposits within the dominantly fluvial Fountain. These commonly had a pink color. One of these units is marked by the arrow on the left.



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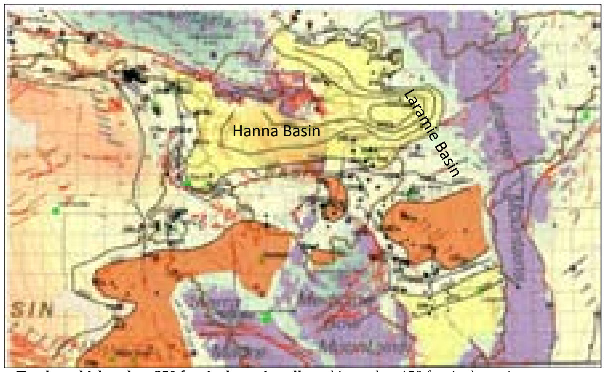
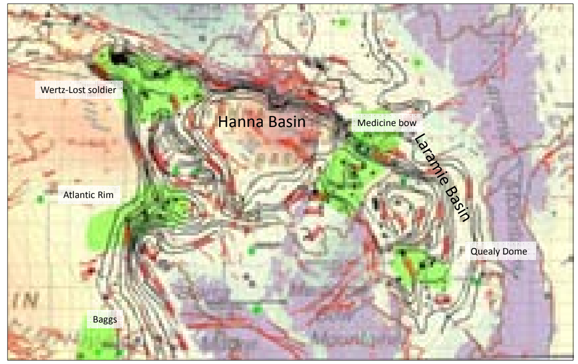
Tensleep stratigraphy

Upper Tensleep thickness

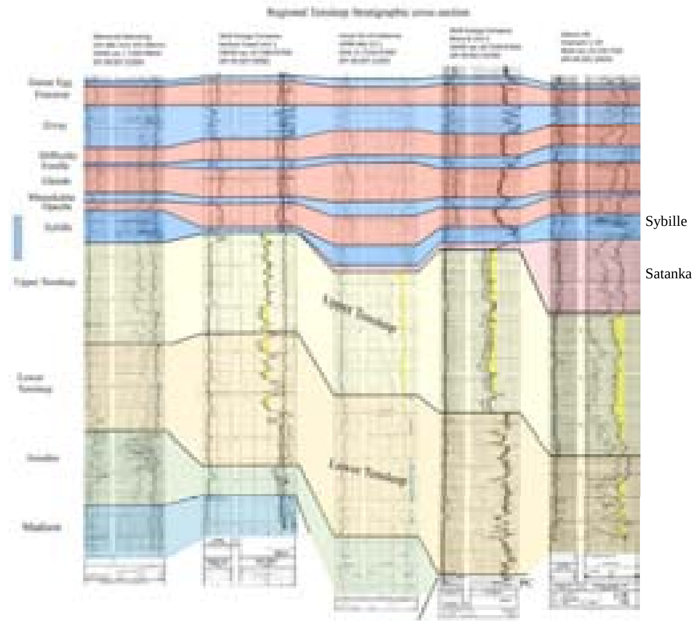


Tensleep thicker than 250 feet is shown in yellow, thinner than 150 feet is shown in orange. Thick Upper Tensleep is associated with the Hanna Basin, Northern Laramie Basin and SE Laramie Basin. Thin in the Laramie Basin follows the Cheyenne Belt of deformation (see next slide).

Upper Tensleep Hydrocarbon shows and Structure

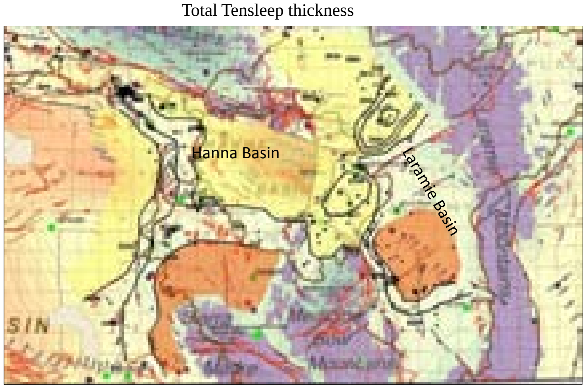


Green areas on this map enclose regions with oil or gas shows in the Upper Tensleep, based on Wyoming Oil and Gas Commission records of production, drill stem tests and some limited core and sample data. This map also shows major faults in red from the state geological map, and structure contours subsea on the top of the Upper Tensleep. There are distinct, structurally-defined shows in Wertz, Atlantic Rim, Baggs, Medicine Bow and Quealy Dome regions.



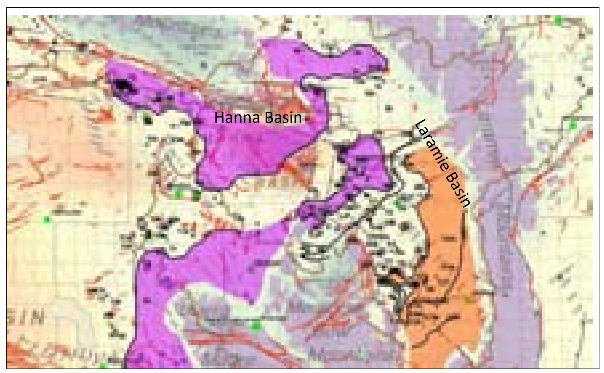
Cross section of the Tensleep Formation in Southeast Wyoming. Section is hung (loosely) on the top Goose Egg Formation

Total Tensleep thickness



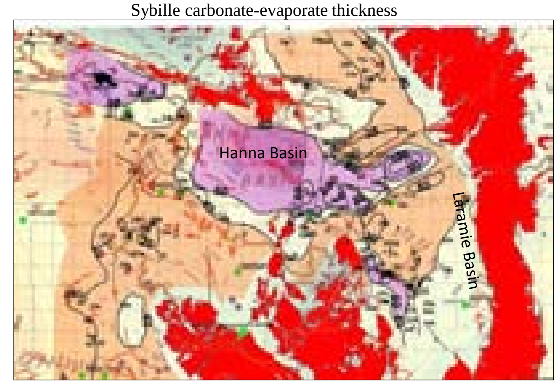
The thickness of the Upper and Lower Tensleep combined follows the pattern of the Upper Tensleep. It is clear that major Laramide uplifts of the Medicine Bow and Sierra Madre Mountains have stripped off the Tensleep. There are also more subtle trends related to local faulting.

Satanka Shale thickness

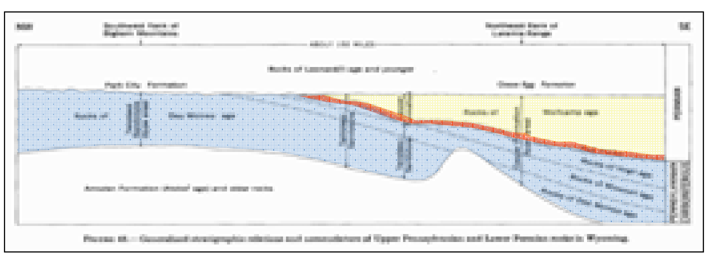


Satanka Shale thickness map (overlies Tensleep regionally). Areas with Satanka eroded colored purple. Orange shading shows thick Satanka in southern Laramie Basin.

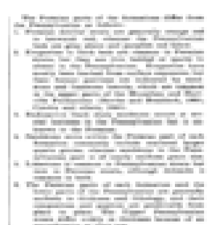
Sybille carbonate-evaporate thickness



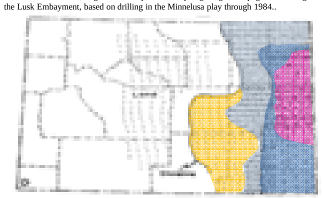
The Sybille carbonate-evaporite sequence of the Goose Egg Formation immediately overlies the Satanka Shale. The thickness is a good indication of post-Tensleep tectonics. Thick Sybille is present in the Lost Soldier-Wertz area, Hanna Basin and a NE-SW trending area defined by faults in the Laramie Basin. On this map, thicks are indicated by purple shading, thins by orange.



Tensleep schematic cross section Southern Wyoming



This 1954 lithofacies map by Agatston is interesting because it shows the evaporites in the Black Hills, and the carbonates of the Lusk Embayment to the south. Generalized loss of carbonates into the dune fields of Central and Western Wyoming is accurate for Lower Permian rocks, in general. Compare with Fryberger figure on page 41 showing the Lusk Embayment, based on drilling in the Minnelusa play through 1984..



Lithofacies map of Eastern Wyoming during Lower Permian. After Agatston, 1954

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Tensleep Formation Common Risk Segment Maps

CRS Overview

The maps on this page illustrate the stages in a "common risk segment" map, with the final product displayed immediately to the right. Not surprisingly, the CRS map finds existing production (red areas on map are oil fields). However, study of the other maps on reservoir, structure and charge (shows) reveal why the fields are where they are, and make visible certain trends that would not be obvious without this technique.

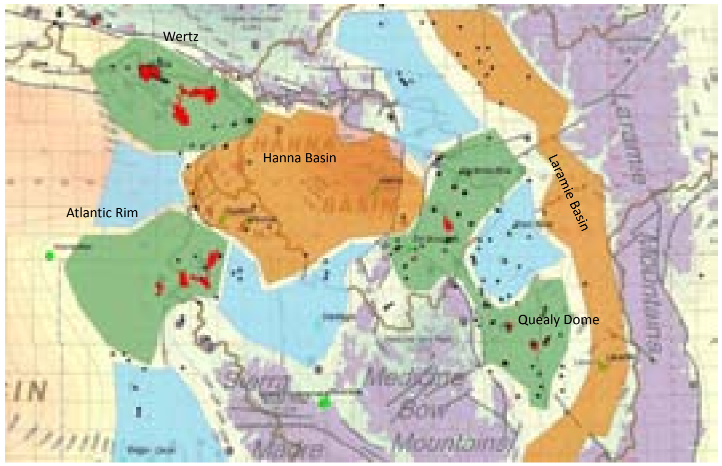
Quealy dome occurs in an area of complex structures related to shear faulting. There may be undetected or incorrectly mapped structures in this area based on older seismic data. Because Quealy Dome has at more than a 300 foot oil column, this area is probably worth another look.

There is also a trend of shows and structures that extend from East Allen Lake, Big Medicine Bow and Pass Creek Tensleep oil fields. Big Medicine Bow and Pass Creek are still on primary production. If water bypassing can be identified, there may be room for additional injection or producing wells. There are strong oil shows in outcrop at Flat Top anticline, that suggest perhaps further exploration is worthwhile along NE-SW trending faults in this area north of East Allen Lake near Medicine Bow.

To the west, the Atlantic Rim area has considerable shows. More production may be found along the Sierra Madre trend and southward following shows including free oil in drill stem tests.
The Lost Soldier Wertz area, including Mahoney Dome has major production with big structures, good upper Tensleep Reservoir and charge presumably from down-dip Phosphoria source rocks.

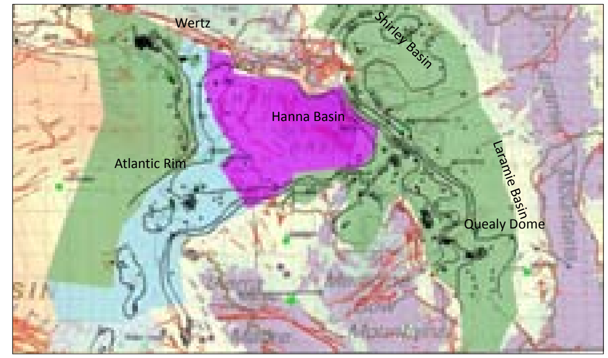
We searched carefully for a reason to be hopeful about the relatively under-drilled Hanna Basin, however the deep burial appears to have reduced porosity in the Upper Tensleep and increased the risk of drilling tight reservoir even if structures could be defined. The high risk CRS along the Laramie range is mainly due to lack of structure. Reservoir in the Upper Tensleep is very good, however the are few shows this close to the Laramie Range. It should be noted however that our main information on shows came from drill stem tests and production, as well as a few lithological logs contributed by operators. We did not have complete sample descriptions (mud logs) for many wells, those sample shows may have been missed.

Upper Tensleep Combined CRS map



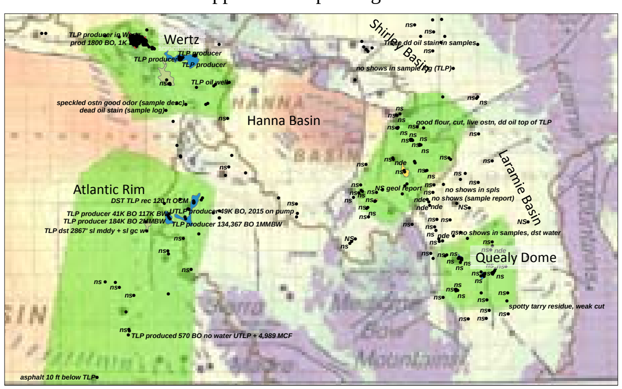
Combined Upper Tensleep CRS map. Green areas show regions of best chance to find new production (lowest risk). Blue areas show moderate risk. Red hachured areas show high risk areas, mainly regions such as the Hanna Basin with tight rock, or areas with insufficient evidence for robust structural traps. State of Wyoming basement map as background.

Upper Tensleep Reservoir risk (quality)



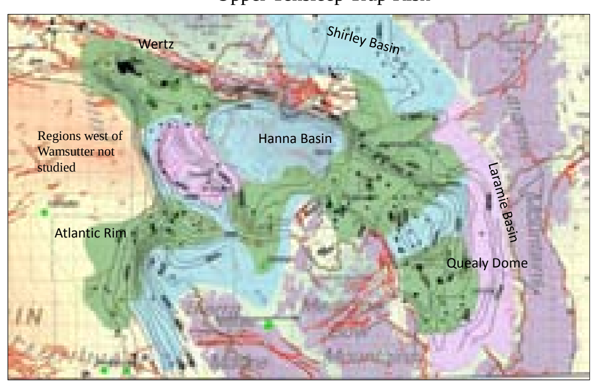
Tensleep reservoir risk map (quality) based on porosity and permeability of Upper Tensleep sandstones. Contours show net/gross in Upper Tensleep, with net cutoff at 65 ms/ft (10% porosity), thus this is a conservative map. The map does not consider fracture-dependent production opportunities. Green, Low risk; Blue moderate risk; purple, high risk. Regional faults shown as red lines, State of Wyoming basement map as background.

Upper Tensleep Charge Risk



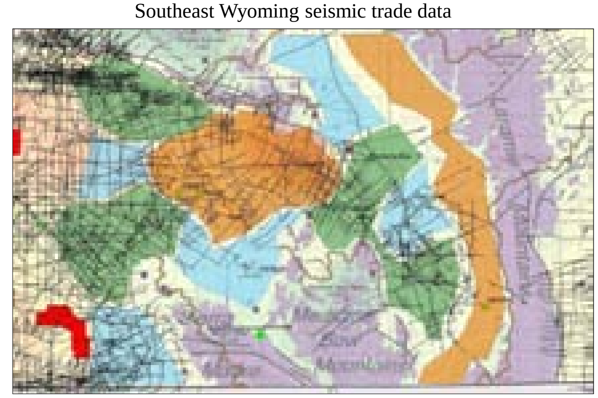
Tensleep charge risk map. Green polygons enclose producing oil fields and oil shows from state records (posted on map). Broader areas extend shows along structural or stratigraphic trends (green hachures).

Upper Tensleep Trap Risk



Tensleep trap (structure) risk map. Contours show subsea top Upper Tensleep. Green shading is low risk; blue shading is moderate risk; purple shading is high risk. Regional faults shown by red lines, background is Wyoming Basement map. This map is based on distribution of known producing structures at Tensleep level, and structural setting. In Southeast Wyoming, there do not appear to be stratigraphic traps above intra-formational (reservoir heterogeneity) level. High risk area near Rawlins is related to very shallow depth of Tensleep, with exposure of the formation in places along the ridge that runs from Sinclair north towards Mahoney Dome.

Southeast Wyoming seismic trade data



Availability of trade seismic data in the SE Wyoming region. Black lines show 2D data, red polygons show 3D surveys. These data are superimposed on the combined CRS map for the region based on this study (see maps this page). Map in background is Wyoming Basement map. Seismic data courtesy of SEI Seismic Exchange data brokers in Houston and Denver.

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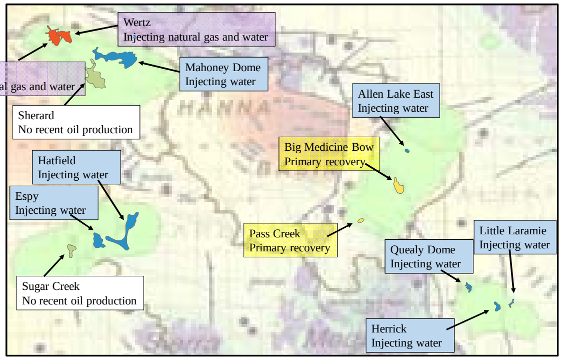
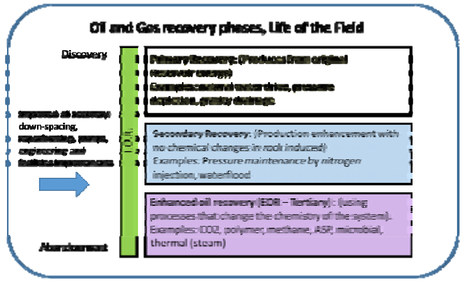
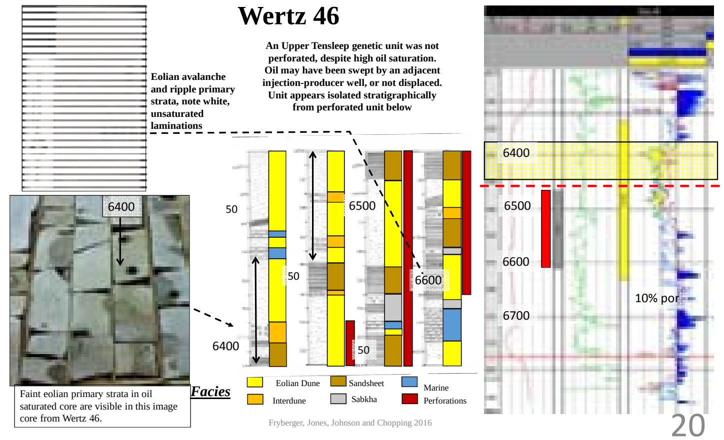
EOR status in Southeast Wyoming Examples

EOR status of Tensleep Fields in SE Wyoming.



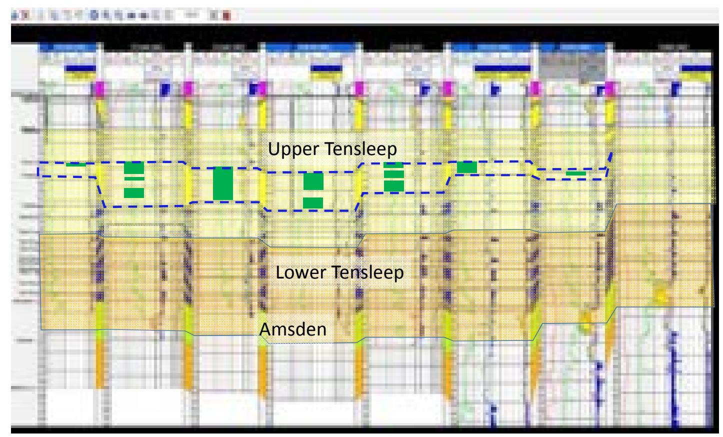
Green shaded areas indicate regions of oil shows. Background: Basement map of Wyoming.



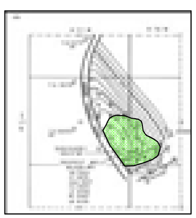


Yellow = avalanche strata; Red = ripple strata

Petrel static model showing Lower and Upper Tensleep at Wertz Oil Field

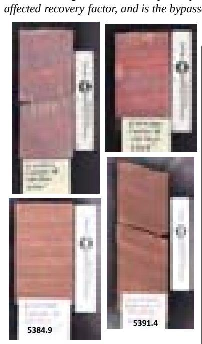


Tensleep producing area

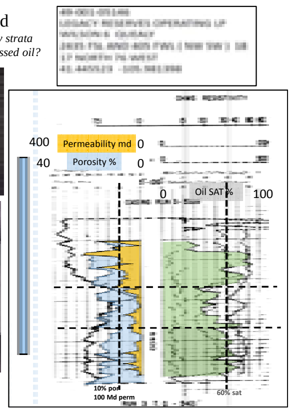


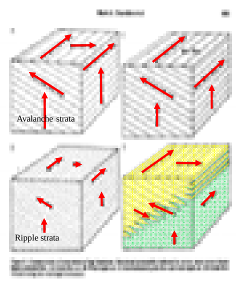
Quealy Dome Oil Field

Have eolian genetic units and primary strata affected recovery factor, and is the bypassed oil?

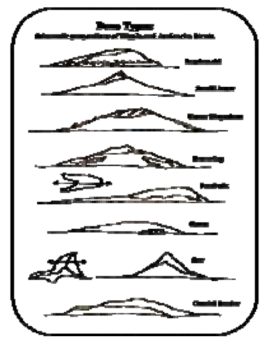


Wilson 6 Quealy Dome
Avalanche and Ripple primary eolian
Strata in all zones



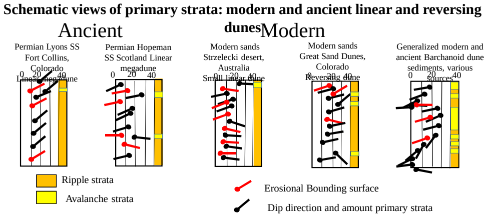


Preferred flow direction and permeability at small (laminar) scale in avalanche and ripples strata. These are predicted from minipermeameter measurements in Jurassic Entrada Sandstone. Red arrows are proportional in length to directional permeability along primary strata. After Chandler, et al 1989

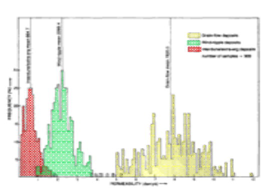


Estimates of the proportions of eolian primary strata types and abundance as a function of dune type. These are rough guesses based on the author's experience and published literature. In detail, there will commonly be mixed associations consisting of some ripple strata and some avalanche strata, but the dominant types are illustrated here. Note that linear dune types, in general, have more ripple strata, and thus lower quality reservoir rock.

Schematic views of primary strata: modern and ancient linear and reversing dunes



An interpretation of the dip angle and primary strata type and erosional bounding surfaces in linear and reversing dune types interpreted in ancient rocks. Note the high proportion of ripple strata observed in all outcrops – which is matched by subsurface core data. For comparison, the typical pattern of barchanoid dunes is illustrated on the right side of the diagram. A concept diagram courtesy of Caroline Hern (2015)



Permeability variations from Page Sandstone outcrops in Northern Arizona. There is about one order of magnitude difference in permeability between "interdune" and "grain flow (avalanche)" deposits. After Chandler, et al 1989

Page Sandstone outcrop in Page, Arizona, viewed by geologists on a Shell Field trip.

Oil Fields in Tensleep - Laramie Basin and environs

Oil Field	Township	Range	Discovery Year	Depth	Porosity	Permeability	Oil Column	API Gravity	Intial Production	Initial Pressure psi	Comment
Little Laramie	16N	75W	1948	3712	23%	unknown	80 ft	18	80 BOPD 24 BW	1600	
Big Medicine Bow	21N	79W	1935	5400	10.3	10-100 md	150 ft	62	500 BOPD 81,000MCF	est. 1900	Sundance/Tensleep production
Allen Lake East	22N	78W	1937	2140	13%	49-400 md	45	20-23.7	unknown	1750	water drive
Quealy Dome	17N	76-77W	1934	3146	16%	140 md	300+ ft	27 api sour	unknown	unknown	3% sulphur, 15 deg F pour point
Herrick	16N	76W	1947	3630	20%	800 md	100 ft	22 api	265 BOPD	1500	
Pass Creek	20N	80W	1977	3542	20%	unknown	unknown	33 api	405 BOPD 3 BW	1671	
Lost Soldier	26N	90W	1930 (Tensleep)	1650	3-21%	.01-300 md	3100 ft	35.4	1800 BOPD	2520	
Wertz	26N	89-90W	1936 (Tensleep)	5886	3.3-18.9%	70 avg	450+	35.3	1700 BOPD	2600	deepend to total TLP prod incr to 8350 BOPD
Espy	19N	89W	1975 (Tensleep)	8500	0-7%	unknown	unknown	45	160 BOPD 764 BW	3228	originally a Niobrara discovery
Hatfield Dome	19-20N	88W	1947 (Tensleep)	5900	3%	fracture	400 ft	43.6	300 BOPD	2600	many producing horizons
Sugar Creek	19N	90W	1968	10500	8%	less than 5 md	100 ft (gas)	gas	4114 MCFGPD	4880	faulted anticline (thrust?)
Mahony Dome	26N	88W	1919	2525	12%	10 md	250+ ft	34.4	65 BOPD	unknown	"lenticular sands" reservoir character
Mahoney Dome East	26N	87W	1940	4280	11.50%	15 md	53+ ft	43	50 BOPD	unknown	UTLP plugged back and completed as gas well