PS A Geometric Approach to the Analysis of Global Eolian Hydrocarbon Reservoirs*

Steve Fryberger[1] and Caroline Y. Hern[2]

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[1]Enhanced Oil Recovery Institute, University of Wyoming, Laramie, WY, USA (steve.fryberger@gmail.com)
[2]Shell International Exploration and Production, Houston, TX, USA

Abstract

It is recognized worldwide that eolian rocks can be very good hydrocarbon reservoirs. The “classic tank” eolian reservoir consists of a framework of well-rounded, well-sorted quartz sand grains that incorporates little matrix due to removal of fines by wind. The real world varies greatly, however, from the “classic tank” because most eolian reservoirs consist of a mélange of complex lithofacies derived from process frameworks operating at multiple scales. Practical geometric reservoir models include local and global climate conditions, sources of sand, wind direction and bedform size, accommodation space, and climatic and tectonic factors that create lacunae in sedimentation at various scales. These phenomena are best recognized through the study of dipmeter and core for any particular field; or less happily, after early water breakthrough at the crest of an oil field signals that unswept rock lies between the off-take well and the oil-water contact. At the global scale, climate variability associated, for example, with Permian glacial cyclicity has stamped a resonant cyclicity on rock units of that age in many parts of the world. At basinal scale, controls on sedimentation operate through both auto- and allocyclic processes. Regional winds bring sand to the local system where it is reworked. Fluvial avulsion and water table fluctuations among other factors also control reservoir sedimentology and stratigraphy. At the oil field scale, the reservoir characteristics are controlled mainly by facies stacking, associated bounding surfaces, and vertical trends in texture. At the outcrop scale, crossbedding typical of the various dune types is a key driver of reservoir complexity. At the microscopic scale within eolian genetic units, the poroperm properties of individual primary strata will affect recovery factors for an entire field by controlling fluid movement in pore spaces of the reservoir. The Wahiba Sand Sea of Oman provides modern analogues for some of the reservoir styles we have seen globally. Flow models demonstrate the heterogeneity of hydrocarbon sweep that would be produced by various eolian lithofacies preserved on coastal outcrops of the Southeast Wahiba Sands.

A Geometric Approach to the Analysis of Global Eolian Hydrocarbon Reservoirs

Poster session at the AAPG-RMS July, 2014

Steven G. Fryberger*1 and **Caroline Y. Hern***2

*1 Enhanced Oil Recovery Institute, University of Wyoming
*2 Shell Exploration and Production, Houston, Texas

Enhanced Oil Recovery Institute

Abstract

In this study we offer a comprehensive approach to the analysis of eolian petroleum reservoirs. Our approach incorporates themes in eolian and related non-eolian sedimentation that repeat through various geometric and time scales. We do not propose a system of classification, merely a tool for thinking about these reservoirs. We have found that our attempt to use sedimentological process frameworks to characterize eolian sand seas, while helpful, can also be misleading when used in industry workflows because of a tendency for oversimplification and neglect of scale factors. Usually models based on one overarching concept, such as sequence stratigraphic history, are too grandiose to be of use in reservoir characterization for appraisal or infill drilling, especially over the long term. The most useful geometric reservoir models must explicitly consider changing climate and tectonic conditions, multiple sources of sand, changes of wind regime and bedform size and migration as well as accommodation space at various levels - including bedform build and fill. These factors have created the discontinuous record of deposition of eolian reservoirs, and the formation of distinct genetic "flow units" that are commonly stacked in hydrocarbon reservoirs.

It is recognized worldwide that eolian rocks can be very good hydrocarbon reservoirs, at least in terms of primary porosity. The "classic" eolian reservoir consists of a framework of well-rounded, well sorted quartz sand grains that incorporates little matrix due to the removal fines by wind. Thus, primary intergranular poroperm is commonly well-preserved in what appears to be a rather homogeneous, isotropic reservoir, namely, a "tank". This is especially true if the rocks are viewed only in terms of porosity logs. Detailed study of permeability data from core, however, often reveals a more complex picture, with some rather porous rocks having poor permeability. While our review confirms a common potential for ultimate recovery factors above 60% for oil and 90% for gas in many eolian reservoirs, there is a caveat. This is that the achievement of such favorable recovery factors commonly requires use of a variety of secondary and tertiary recovery techniques. These must be correctly applied to an accurate three dimensional model of the productive rocks. Moreover, high recovery factors are often the result of dense infill drilling not anticipated in original reservoir planning. **The real-world varies from the "classic" eolian reservoir "tank" because most eolian reservoirs consist of a mélange of complexities derived from process frameworks operating at multiple scales, any of which can be a dominant control on reservoir performance.**

At the global scale, climate variability associated, for example, with Permian glacial cyclicity has stamped a parallel cyclicity on rock units of that age in many parts of the world. Glacial cyclicity for example has created eolian reservoirs interbedded with non-eolian, non-reservoir genetic units (such as marine muddy carbonates) as sea levels rose and fell. In places, properties of stacked sand seas such as crossbed size and lithology change vertically in response to differences among wind regimes of different glacial cycles, or within glacial-interglacial cycles. In the Casper Formation of southeast Wyoming, Permian-Pennsylvanian dunes, shallow marine carbonates and alluvial fan deposits inter-tongue due to both sea level changes and tectonics. The more moderate climates of the Mesozoic, on the other hand, created stacked sand seas within which eolian crossbedding alone is one of the main complicating factors of petroleum reservoirs—as reflected by outcrops in the Mesozoic eolian reservoirs of the Colorado Plateau such as the Navajo-Nuggett sandstones of Utah and Wyoming.

At basin scale controls on sedimentation operate through both auto- and allocyclic processes. Local winds may control proximal source terrains, while regional winds bring sand to the local wind and fluvial systems. Local fluvial systems may also bring distinctive mineralogical suites to sites of deposition or for redistribution by wind. Fluvial avulsion and water table, among other factors, also control reservoir distribution. At this scale, reservoir heterogeneity reflects sand sea migration, sediment pathways, diagenesis and mineralogy, burial history and various preservational dynamics. Stacking of formation or group stratigraphic units is common at the basin level. The resulting pile of eolian rocks thus may represent the repeated development of eolian sand seas in a single place over time. A good example of this is the stacking of the various eolian formations of the Colorado Plateau from the Triassic through the Cretaceous. This is well displayed at Canyonlands National Park, Utah where Permian Cedar Mesa dunes are at the base of a stack of eolian sands extending, with few interruptions, upwards through the Jurassic dunes of the Entrada Formation.

At the Sub-Basin scale, reservoir characteristics are controlled mainly by the geometrical arrangements of flow units (usually genetic units) caused by facies stacking. Along with this are associated bounding surfaces, and secular trends in texture, mineralogy, and ultimately diagenesis. In some places reservoir geometry reflects fill by younger dunes of antecedent eolian topography. Lateral migration of individual dunes and the stacking of eolian facies-variants including dune fields, sand sheets and sabkhas with contrasting bulk porosity-permeability characteristics can horizontally stratify reservoir flow units. Eolian facies-stacking occurs more frequently in proportion to the rapidity of eolian facies shift laterally, commonly by superposition of those facies across erosional diastems created wind regime and climate changes. In some places, for example Rangely field of Colorado, redbed (tight) fluvial extradune and interdunal sediments isolate individual eolian dune flow units. The stacking of genetic units within eolian reservoirs is forced by wind regime characteristics that create and move individual dune forms, as well as local processes involving mixtures of wind, lacustrine and fluvial sediments. This process may stack genetic units of much different age, although this may be overlooked within petroleum reservoirs unless contrasting patterns of crossbedding are revealed using dipmeters, or diagnostic fossils are present. Intercalation with non-eolian units also reflects processes working at this scale. In our scheme, the non-eolian (extradunal) sediments might be lime mudstones, evaporites, playa mudstones or other impermeable lithofacies that create reservoir compartmentalization.

At the outcrop/oil field scale crossbedding typical of the various dune types is a key driver of reservoir complexity. Size of dunes may be important, because large (preserved) dunes commonly have simpler patterns of crossbedding (fewer laminar intersections) per unit of volume than small dunes. Barchanoid ridge dunes formed in a wind regime with a single dominant wind direction may be less compartmentalized by cross stratification than linear dunes formed in multi-directional wind regimes. Linear dunes in bulk commonly have more ripple strata than barchan dunes and thus tend to be poorer reservoir. Like many attractive generalizations in eolian sediments, this in itself is an over-simplification, due to complexities inherent in construction of genetic units for example from small barchan dunes. The best tool for sorting these relationships on outcrop is to measure strikes and dips of beds and bounding surfaces and make a sketch that is hopefully representative, and might be of use to model a petroleum reservoir nearby. In the subsurface, the best tool is the dipmeter, core and some imagination.

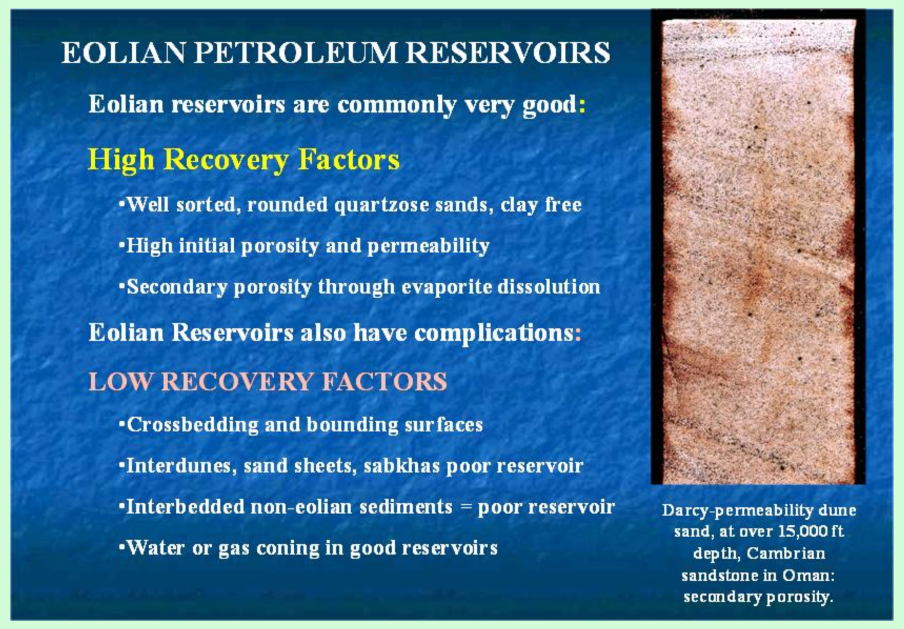
At the microscopic scale within eolian genetic units, the poroperm properties of individual primary strata will negatively affect recovery factors for a field by restricting oil movement in the reservoir. Indeed, there is commonly an extreme permeability contrast among and within primary eolian avalanche, grainfall and wind ripple strata in any eolian reservoir. For example, consider the fact that both avalanche and wind ripple strata are commonly inverse-graded. Permeable, well sorted, coarser sands of a single lamination are separated from the next lamination by a nearly impermeable pin-stripe layer a fraction of a millimeter thick. Hydrocarbons can move along the porous part of the lamination, but cannot cross the pin stripes, or cross only with difficulty due to relative mobility, capillarity, wetting phase and other factors operating at this small scale. This microscopic factor, combined with the specific permeability-porosity architecture at various higher scales defines a compartmentalization of eolian reservoirs that is related purely to cross bedding. Without proper handling, reservoirs that appear porous and permeable in core plugs may have low recovery factors, the result of drastically reduced sweep efficiency due to these microscopic effects. This phenomenon is best recognized through the study of dipmeter and core for any particular field; or less favorably, after early water breakthrough at the crest of an oil field signals that unswept rock lies between the off-take well and the oil-water contact or injector.

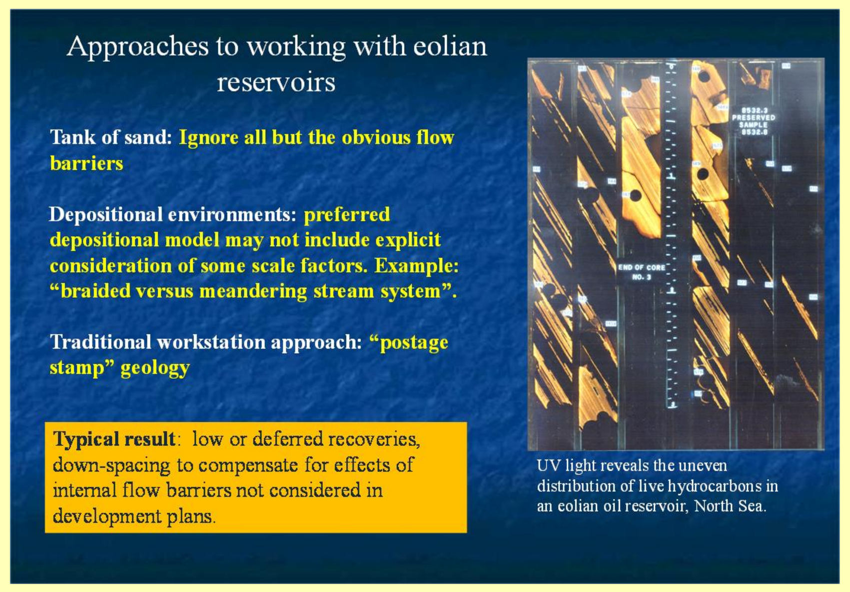
The chart of eolian geometric reservoir styles shown here is based on the following variables: (a) dune crossbedding complexity for which dune type serves as the proxy; (b) complexity and number of eolian diastems and unconformities (that are likely to separate reservoir flow units); and (c) degree of any intercalation of non-eolian depositional environments. Our simple 9-box diagram of eolian reservoirs is based on geometrical styles, in preference to names based upon perceived environmental drivers. It can represent reservoirs and reservoir components at different scales. As sedimentologists ourselves, we don't negate the importance of understanding how reservoirs form in fundamental depositional environments, or process frameworks. However, we pause at the idea of characterizing reservoir using sedimentological terms. This is because similar arrangements of porosity and permeability can form from different mixes of depositional environment. For example, good dune sands may intercalate with tight alluvial fan sediments or tight carbonate mudstones to create petroleum reservoirs with roughly similar production behavior. We offer our approach simply as a tool for working with - or thinking about - eolian reservoirs, not a prescription for any nomenclature or production strategy. Most importantly, our modest chart at least encourages the consideration of all scales at which reservoir heterogeneity might have been created.

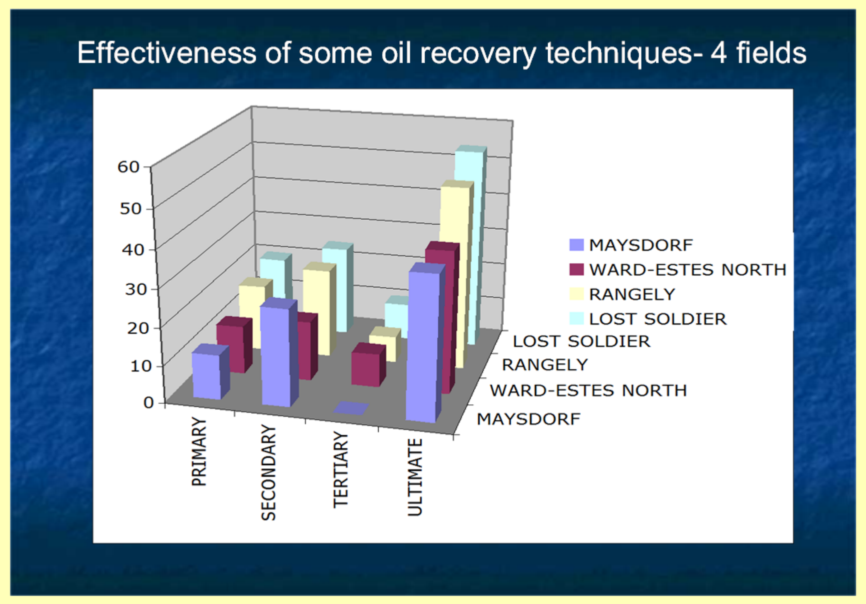
The Wahiba Sand Sea of Oman provides modern analogues for a few of the basic reservoir styles we have observed. The large-scale process driving the evolution of the Wahiba Sand Sea is the southwest Indian monsoon, which has prevailed during both glacial and interglacial times - with some changes in wind strength and direction. At the outcrop scale, build-and-fill processes are important in the formation of eolian genetic units. Additionally, the stacking of various dune types; as well as facies-stacking due to climate changes, and the intercalation of various eolian lithofacies with non-eolian deposits can be seen at outcrops within the Wahibas. We modelled some of the outcrops as if they were petroleum reservoirs with interesting results.

Additionally, many of the production characteristics of older eolian reservoirs of the Rocky Mountains, USA, illustrate the basic ideas proposed here. We include some interesting examples here from older publications, and our new work on build-and-fill in the Minnelusa Formation of Wyoming.

The Flat Top anticline, an outcrop of oil-saturated eolian Tensleep Sandstone a few miles north of Medicine Bow, Wyoming. Different styles of crossbedding, with varying amounts of ripple and avalanche strata, comprise potential flow units in the subsurface. Major bounding surfaces are visible on this image. View to the north.

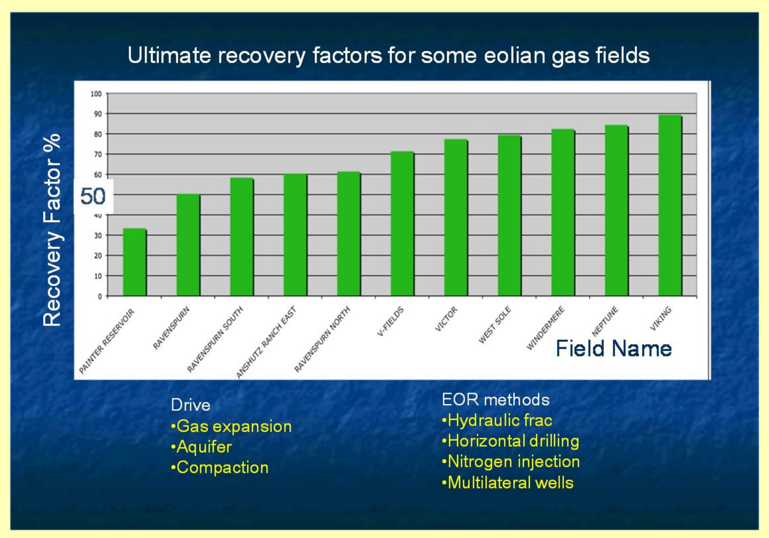


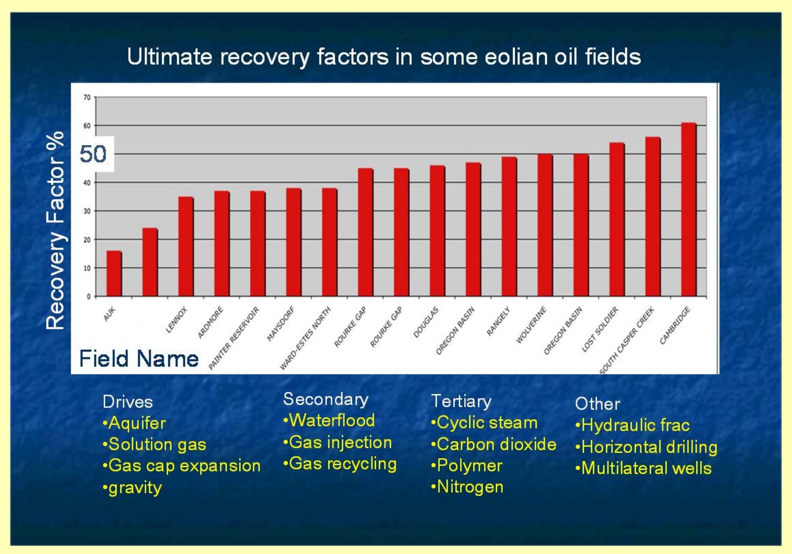




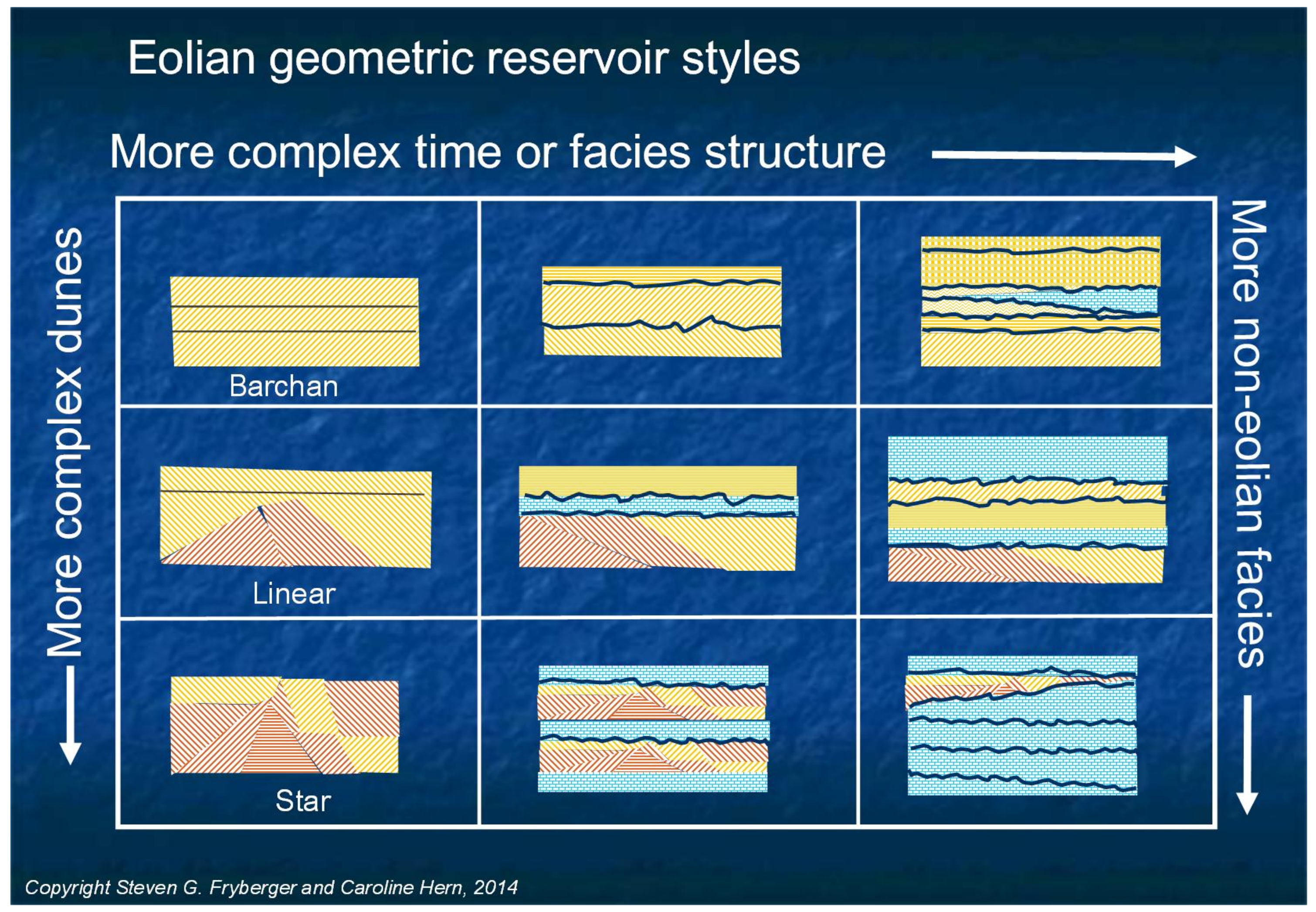
The core on the right (above) illustrates the very small scale differences in permeability to oil typical of many eolian reservoirs. Such effects can drastically reduce sweep efficiency despite apparent high porosities on logs or even plugs taken at one- foot intervals.

Obtaining the optimal recovery factor from eolian reservoirs in the USA or globally requires a variety of techniques, with most recovery commonly in the secondary phase of development.

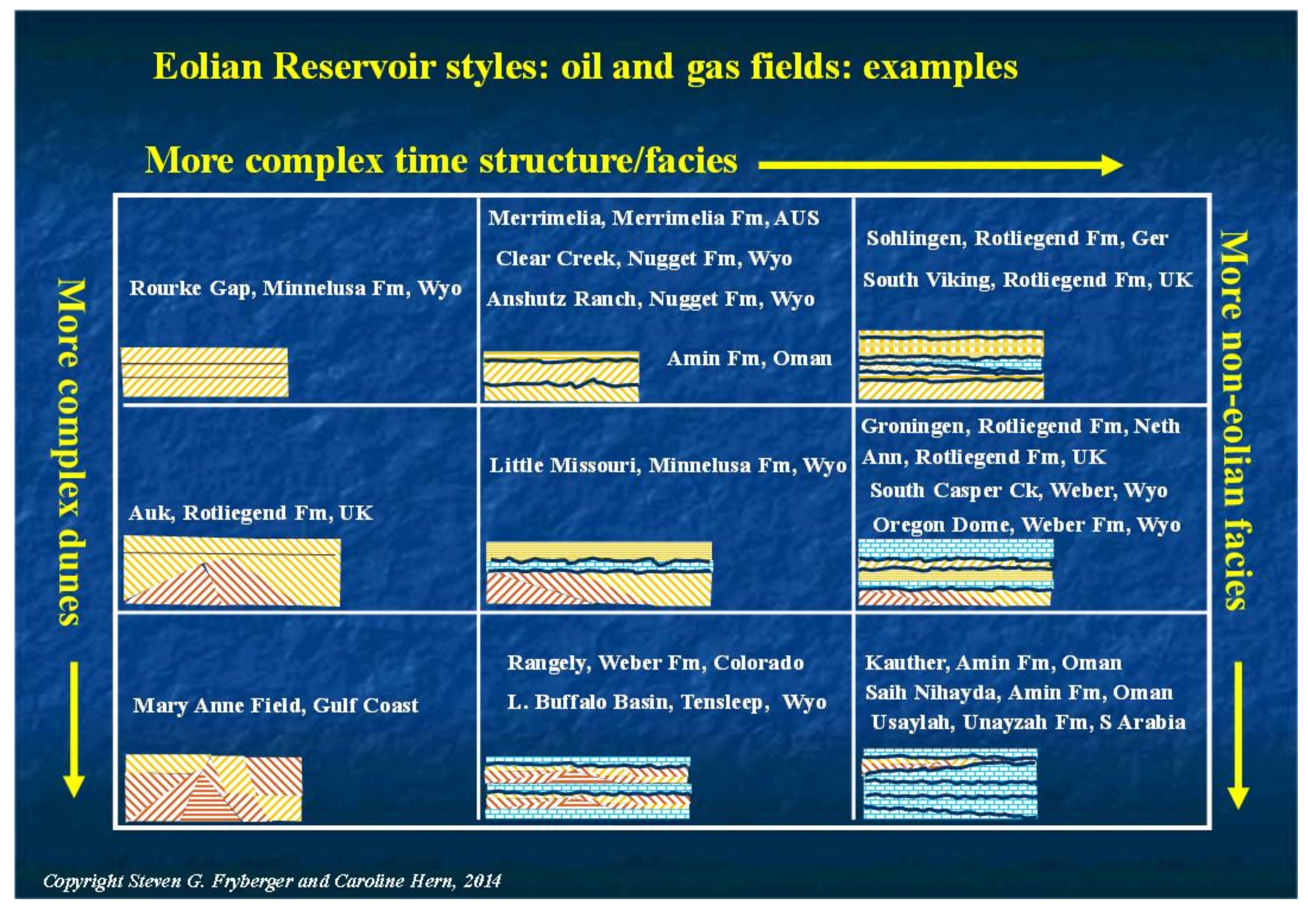




Ultimate recoveries of oil and gas can be impressive, if correct secondary and tertiary recovery techniques are used, which involves careful consideration of infill pattern versus reservoir geometry. From a commercial standpoint, planning that constrains over-optimistic assumptions about kH (permeability height) can improve estimates of the number and style of flood patters (input-offtake points) in both new and older fields. Colors of these diagrams follows the Shell scheme: red for oil and green for gas.



On this diagram dune type is a proxy for crossbed complexity at various scales and for various eolian facies groups with different styles of crossbedding. The ultimate style-group of any reservoir depends upon the number of significant bounding surfaces (shown on slide by wavy black lines) and the number/complexity of interbedded non eolian, non-reservoir rocks in the system. We do not undertake to show microscopic factors explicitly in this diagram - although the diagram is essentially without scale and thus could be used for this small-scale analysis.



The association, roughly, of styles of oil field lithology versus the basic geometric types shown on our diagram above. There is an oil/gas field for every architecture. Assignments are for discussion only, we have not completed exhaustive studies of these fields. Assignments are based on published data only.

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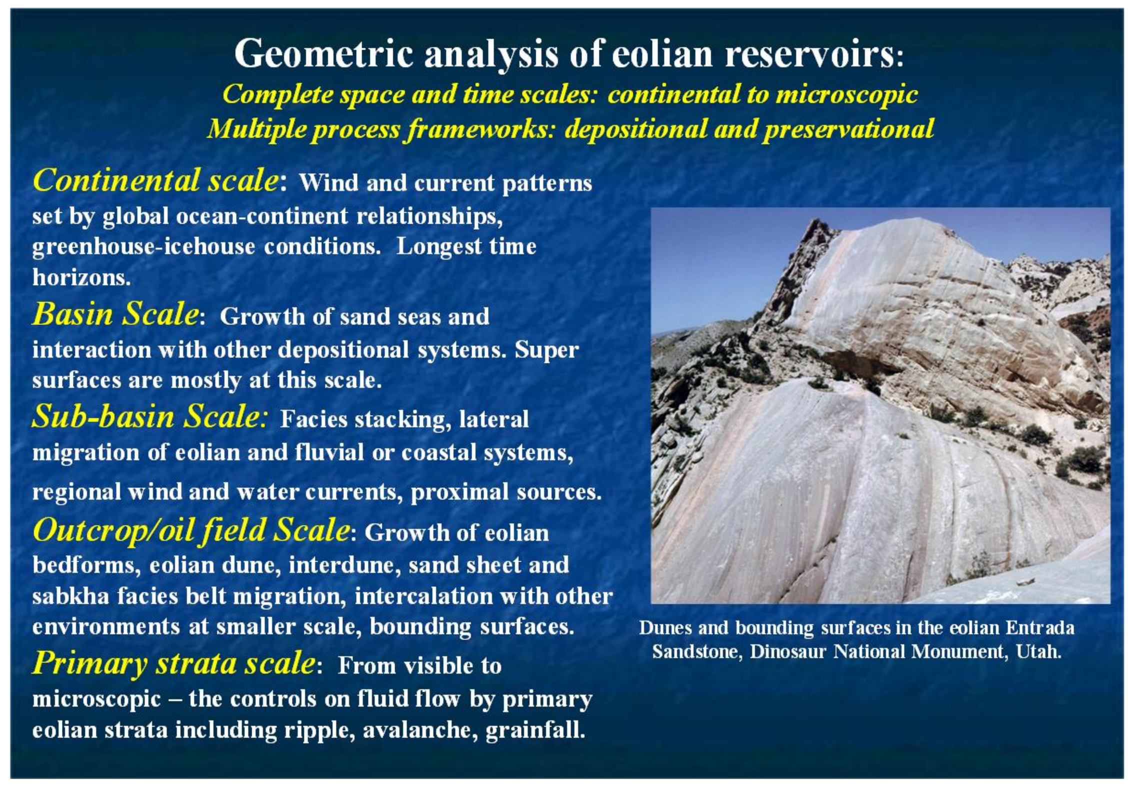
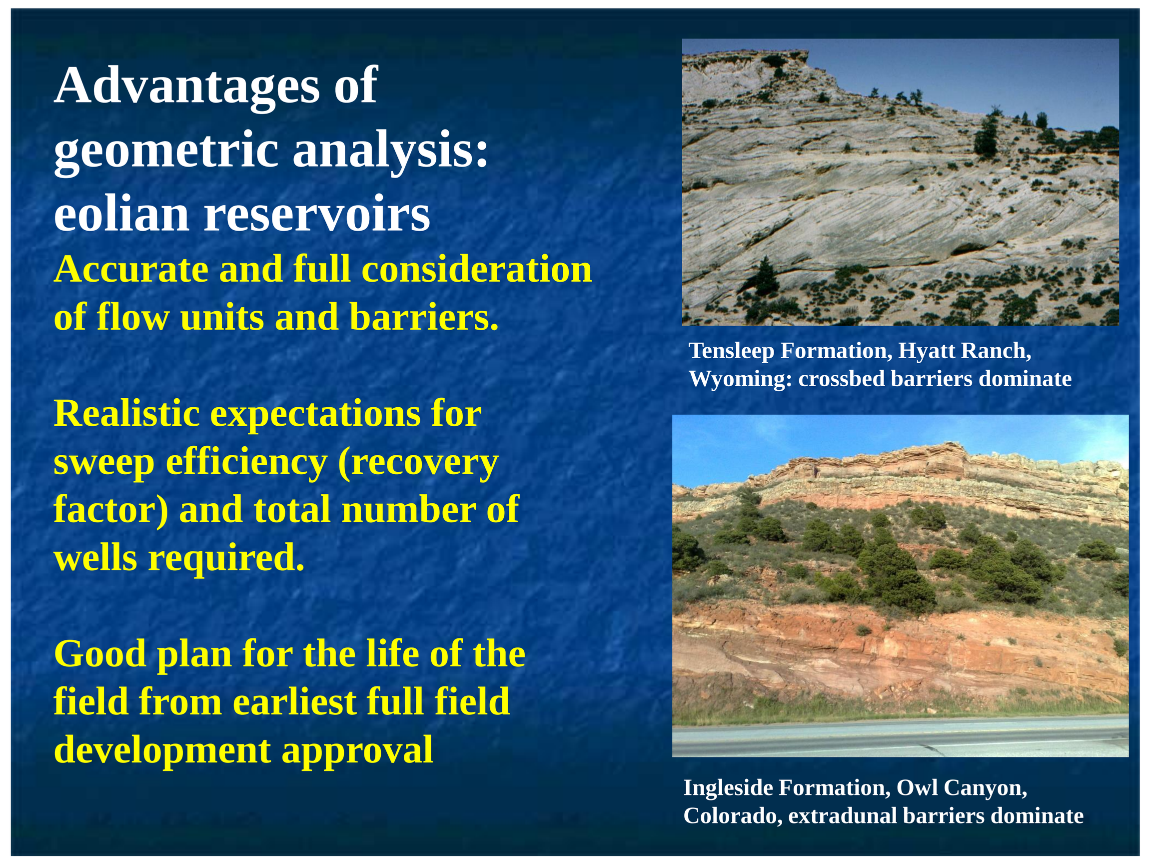
*1 Enhanced Oil Recovery Institute, University of Wyoming
*2 Shell Exploration and Production, Houston, Texas

Enhanced Oil Recovery Institute

Poster 2: Visualizing Scale Factors

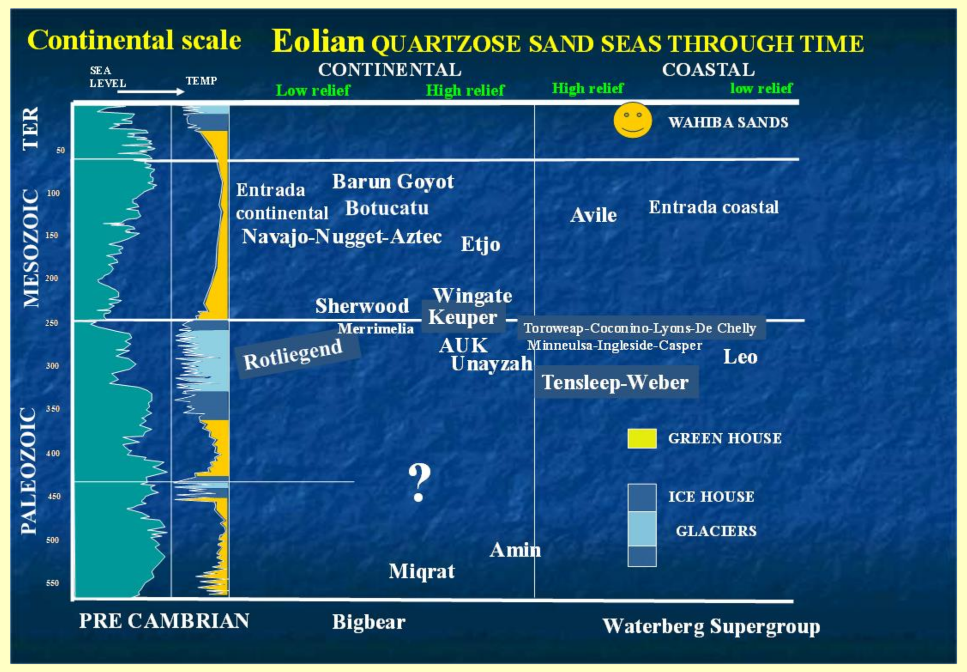


This figure summarizes the five scale elements that commonly exist in eolian reservoirs worldwide. One could split out more of them. The important idea is to recognize that in a given reservoir, any one of these scale factors and associated process frameworks could dominate the performance of the reservoir. Part of the art of development geology is to recognize, then sort out lithologies that result from the operation of processes at the various scale factors. Implicit in all these factors is TIME involved in creating the reservoir, and missing section (time) due to erosion or non-deposition.

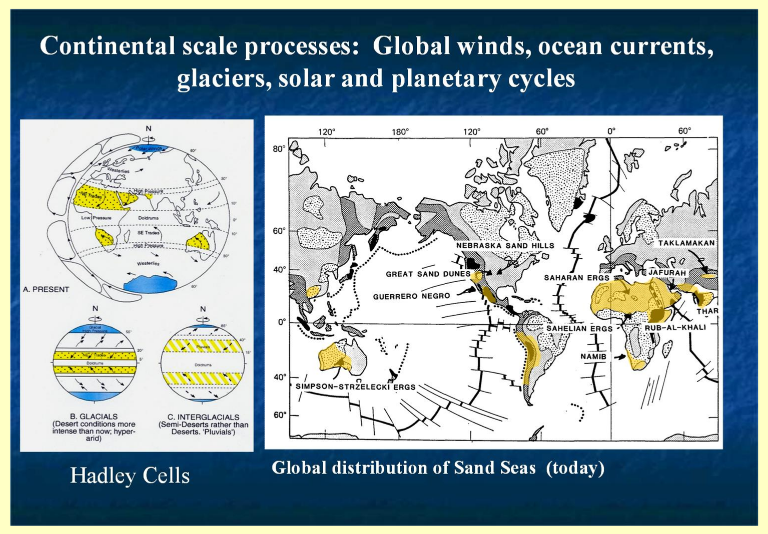


The advantage of using a so-called "geometric approach" to eolian reservoirs is that it requires one to seek out the correct scale elements in populating a reservoir model. Using a table that implies scale and compares geometries invites consideration of the most appropriate analogue. It also suggests full consideration of all parameters of a reservoir explicitly - as opposed to approaches that might be overly focused on one or another of several scale effects present in a reservoir. For example, over-concentration on interdune distribution, might neglect primary strata type as a control on ultimate recovery. On the left, a couple of our favorite images. Above, the (Permian) Tensleep Sandstone, Hyatt Ranch Member, doing an impersonation of the Navajo Sandstone, with many dunes stacked vertically. At the other extreme, the image on the bottom shows interbedded eolian and fluvial sandstones (Lower Ingleside-Fountain) near base of the outcrop. Above at the top of the cliff are stacked dunes, shoreline sands and nearshore marine carbonates. This is part of the Owl Canyon (Permo-Penn.) Ingleside Fm. outcrop near Fort Collins, Colorado.

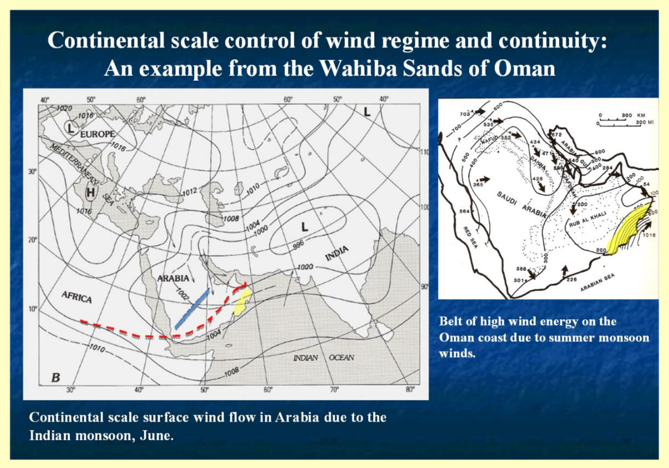
Continental scale, deep time



At the global scale, climate, sea level and continental position can be key drivers of reservoir evolution. Reservoirs deposited during drastic climate changes of glacial times "Icehouse earth" are likely to differ from those of warmer "greenhouse earth" times.

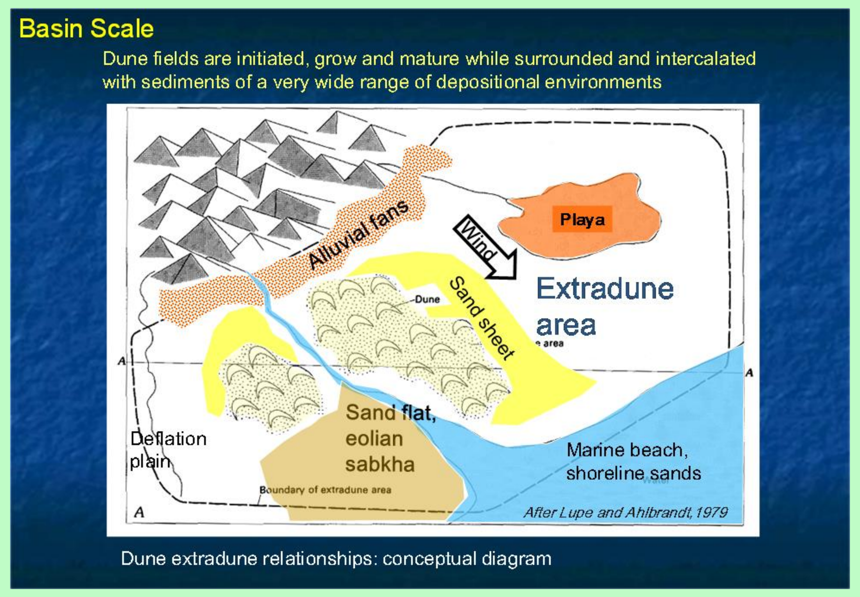


Position of a sand sea with respect to continental land masses, global circulatory systems and oceanic currents can have a dominant effect upon the evolution of the sand sea.

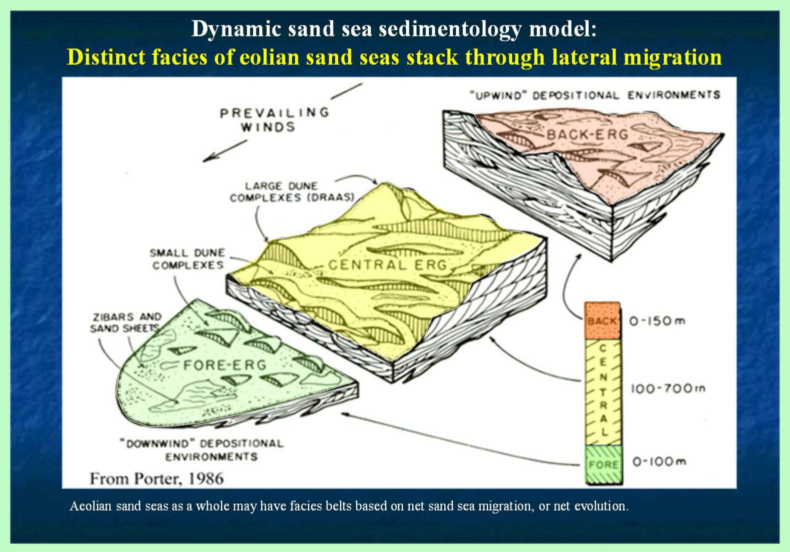


The Wahiba Sand Sea of Oman is dominated at the highest scale order by the Indian Monsoon, a result of the position of that sand sea with respect to the Arabian peninsula, the Indian Ocean, and the Indian Subcontinent. Thus, winds from the south have dominated the Wahibas during its evolution.

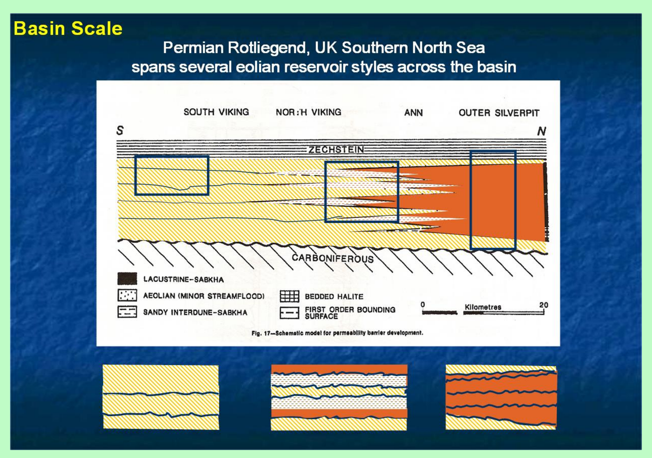
Basin and sub-basin scale



An example of a basin-scale, or perhaps down to "dune field" scale view. In nature these geomorphic elements constantly shift, stacking various eolian and non-eolian sediments.

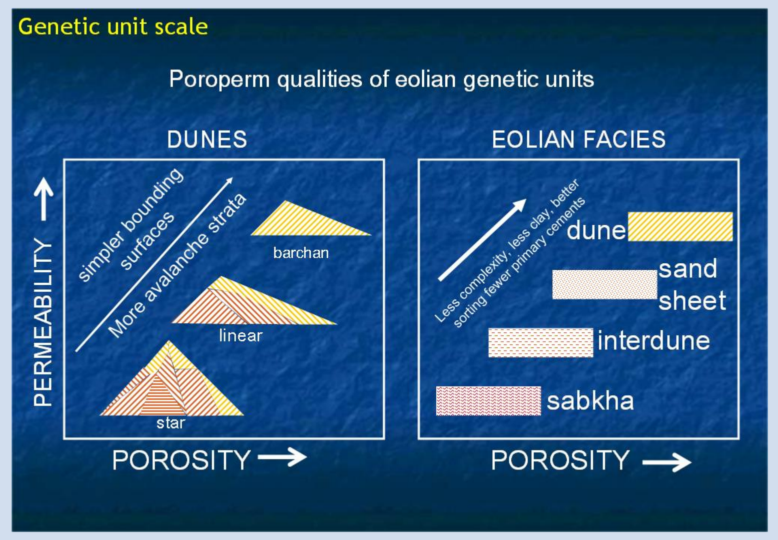


A basin-scale scene viewed from the perspective of a migrating sands sea. In this vision, which is one of our favorites, upwind and downwind elements stack over time. Complete preservation would include the fore- and back- erg facies, all fundamentally dependent upon wind regime. This could also represent a small dune-field with analogous elements.

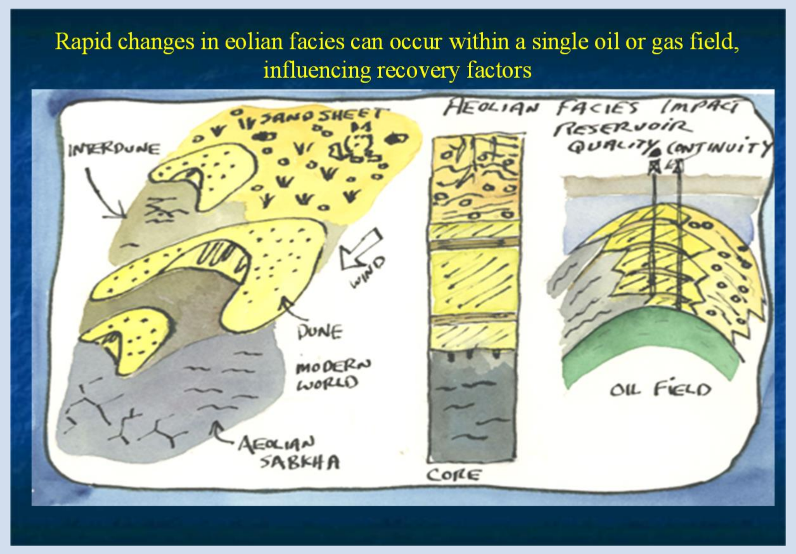


At basin scale, the geometric style of a reservoir within a single formation can change laterally. This example from the Southern North Sea gas province.

Outcrop and oil field scale



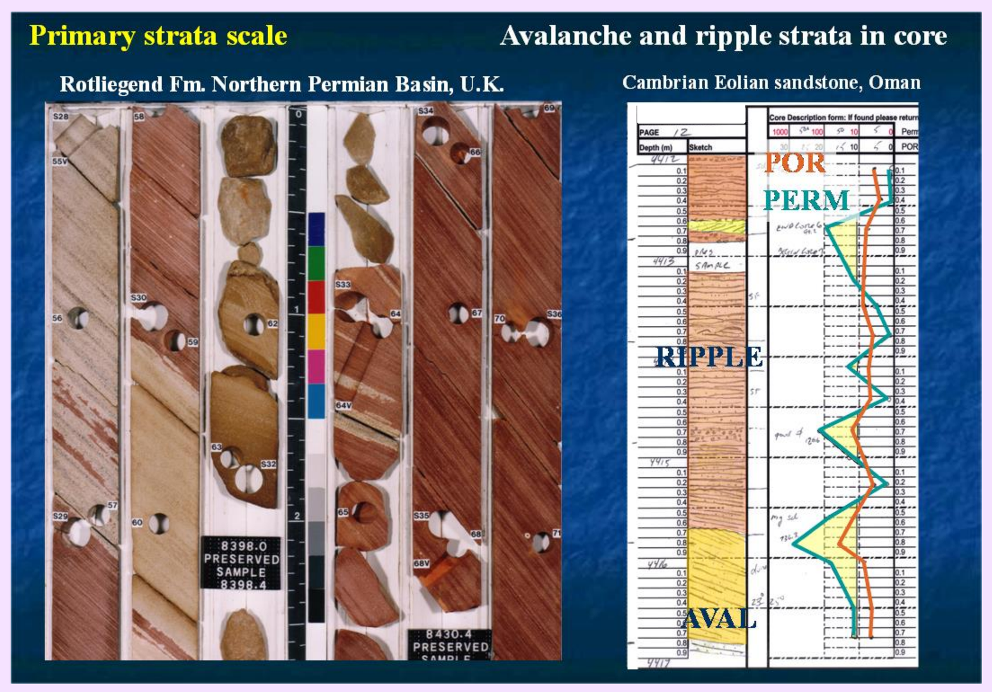
Above: Relative complexity of dune types and eolian facies groups in a simplified manner. There are of course myriad exceptions.



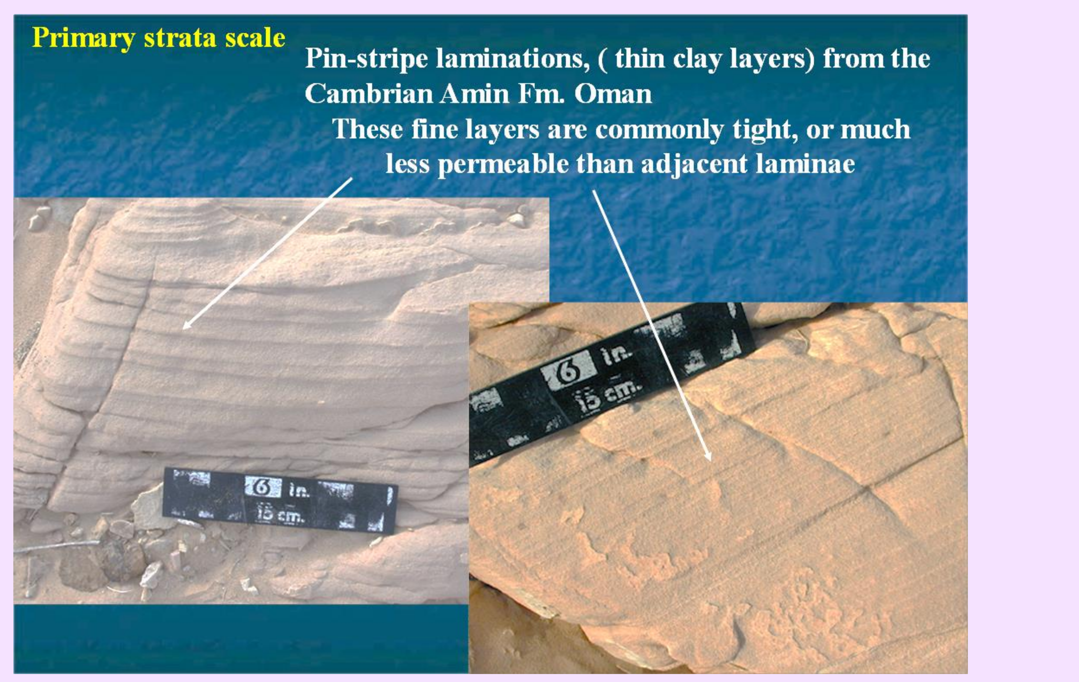
Above: The basic dune types. The images also hint at the possible complexities (individualities) that can occur within a dune type. Note that virtually none of these dunes fits any convenient "cartoon" model. Nevertheless, the idea that arrangement and composition in terms of primary strata will reflect dune type, even considering migration and preservation, is fundamentally correct.

Left: an imaginary landscape becomes a petroleum reservoir. Implications of such a facies belt draped across an anticline are illustrated. This effect would operate at the outcrop or sub-basin scale.

Laminar, bed and microscopic scale



Further examples of the strong impact of primary strata on reservoir properties, and ultimately performance. Note that in the well on the right, a slight increase in porosity results in a drastic increase in permeability, possibly due to larger pore throat sizes.



Inverse-graded eolian ripple strata in the Cambrian Amin Formation, Oman. Pin-stripes separating each lamination commonly have much lower permeability to oil than the lamination as a whole.

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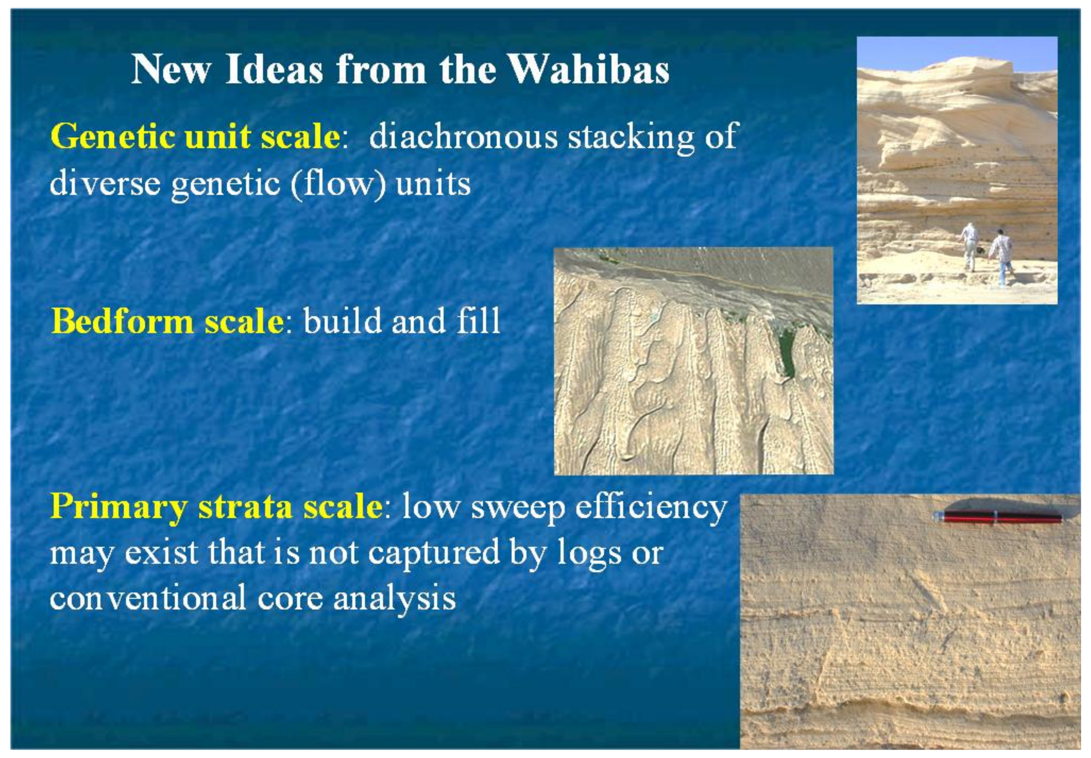
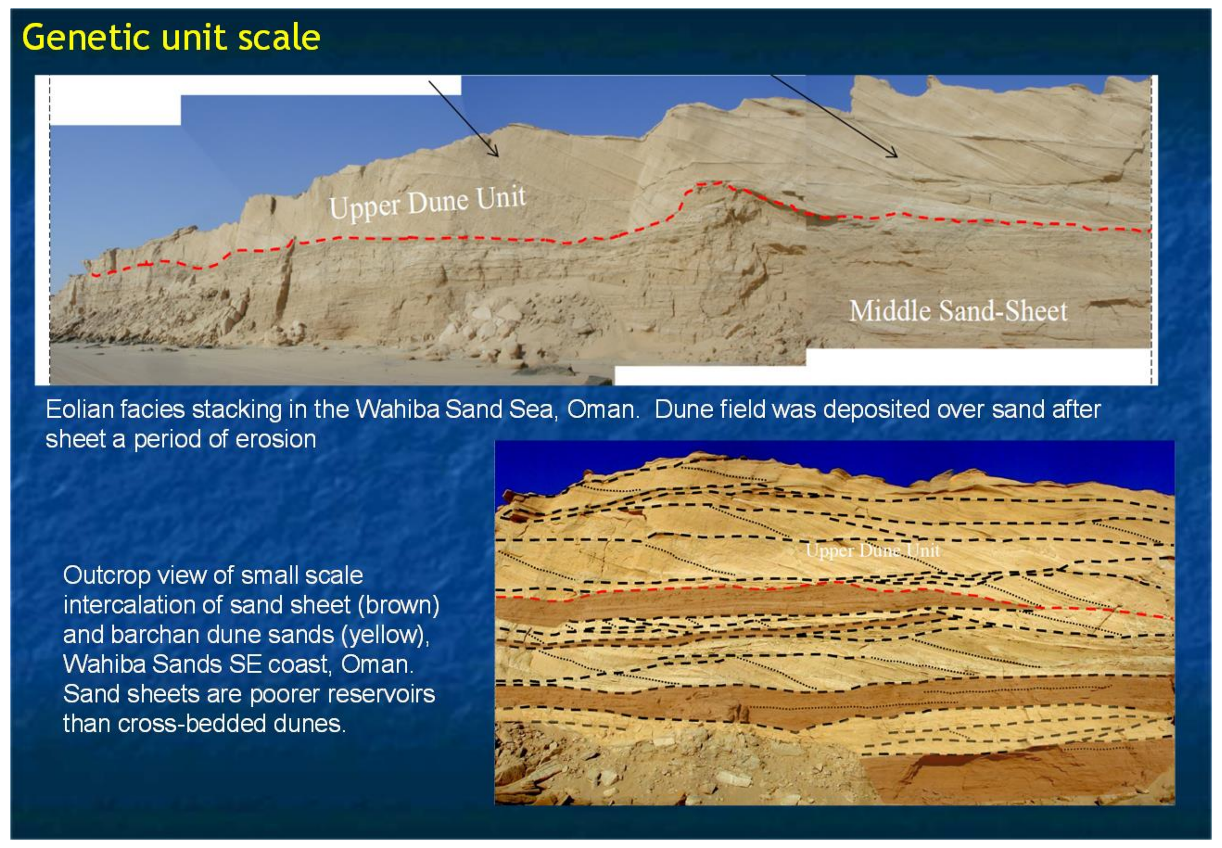
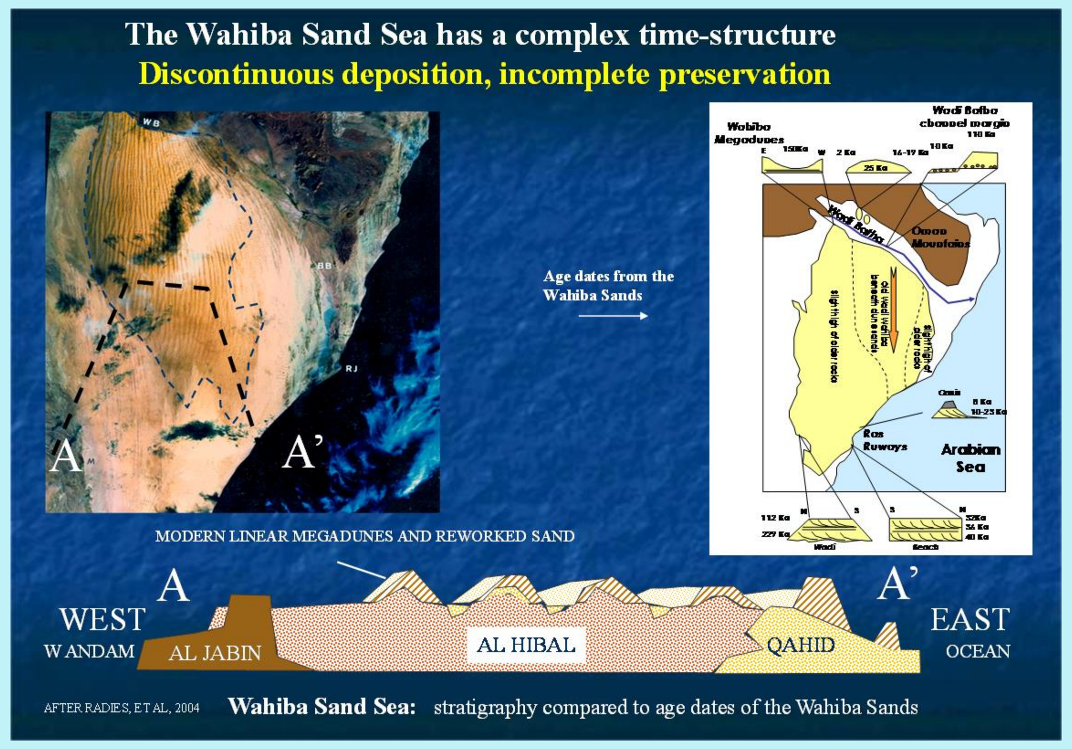
Poster 3: Examples of reservoir geometries derived from modern sediments of Oman- The Wahiba Sand Sea.



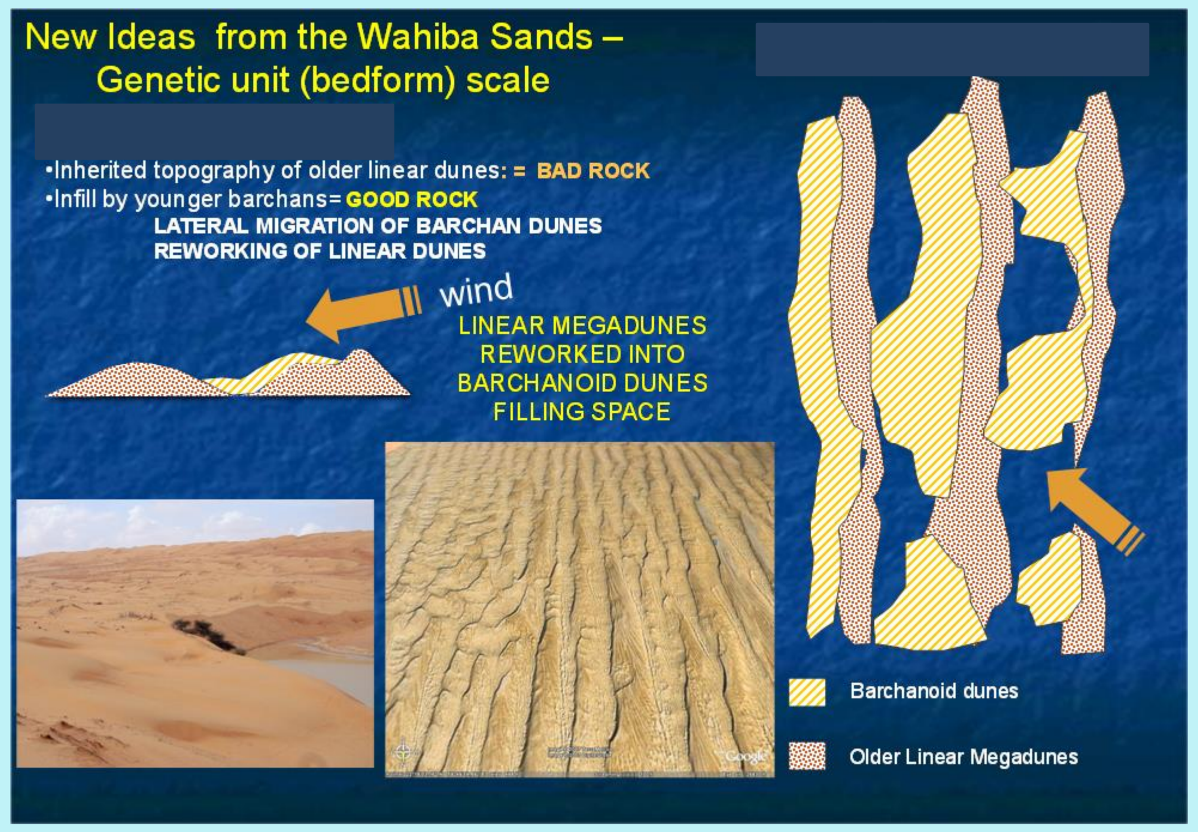
In this poster we illustrate, using the Wahiba Sand Sea as an example, how various processes at various scales can impact reservoir performance. At the bottom of this page, we show the results of simulated petroleum flow driven by these models based on real examples from the Wahibas.



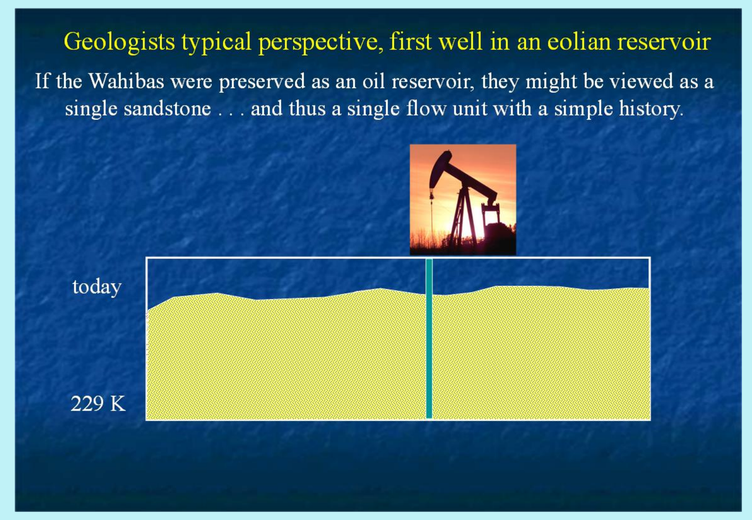
Above: A glimpse of the heterogeneity preserved in outcrops of the Wahiba Sands and modelled for oil production below by co-author Caroline Hern. Outcrops are cemented by carbonate. At the top are two of the major genetic units visible along the coast; the Upper Dune Unit, which preserves build and fill structures, and the Middle Sand Sheet, which is older and more cemented. The bottom panel shows small scale interbedding of crossbedded and sand sheet or interdunal facies at the base of the Upper Dune Unit.



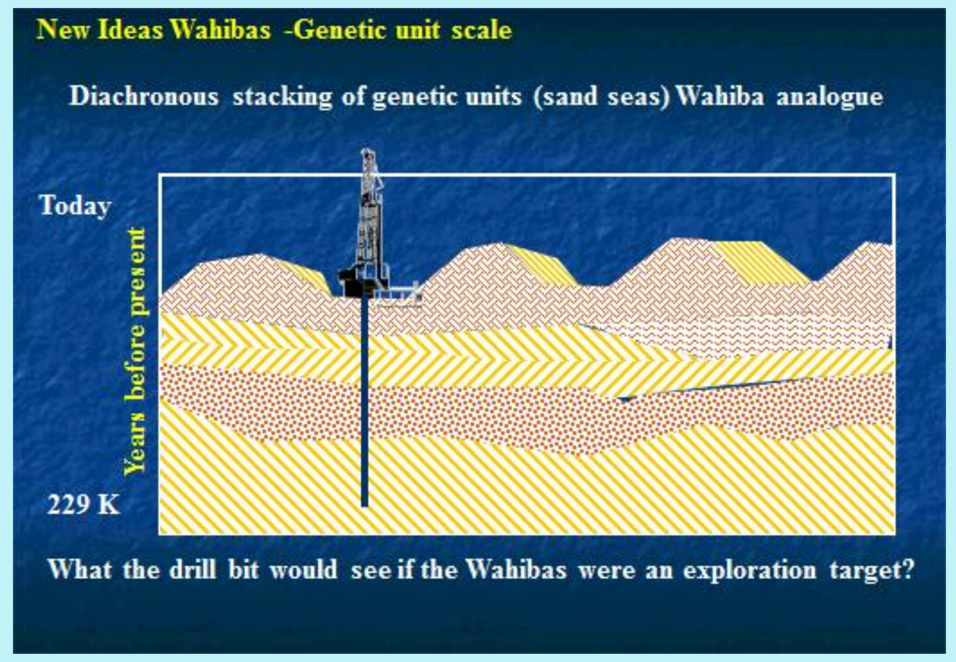
The Wahiba Sand Sea represent at least four sand seas stacked over approximately 200,000 years.

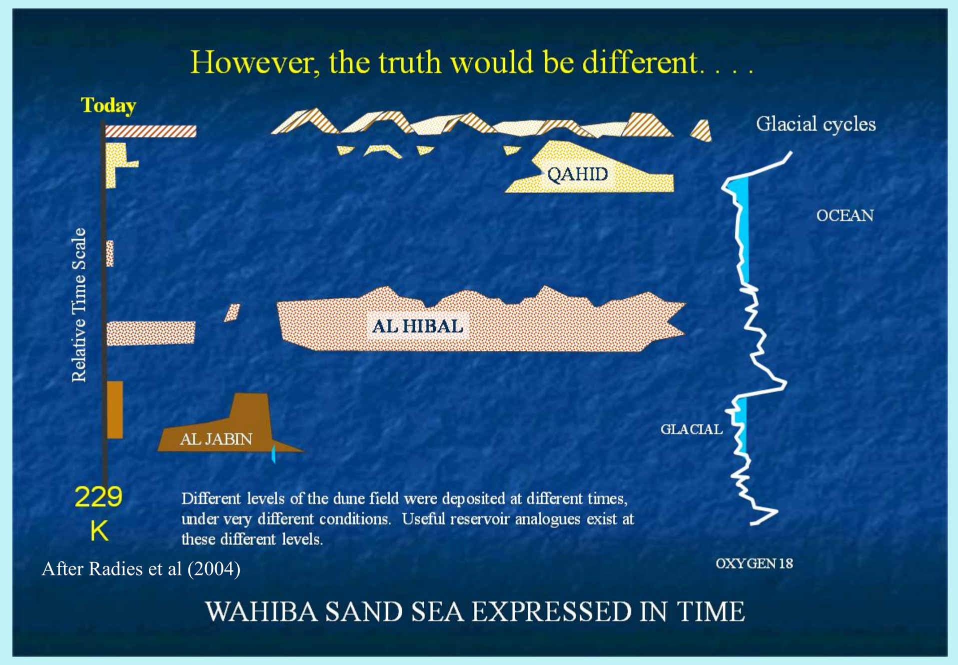


Although bedform climb is an important principle in the accumulation of sand seas, a less familiar process is geomorphic build-and-fill; that is, the creation of local accommodation space by one set of bedforms and subsequent fill by younger bedforms, often of a different type, as illustrated above. Although in some ways counter-intuitive (how could the older bedforms resist the wind?) the fact is that bedform shapes are commonly preserved in ancient rocks, and they can relate directly to oil accumulation and production (see also examples from Minnelusa on Poster 4). In some places such as the Wahibas, the accommodation space is filled by rollover of portions of the earlier bedforms.



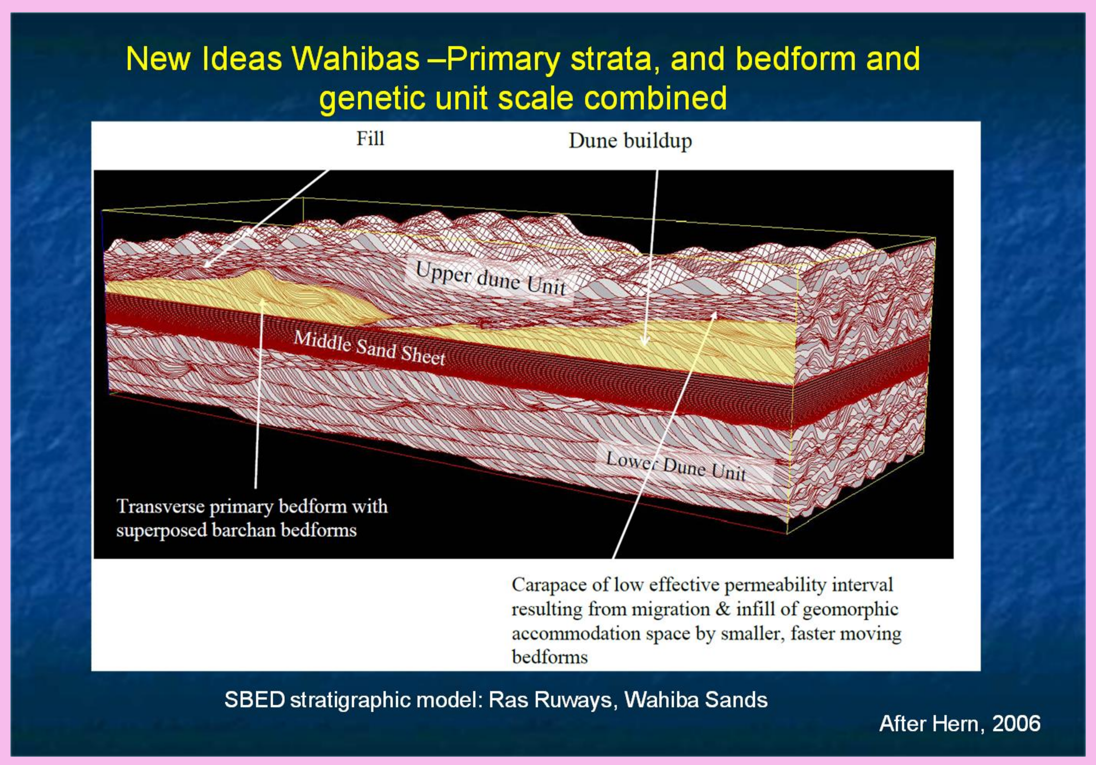
Left: This "tank" of sand is what geologists typically see upon discovery of a new oil field in an eolian reservoir. Early identification of "flow units" may boil down, incorrectly, to "stacked tanks of sand" rather than distinguishing unique qualities of each flow unit. For a fuller story, see below.

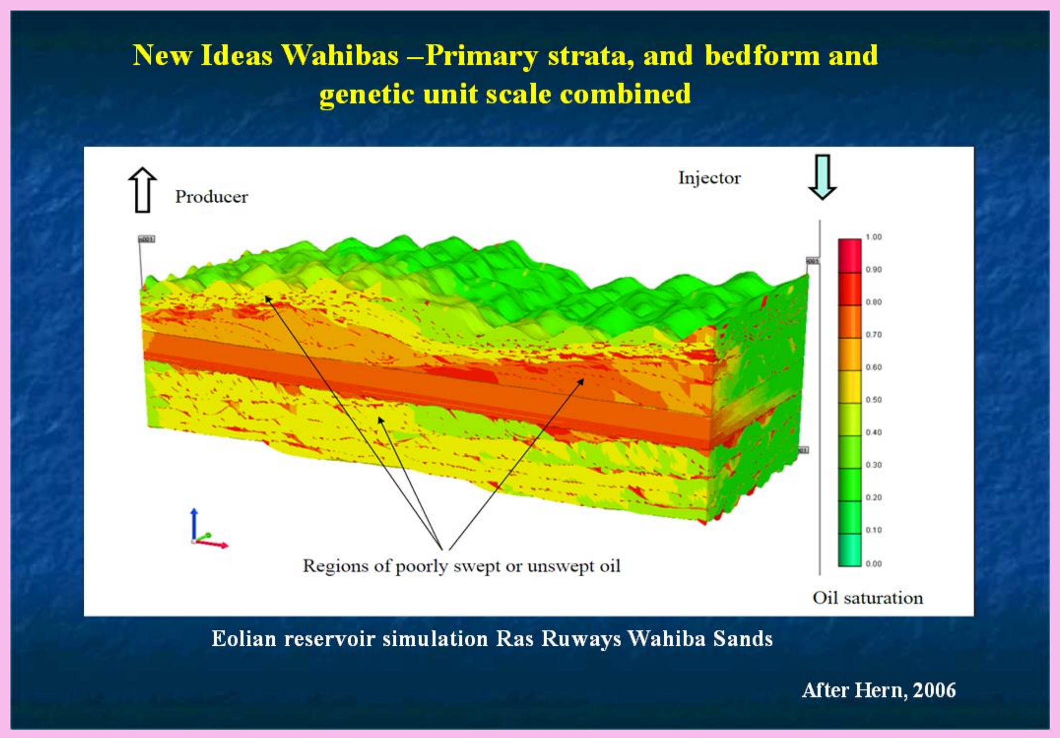


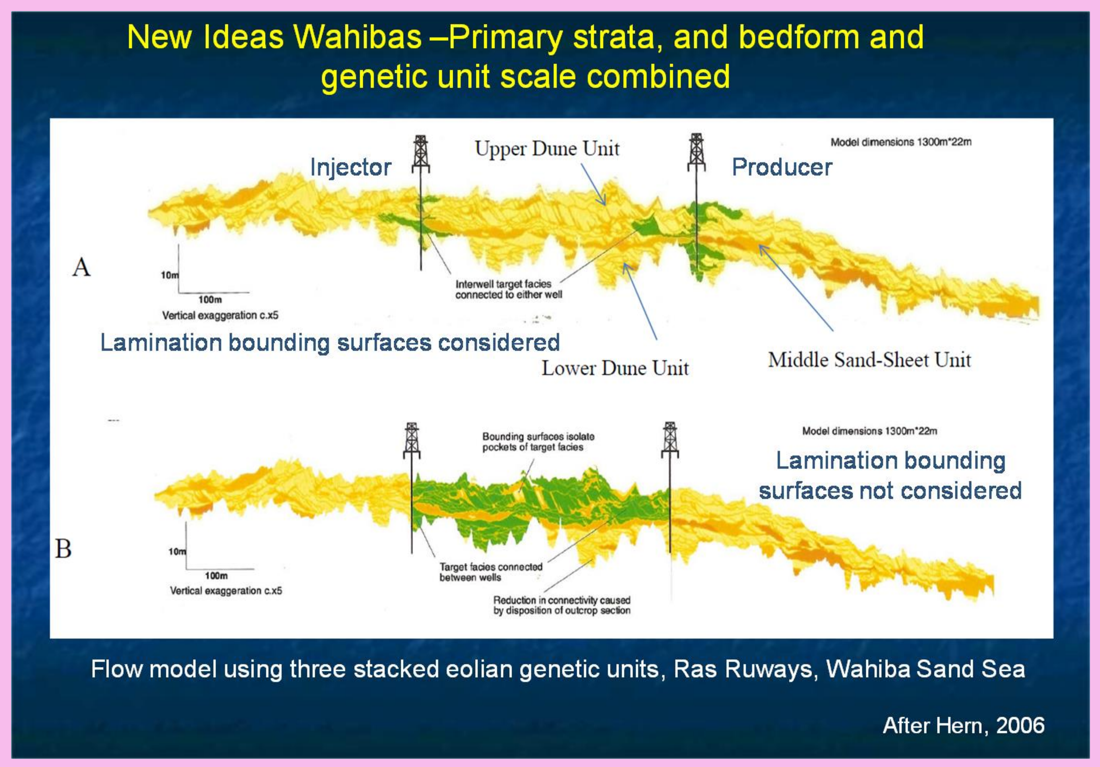


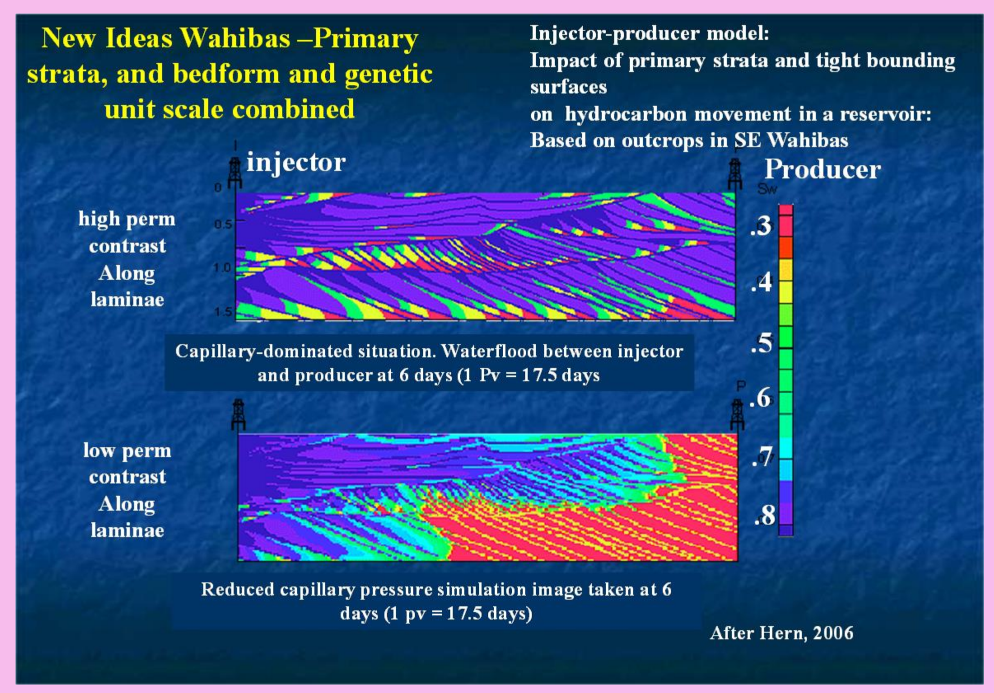
Above: The Wahiba Sand Sea was deposited not as a single "tank of sand" (considered as a petroleum reservoir) but as a series of distinctive genetic units during both glacial and interglacial time. Studies of outcrops and core indicate that each major unit is likely to have different reservoir properties including cementation and crossbedding as well as petrography.

Injector-producer models (oil) based on outcrops at Ras al Ruways, Oman









Above: Complex eolian reservoirs commonly include flow units created by build of dunes and subsequent fill of created accommodation space by eolian sedimentation. Note also (on the far left slide) not only build and fill, but stacking of eolian genetic units that become flow units in the model to the right. The results of the modelling suggest that microscale laminations may greatly reduce sweep efficiency even in reservoirs that appear to have good porosity and permeability in plugs. Build-and-fill concepts need further research, however the Wahibas provides very good modern examples of the processes involved.

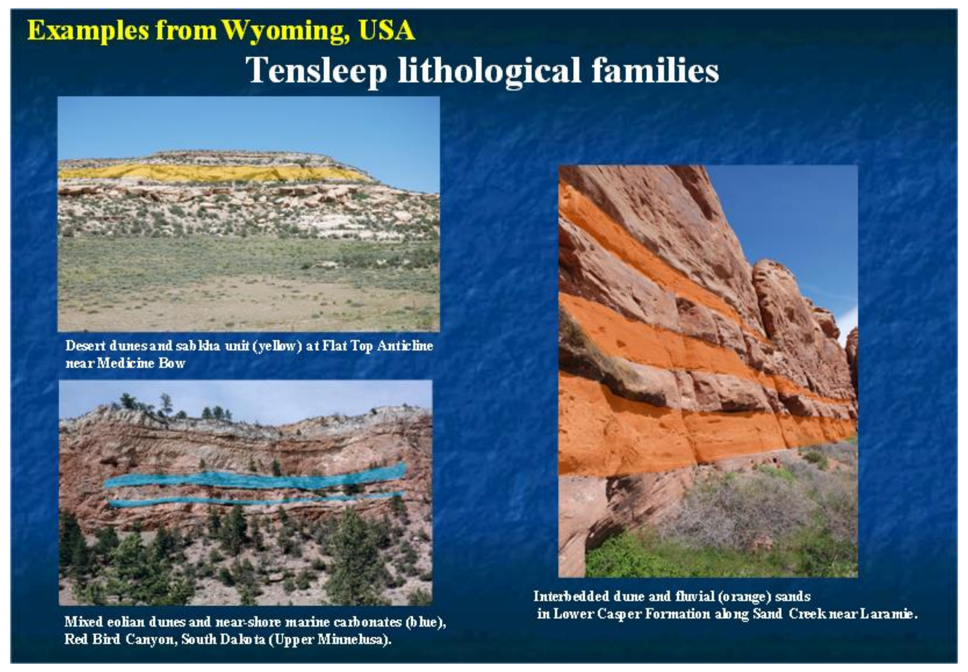
A Geometric Approach to the Analysis of Global Eolian Hydrocarbon Reservoirs

Steven G. Fryberger*1 and **Caroline Y. Hern***2

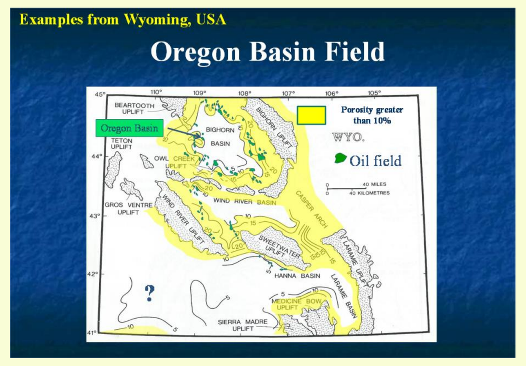
*1 Enhanced Oil Recovery Institute, University of Wyoming
*2 Shell Exploration and Production, Houston, Texas

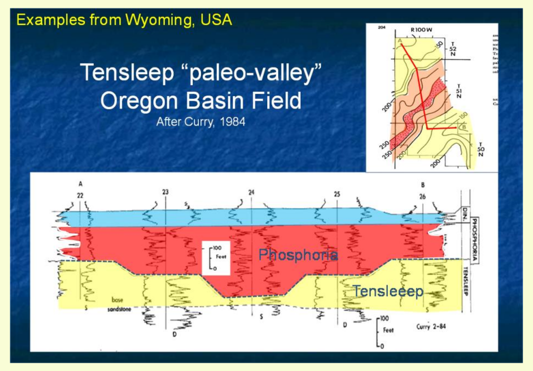
Enhanced Oil Recovery Institute

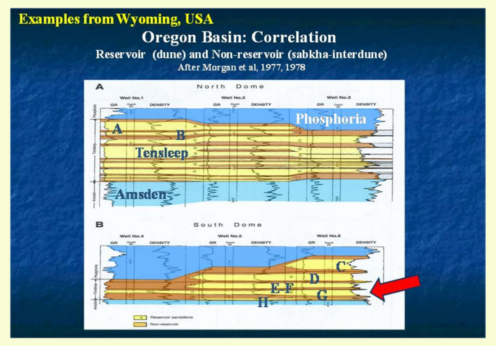
Poster 4: Ideas and examples from Wyoming, USA

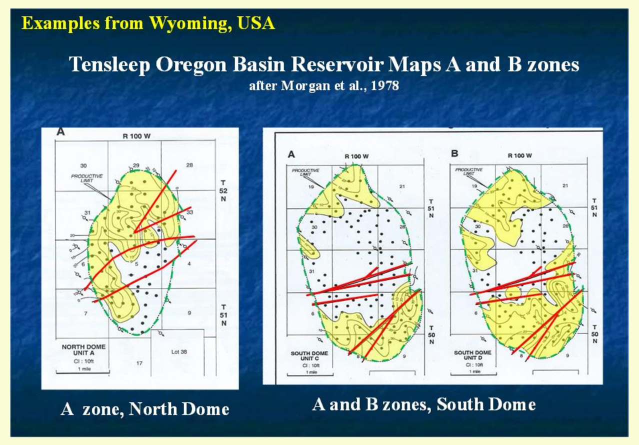


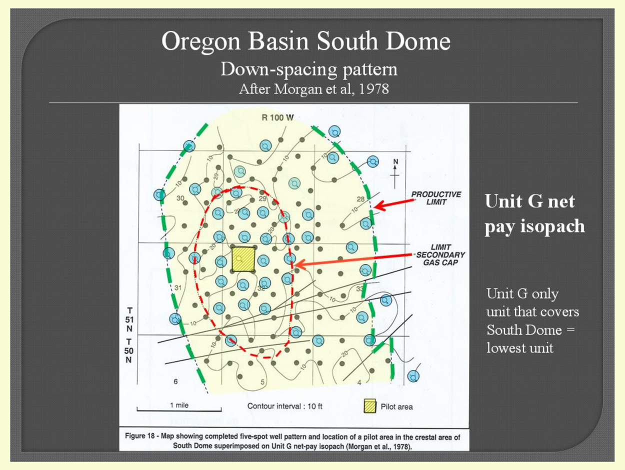
Oregon Basin Oil Field

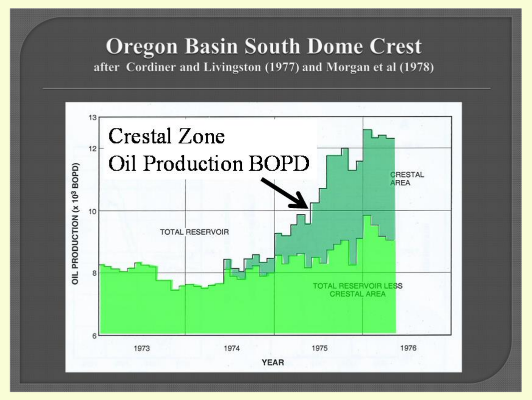


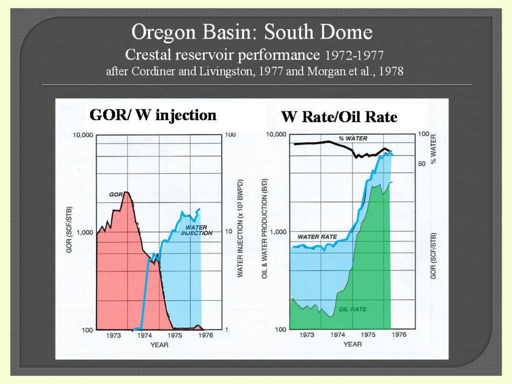


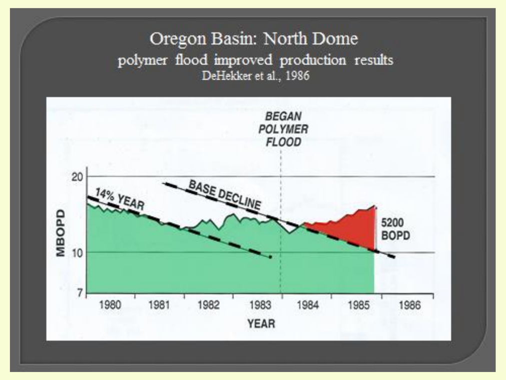






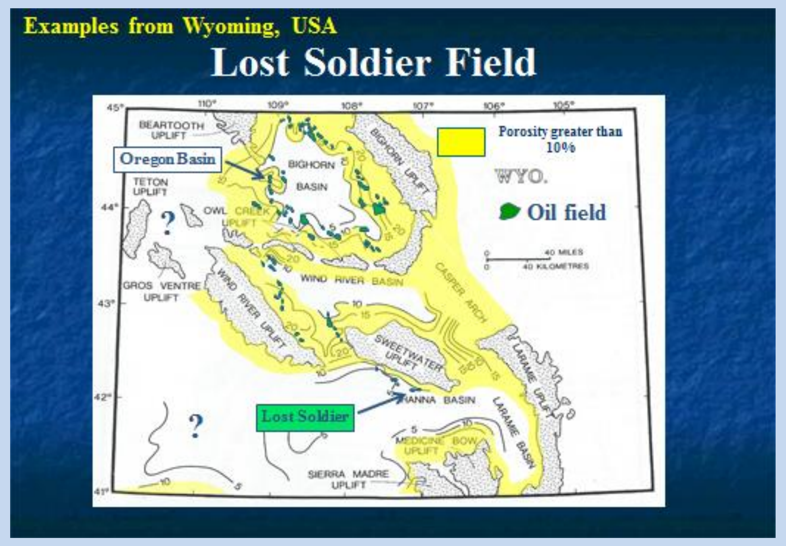


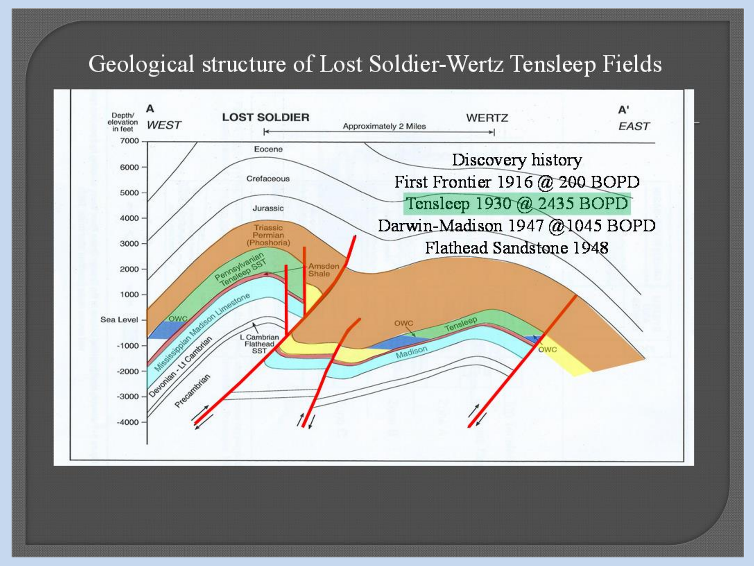


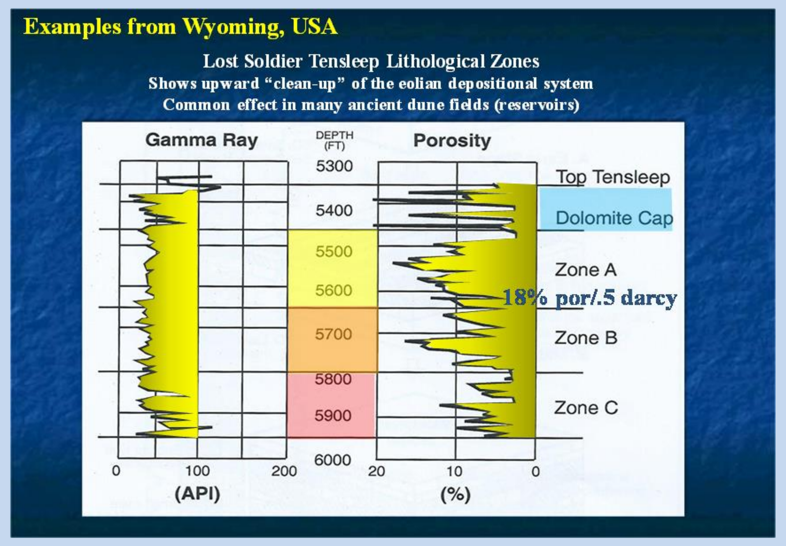


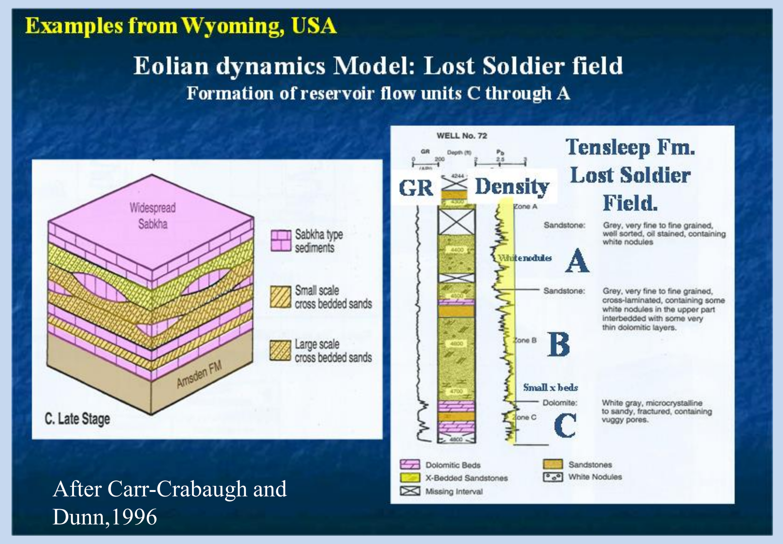
Above: Most Rocky Mountain eolian reservoirs illustrate the need to constantly down-space wells over the life of the field, and to change flood patterns. In some instances, poor sweep efficiency has required this down-spacing in order to recover oil sequestered (stranded!) within the reservoir due to heterogeneities at various scales. At Oregon Basin, the unconformity at the top of the Tensleep chopped the field into a number of separate reservoirs. The crestal zone on the South Dome responded very well to polymer flooding of the G zone, as illustrated in these slides.

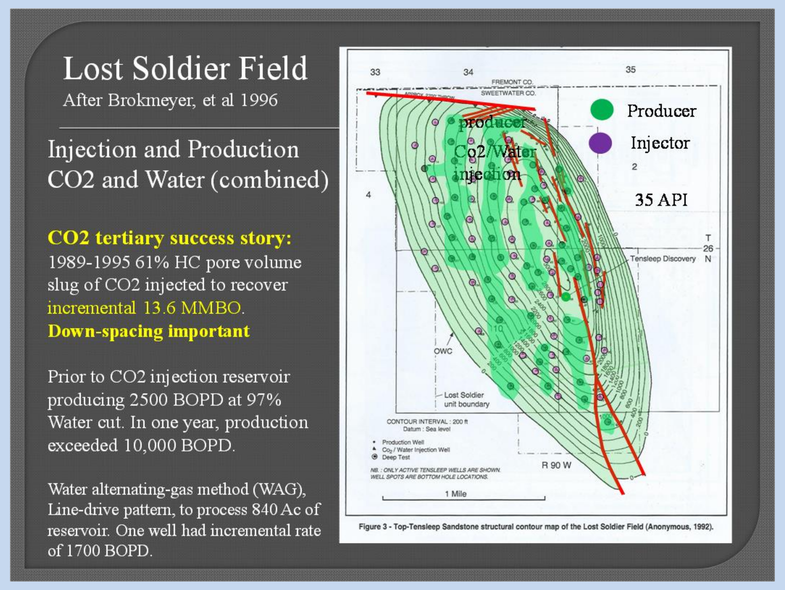
Lost Soldier Oil Field

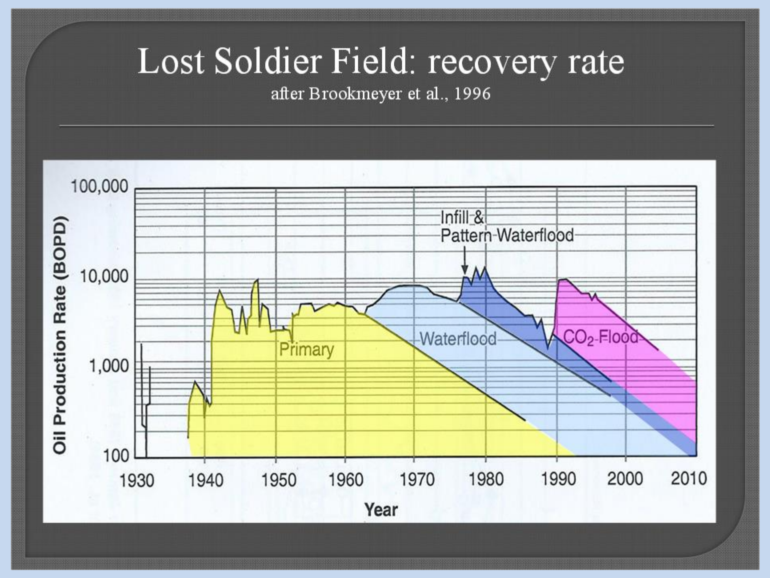






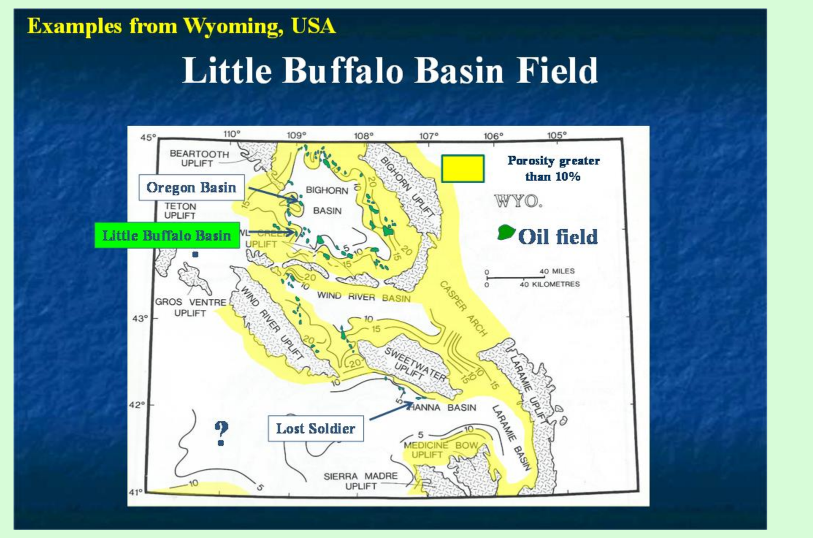


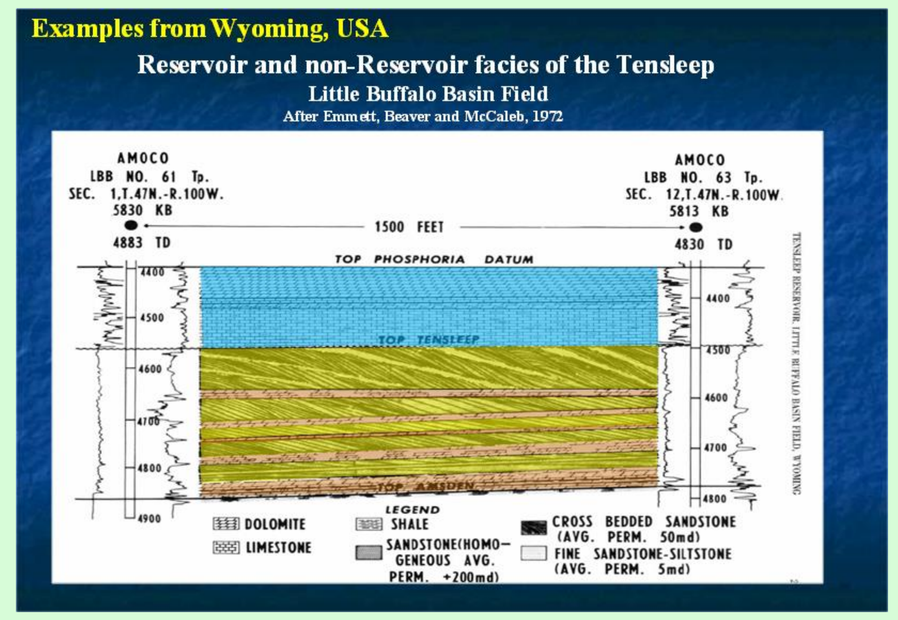


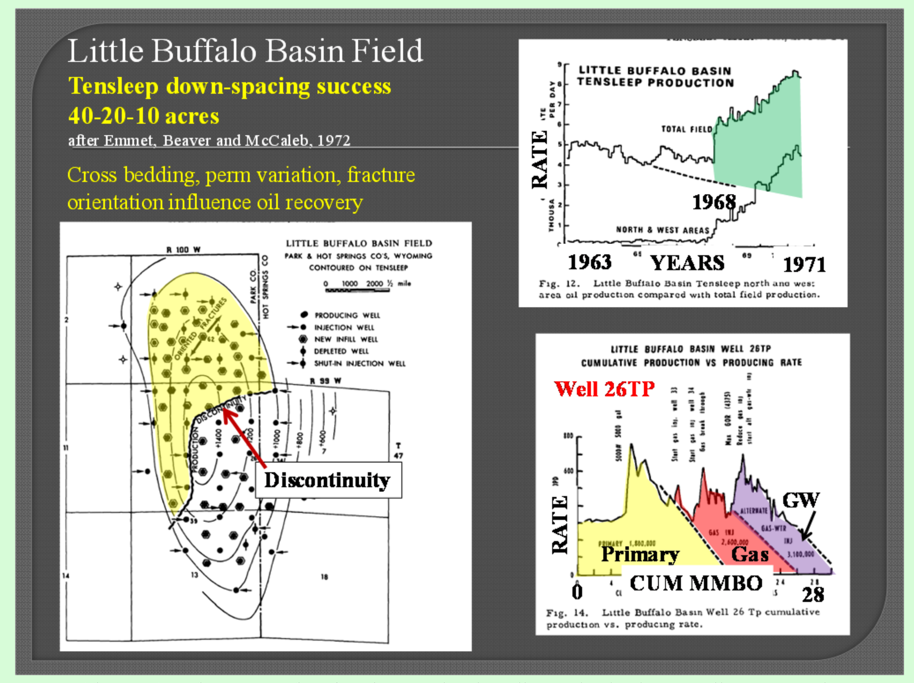


Above: Lost Soldier is one of the large, older eolian reservoirs of the Rocky Mountains. The rocks are a mixture of eolian and nearshore marine sandstones and carbonates in complex stacks. Over time, the field has been down-spaced repeatedly as the rise in oil prices facilitated production of smaller and smaller flow units. The stacking of impermeable marine carbonates between dune units has broken the reservoir into many flow units. Additionally, small-scale cross bedding has probably reduced the sweep efficiency of the heavy oils. Particularly noticeable is the upward improvement in porosity-permeability within the Tensleep as a whole, and evolutionary pattern very common to eolian reservoirs globally.

Little Buffalo Basin Oil Field

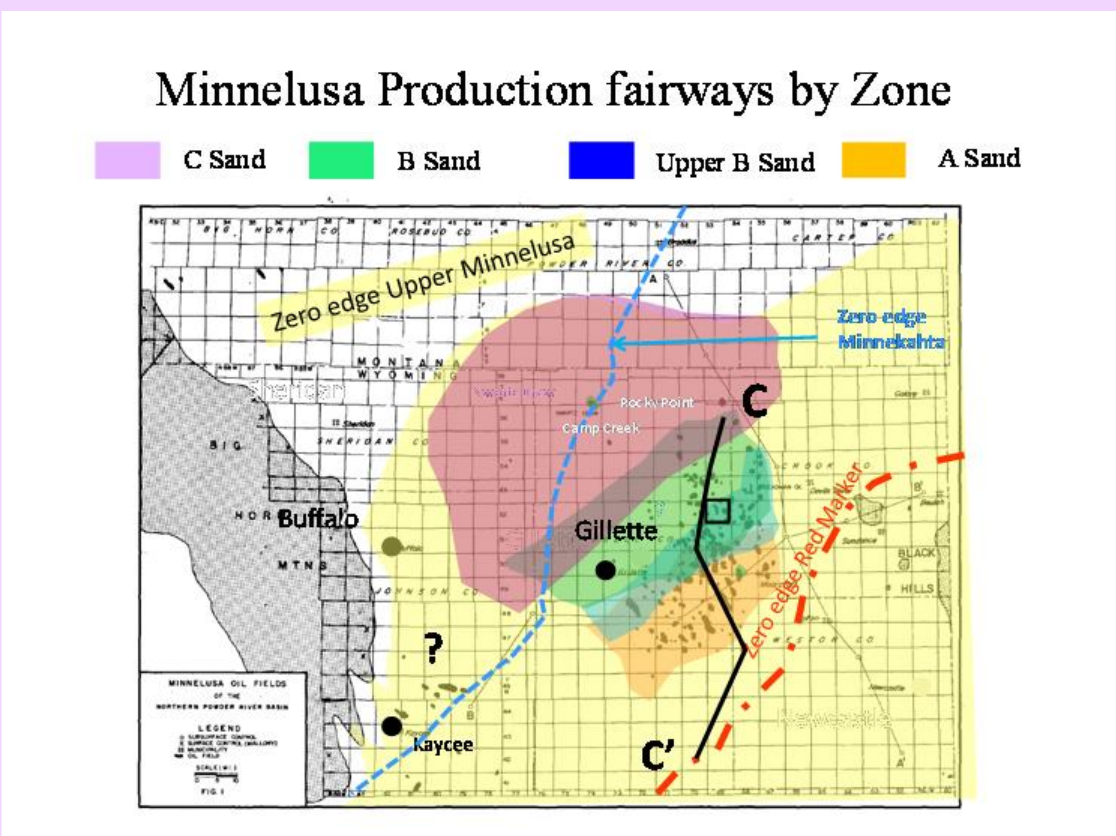


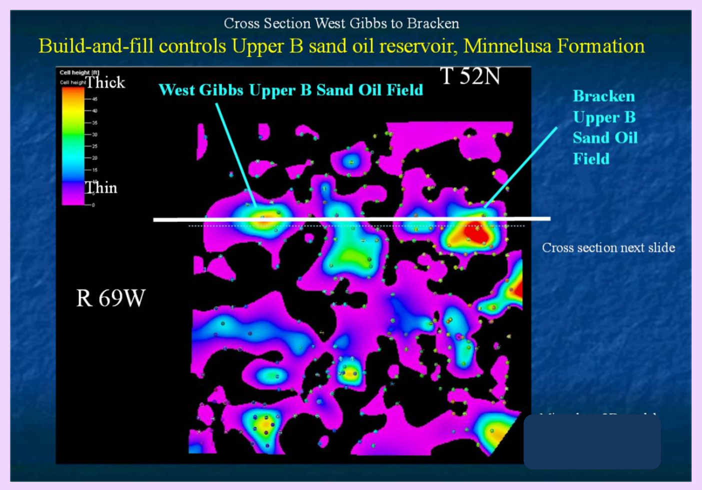


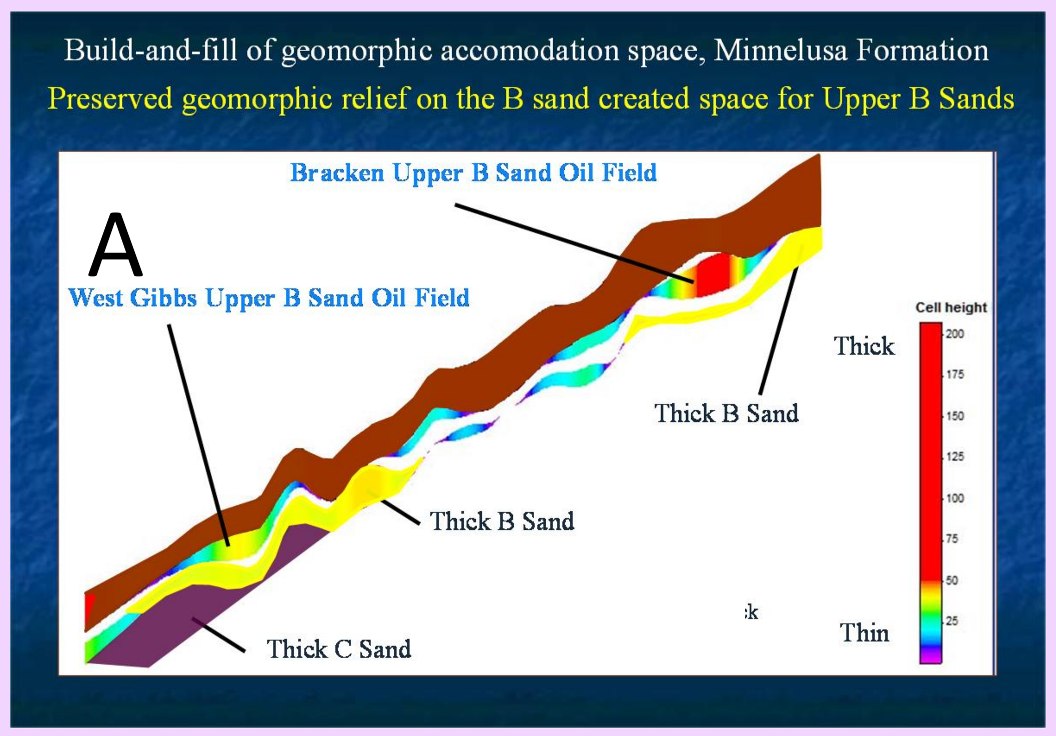


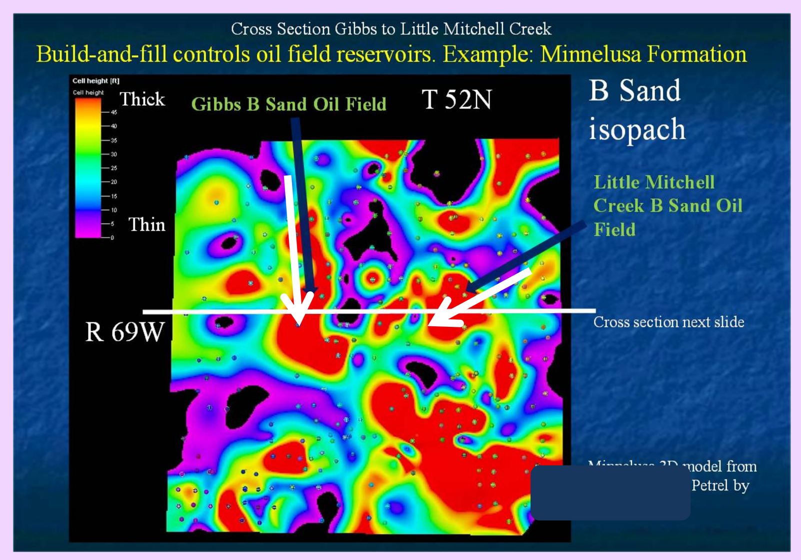
Above: Another example of major production discontinuity in an eolian reservoir. Note the impressive down-spacing required to drain this complex reservoir, as well as the good response to secondary and tertiary floods.

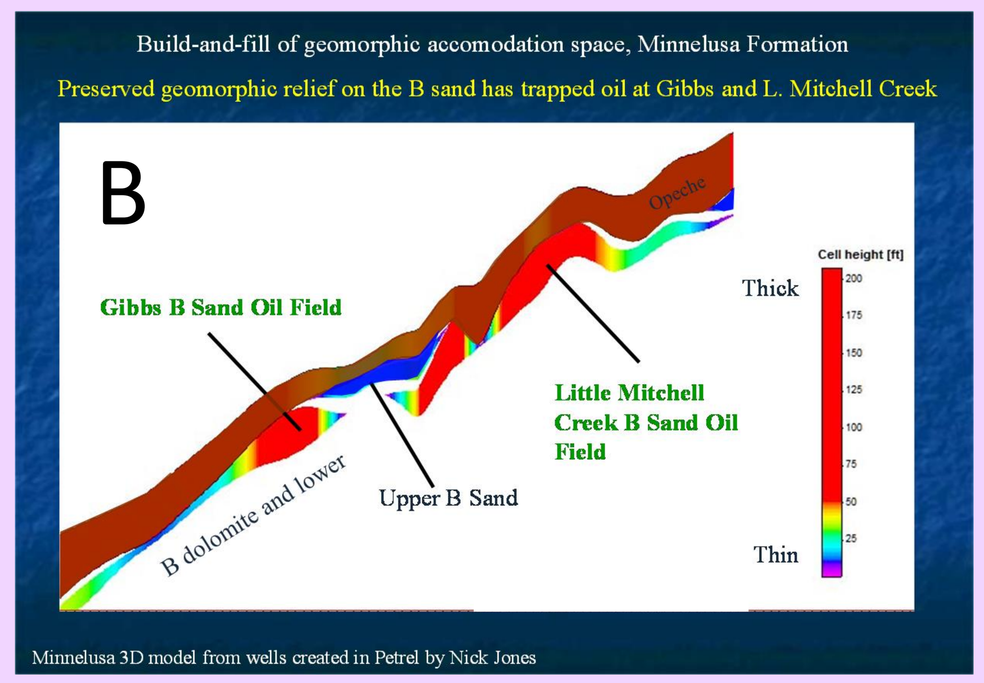
Permian Minnelusa *build-and-fill* eolian hydrocarbon reservoirs, Powder River Basin: the views shown below were created in Petrel by Nick Jones at EORI using subsurface control.











Above: The Minnelusa Formation of Wyoming a fine example of the build-and-fill creation of eolian reservoirs. The examples shown are from T52N R69W in the Powder River Basin. Thickness contours and cross sections were created from well picks by the senior author for this poster session. The figures above illustrate how the Upper B Sand reservoir at West Gibbs and Bracken developed by fill of accommodation space created by underlying B Sand buildups (cross section A). Likewise, B sand fields sand buildups, in part, developed where the underlying C Sand is thin, thus creating accommodation space between the C Sand dunes (Cross section B). Reservoir properties roughly follow thickness in the Minnelusa sands, thus we highlighted thickness values in the cross sections and maps. Red zones are likely to have better porosity and permeability, roughly, than blue zones. The build and fill reservoirs here, developed in the Minnelusa in mainly barchanoid dunes are analogous to the modern example in the Modern Wahibas shown on poster 3, although in the Wahibas we found build-and-fill of both barchanoid forms and linear dune forms rolling over into barchans, partly through reworking of the tops of the linear megadunes into smaller barchanoid dunes. Petrel model showing build and fill was created by Nick Jones of EORI.