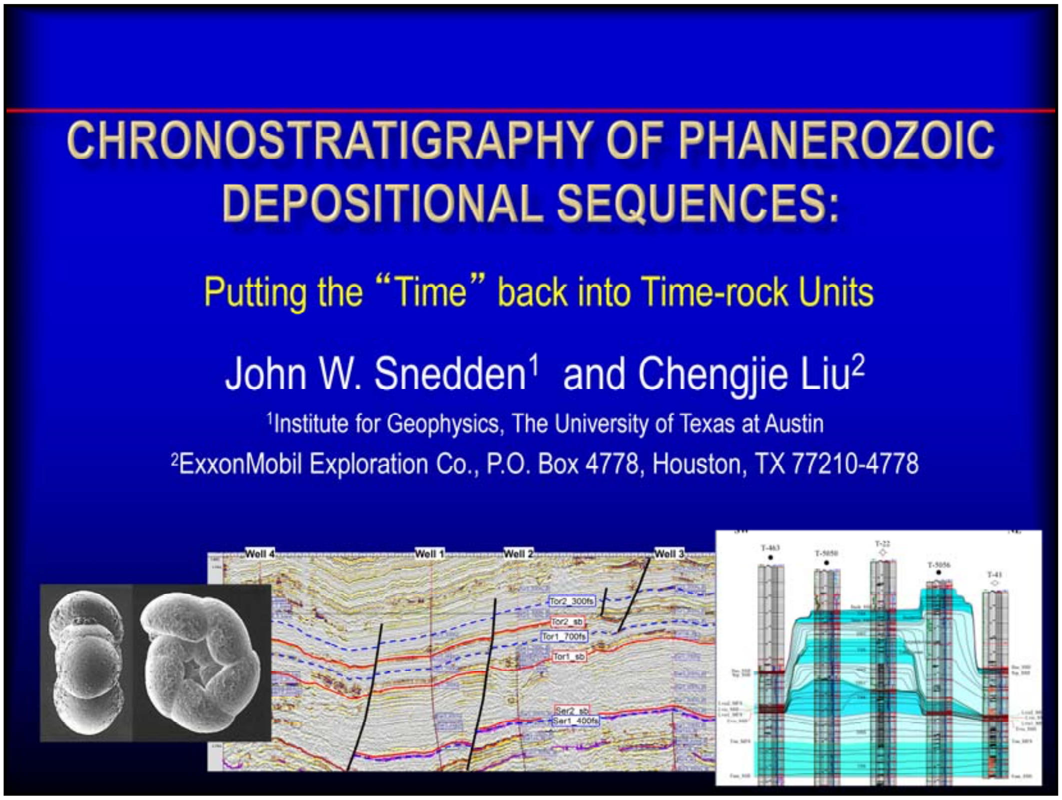
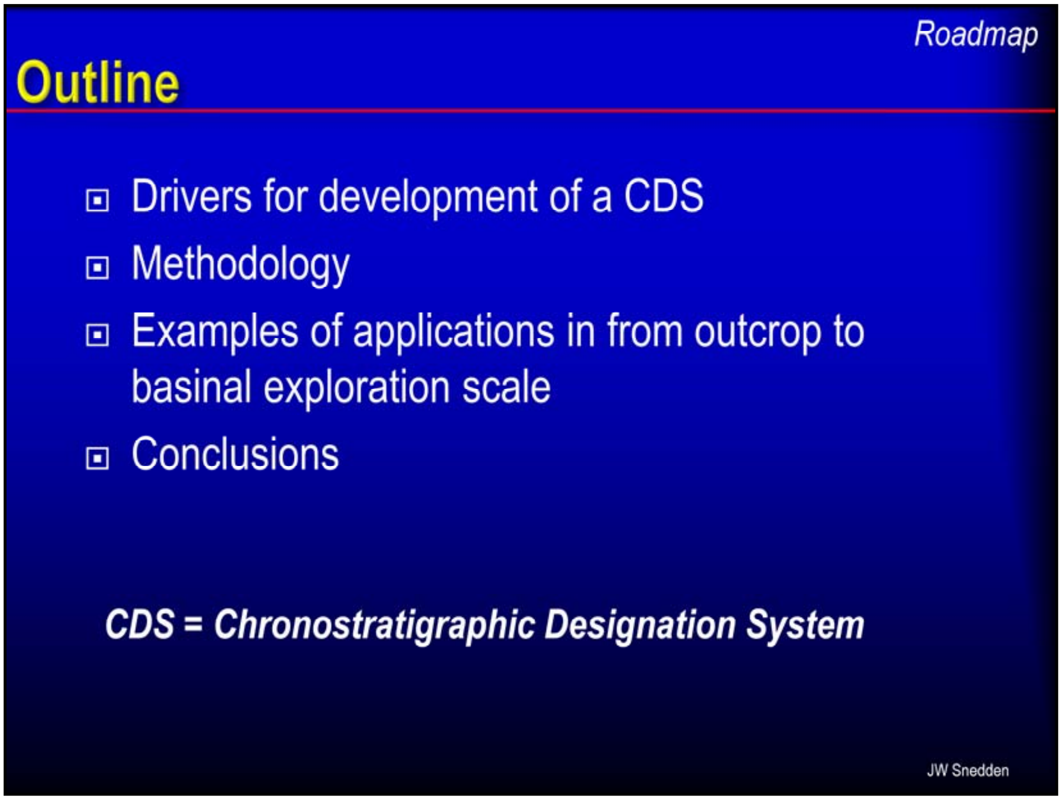


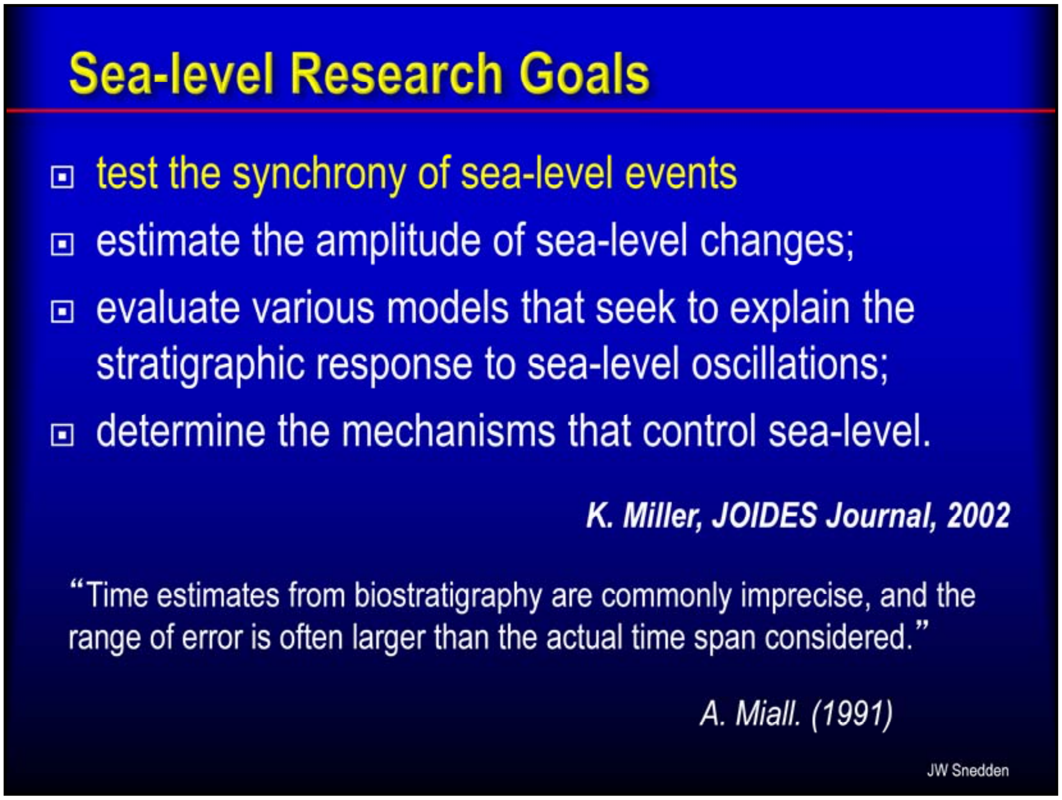
Thanks, I will talking about a chronostratigraphic designation systems that Chengjie Liu, a former Ken Miller Ph.D student, who has worked for us for about 15 years, and I developed and implemented over the last 10 years at EM. While a lot of people identify and correlate surfaces like sequence boundaries, flooding and maximum flooding surfaces they don't always designate these with pertinent age information, as there really is no uniformity in how to do that.

So I guess the subtitle of this talk could be" Putting the "time" back into "time-rock" units, the "chrono" back into "chronostratigraphy". By the way this methodology is being released in a June 2011 AAPG Bulletin.



The roadmap for my talk is shown here, and on each slide in the upper right will be a reminder of where we are. I will first discuss the drivers for and benefits of a chronostratigraphic designation system, then the methodology we used for other last 10 years to integrate physical observations of stratigraphy (like toplap, downlap, etc) with age-constraining data like biostratigraphy to construct the chronostratigraphy of many global basins. I will the show some examples of where we applied this in places like deepwater West Africa, the Paleozoic carbonates of Kazahstan, and even the an outcropping Turonian delta, the Ferron, of Utah.

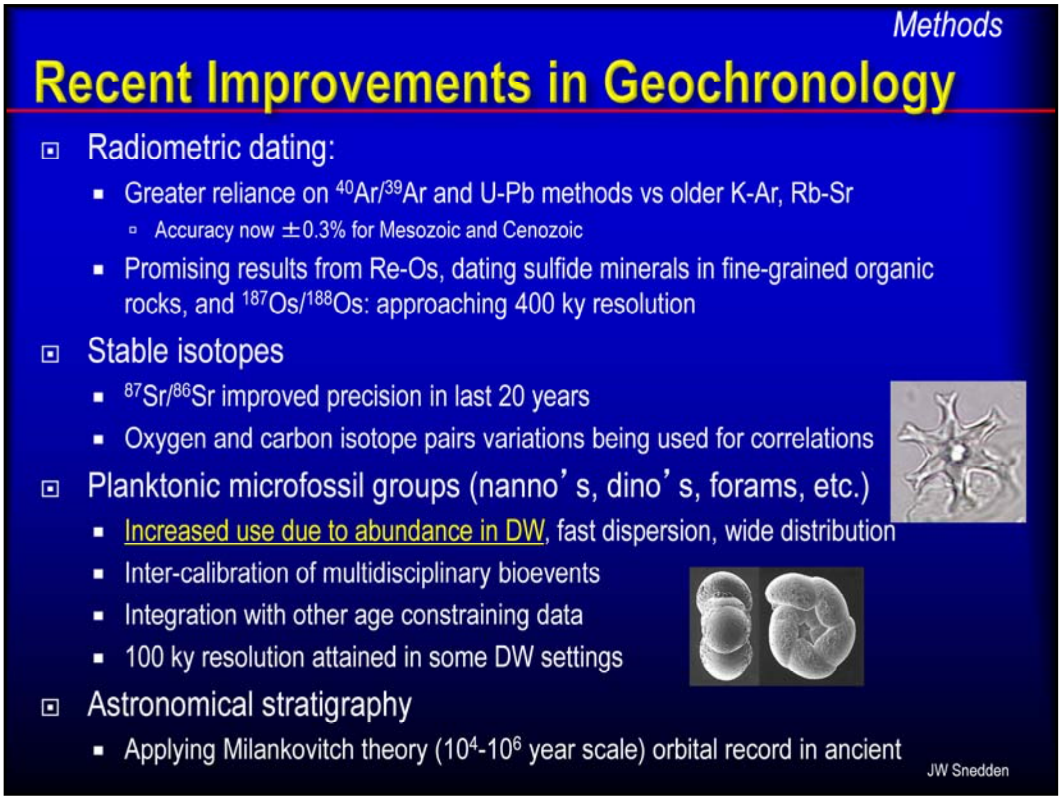
Finally, I will provide some ideas on how this might be implemented in the GBDS project, where there already is a strong foundation built by Bill Galloway and his students over the last 10 years and thus faciliating some potential source to sink reconstructions in the Paleogene and other intervals. Caution: there will be acronyms used here like CDS, chronostratigraphic designation system.



There are also some other, perhaps loftier goals than just finding and exploiting oil and gas. Ken Miller wrote in JOIDES journal nearly 10 years ago that one of the goals of sea-level research is to test the synchrony of sea-level events. Of course, there has been a long colorful history of of discussion in the stratigraphic science since publication of the Haq chart in 1987 about whether depositional sequence boundaries are synchronous globally.

Andrew Miall raised a lot of points, some of those good ones, about the validity of this assertion. One of his most telling remarks, shown here, was that in the late 80's and early 90's, biostratigraphic resolution was not good enough to prove (or disprove) global synchrony of sequence boundaries, particularly outside of the Oligocene to Recent where glacio-eustatic processes are well-documented.

BU: IODP goals: Oligocene to Recent (icehouse); Mid-Cretaceous to Eocene (greenhouse). Miller et al 33. K. G. Miller, et al., Geol. Soc. Am. Bull. 116, 368 (2004). Drilling on the New Jersey margin has provided new insights into the amplitudes of and mechanisms for 106ky scale sea-level changes. Fourteen Late Cretaceous sequences and 33 Paleocene-Miocene sequences were identified in New Jersey coastal plain coreholes (13, 33) and dated by integrating biostratigraphy, Sr-isotopic stratigraphy, and magnetostratigraphy to produce a chronology with age resolution of better than ±0.5 my for the Cenozoic (13) and ±1.0 my for the Late Cretaceous (33).



Well, we have come a long way from the late 80's to where we are today with geochronology. I won't read all of this but highlight a few of the notable advances:

-There is now greater reliance on the analytically more precise 40Ar/39Ar and U-Pb methods than the older K-Ar and Rb-Sr methods. These are significant improvements, remembering that Rb-Sr methods which constitute over 90% of the ages in the old timescale of Harland and others.

The precision in measuring 87Sr/86Sr ratios has steadily improved In certain stratigraphic intervals of the Mesozoic and Cenozoic, strontium stable isotope age-constraints can surpass biostratigraphy.

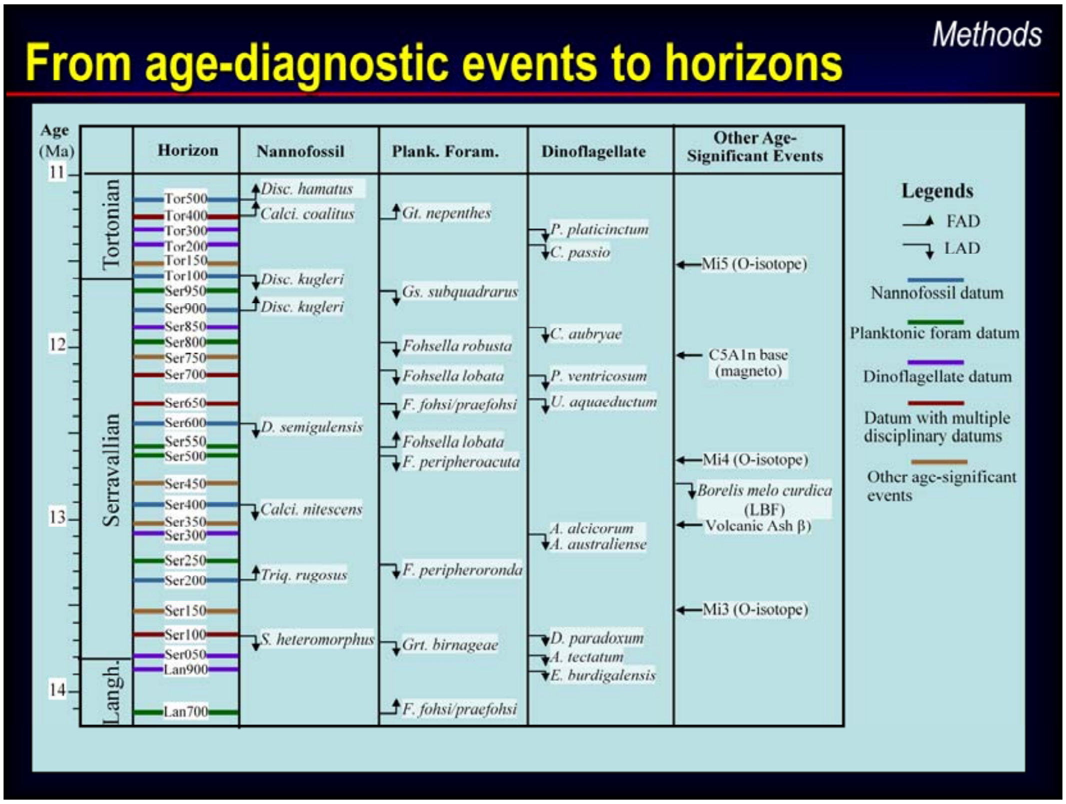
Just in the last decade, we have seen major improvement in resolution via use of planktonic microfossil groups, like nannofossils, dinocysts, and forams. Calcareous nannofossils have been particularly helpful. This has been added by inter-calibration of bioevents among fossil groups. In some DW basins resolution approaches 100ky.

And astronomical stratigraphy where you apply Milankovitch theory to ancient rocks records looks promising but keep in mind it still is a floating time scale that needs biostratigraphy for pinning points.

BU

These advances include ±0.1% or better precision by the U-Pb dates from the TIMS (Thermal Inonization Mass Spectrometric) method for Paleozoic and Mesozoic rocks. The accuracy is now ±0.3% from 40Ar/39Ar method for Mesozoic and Cenozoic rocks.

to around ±0.000003 for replicate analysis from ±0.000020 in the last 20 years (McArthur and Howarth, 2004)



This is an example of the Middle Miocene section, showing different fossil groups and other age-constraining non-biostratigraphic events like volcanic ash, oxygen isotopes and magnetostratigraphic events. Mostly, these are the high quality last appearance datums (LADs). The 28 age-diagnostic events, when combined, provide 26 unique horizons shown on the left column. This is in an interval of 3 million year, about 100ky duration per cycle. It is not uncommon to identify 80% or more of these horizons in a single well from cuttings.

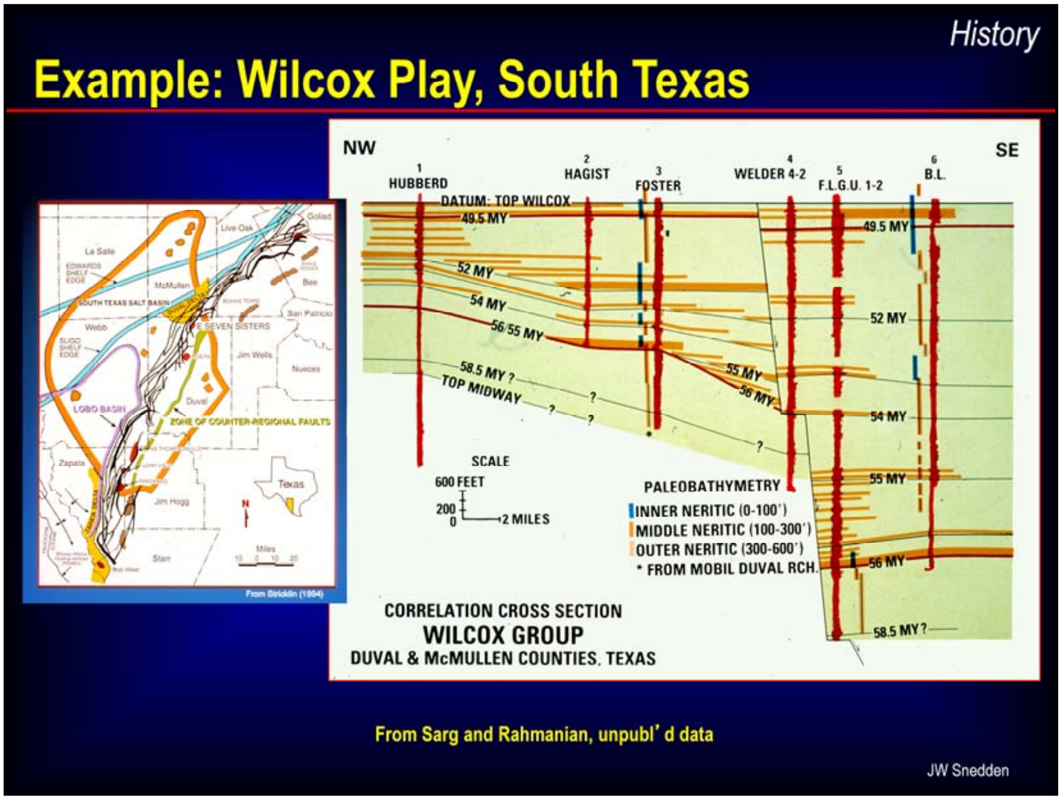
History

Diversity of Sequence Stratigraphic Designations

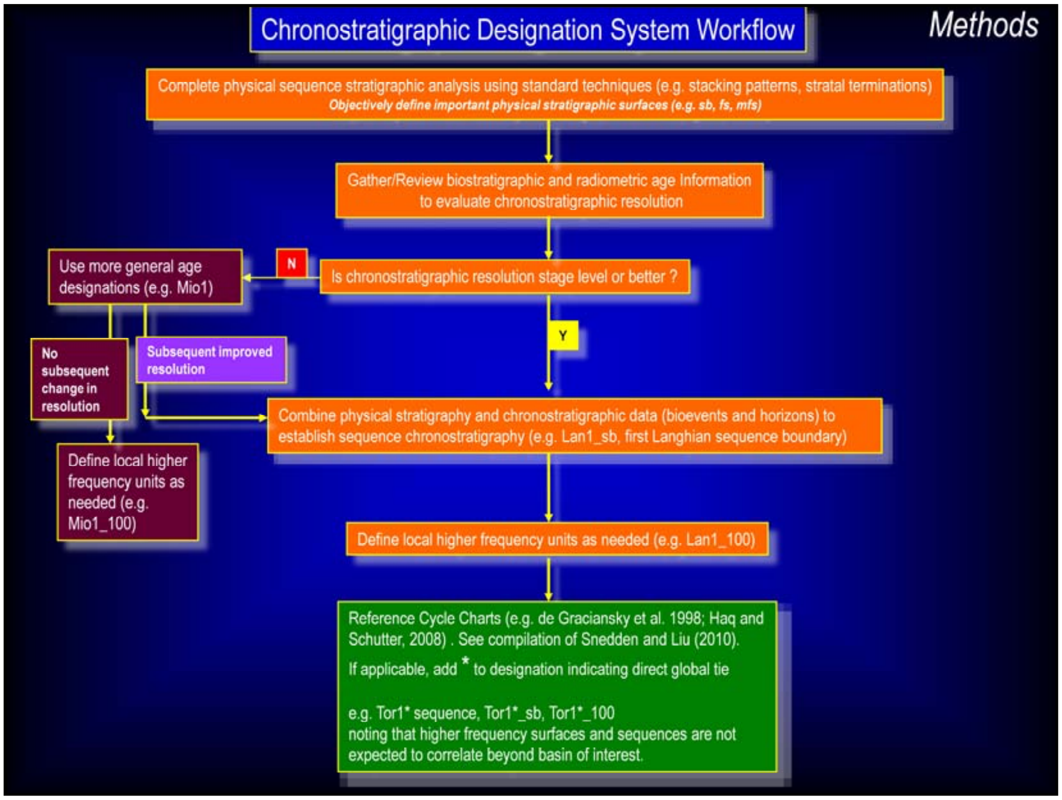
DESCRIPTION	EXAMPLE
ABSOLUTE AGES DERIVED FROM GLOBAL CYCLE CHARTS	15.5 MA SB
BROAD AGE CONNOTATION WITHOUT REFERENCE TO GLOBAL CYCLE CHART	L_MIOCENE_SB1
AGE CONNOTATION WITH A LOCAL REFERENCE	TUSIN 1, *WHERE TU DENOTES THE TURONIAN STAGE AND SIN REFERS TO THE SINAI PENINSULA STUDY AREA.*
LOCAL NUMERICAL SCHEME REFERENCED TO GLOBAL CHART	SB 150
NON-AGE CONNOTATIVE, WITH REGIONAL REFERENCE	GC11
SIMPLE LETTER DESIGNATION	SEQUENCE A
PURELY BIOSTRATIGRAPHIC TERM	CIB21 (*CIBICIDES* 21), ROB58 (*ROBULUS* 58)
LITHOSTRATIGRAPHIC NAME	MAU100_SB *WHERE MAU = MAUDDUD FORMATION OF THE BURGAN FIELD, KUWAIT*
COMBINATION OF LITHO- AND BROAD CHRONOSTRATIGRAPHIC DESIGNATIONS	N_2M^U *WHERE N=NEOGENE AND* M^U *= UPPER MINGHUAZHEN FORMATION*
ASTRONOMIC (ORBITAL) STRATIGRAPHY	$DS^3N.5$, *THE* 5^{TH} *THIRD ORDER DEPOSITIONAL SEQUENCE IN ONE SECOND ORDER SEQUENCE*

JW Snedden

The problem we face in using this newly improved biostratigraphy is that there is a lot “diversity” in how to use this information and integrate it together with physical observations of stratigraphy. Just surveying the literature showed a wide range from surfaces that are designated with absolute ages, to numerical schemes to purely biostratigraphic systems to lithostratigraphy.



I won't point any figures and in fact is an Exxonmobil internal graphic showing sequence boundaries designated with absolute ages. This is a problem, as you there has been a lot of change in the geologic time scale over the last 20 years from Berggren et al., 1985; Harland et al., 1990; Berggren et al 1995; Gradstein et al., 2004; Ogg et al., 2008. So we need to designate with something besides absolute ages. By the way, the age of the thick sandy package here is Paleocene, not Eocene, an important which we will return to later in this talk.



We are ExxonMobil and we have a workflow. The first step, as in any stratigraphic analysis, seismic or otherwise, is to objectively define the important physical stratigraphic surfaces (sequence boundaries, flooding surfaces, etc.) using outcrops, cores, borehole logs, and seismic data as is available, before attempting to employ this CDS. This would include the workflow described by Brown, Loucks, and Trevino (2005) to construct site specific sequence-stratigraphic section benchmark charts where this data is readily assembled and displayed and which makes this part far easier. (animation in and out).

Then review the biostratigraphic and/0r radiometric data to evaluate the chronostratigraphic resolution. Our system is based on use of Stages which are quite stable time-rock units. If you don't have stage level or better resolution then this track for general age designations like Mio1_100sb, if you do then this track where the bioevents and horizons are combined with physical observations to define the sequence level chronostratigraphy. We use a simple three letter abbreviation for the stage names, like Lan1 for the first Langhian sequence and Tor1 for the first sequence observed in the Tortonian strata of your basin, region, or local area.

Higher frequency units are then defined as needed. At this point, you may be choose to reference one of the available sea-level cycle charts, such as de Graciansky et al 1998 for the Mesozoic and Cenozoic and Haq and Schuttter fore the Paleozoic. You don't have to. It is not a requirement. For example, at this point The Tor1 is just the first sequence in the Tortonian of your area and may not be the Tor1 of another area. But you have at least constrained your sequence to the Tortonian and that will be immediately apparent to anyone looking at your stratigraphic correlation framework. If you do choose to compare to global charts and have diagnostic age information and demonstrable tie, then it is designated with "asterick" indicating a direct global tie.

Chronostratigraphic designations with stage-level or better biostratigraphic resolution

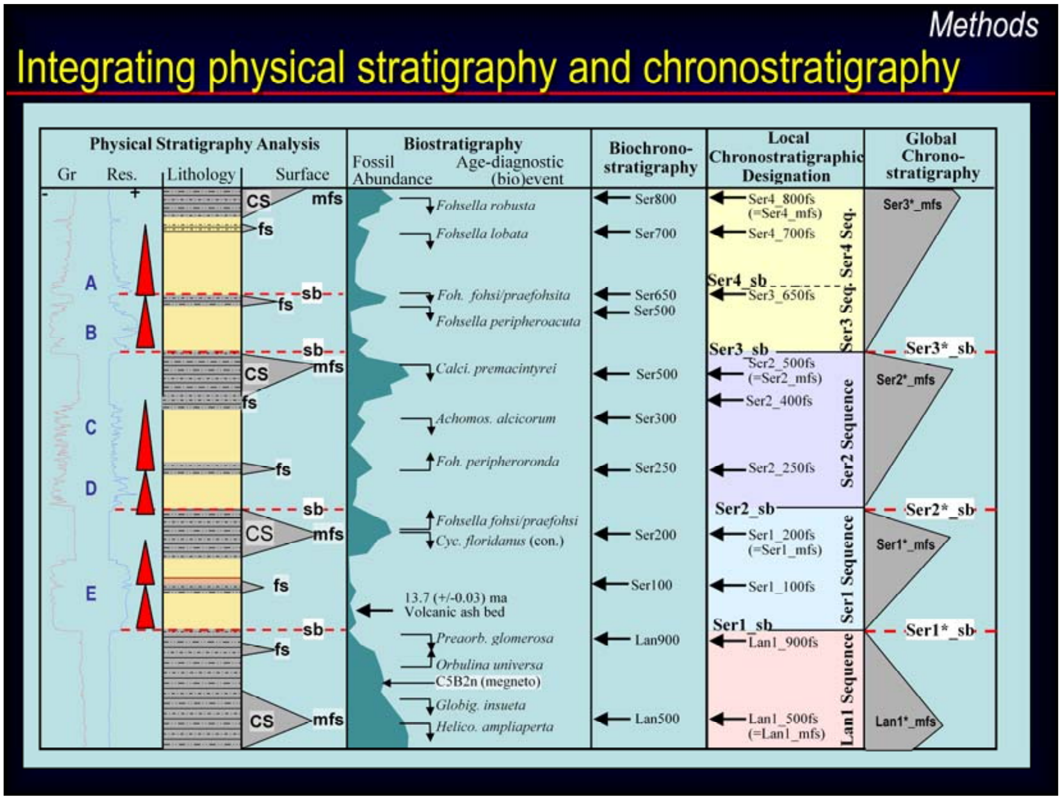
Methods

Frequency	Example Sequence	Surface Type	Example Local Chronostratigraphic Designation	Example Global Chronostratigraphic Designation
Lower Frequency	Tortonian 1	Maximum Flooding	Tor1_mfs	Tor1*_mfs
	Tortonian 1	Sequence Boundary	Tor1_sb	Tor1*_sb
Higher Frequency	Tortonian 1	Flooding Surface	Tor1_275fs	Tor1*_275fs
	Tortonian 1	Flooding Surface	Tor1_200fs	Tor1*_200fs
	Tortonian 1	Flooding Surface	Tor1_100fs	Tor1*_100fs

JW Snedden

I will show and example of how this is done in a moment. Basically, the alphabet soup breaks down to lower frequency surfaces, what we used to call 3rd order, like Tor1 _mfs and Tor1_sb or higher frequency (what we used to call fourth order or higher, surfaces like Tor1_200fs and Tor1_100fs.

Again, if you so choose to make a tie to De Graciansky or Haq and Schutter, then the asterisk is added. Please keep in mind that the higher frequency surfaces themselves are not expected to extend beyond a single basin, which is why the asterisk stays put next to the Tor1.



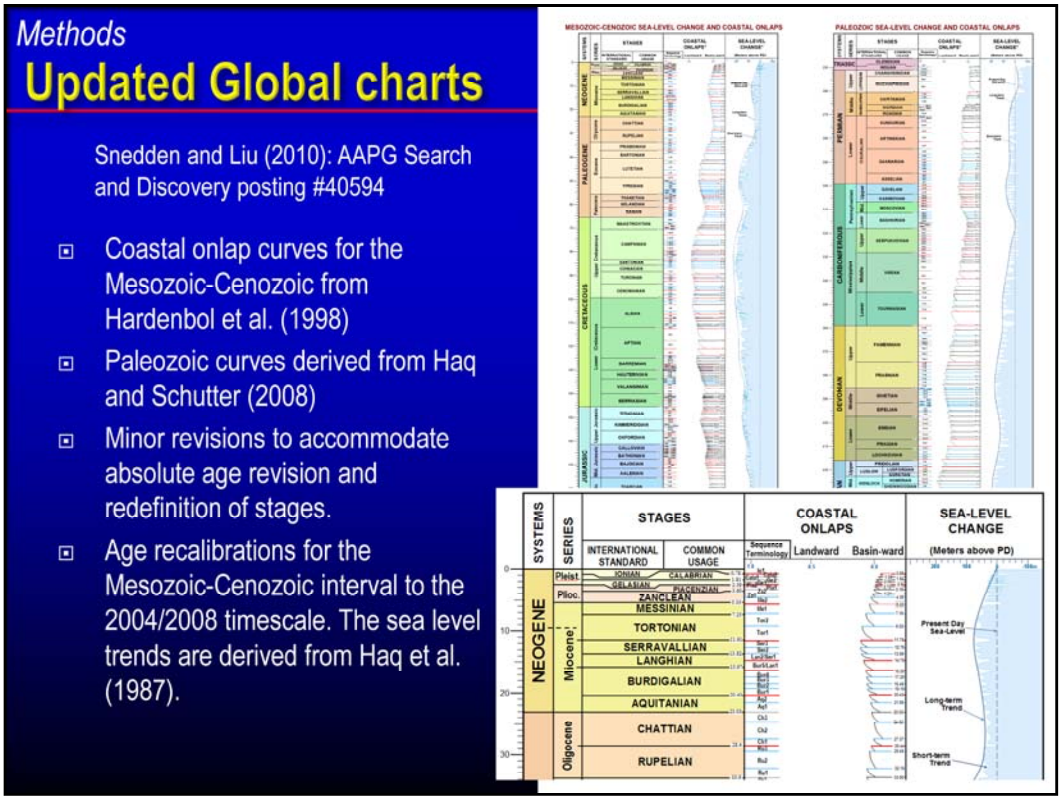
This is an example, drawn from a real GOM DW well, which unfortunately is proprietary. The well cuttings provide better than stage level resolution so we follow the workflow as such: The stacking patterns of the sandstone (point) and stratal terminations from seismic stratigraphic analysis point to candidate sequence boundaries, flooding surfaces, and downlap surfaces (point). Biostratigraphic analysis provides age constraints

and candidate condensed sections or flooding surfaces where microfossil abundance significantly increases (due to decreased siliciclastic influx). Bioevents and other age constraining data are posted on the log. These datums are calibrated to horizons with reference to the alphanumerical chronostratigraphic designation system which discussed earlier with the three letter suffix denoting the stage.

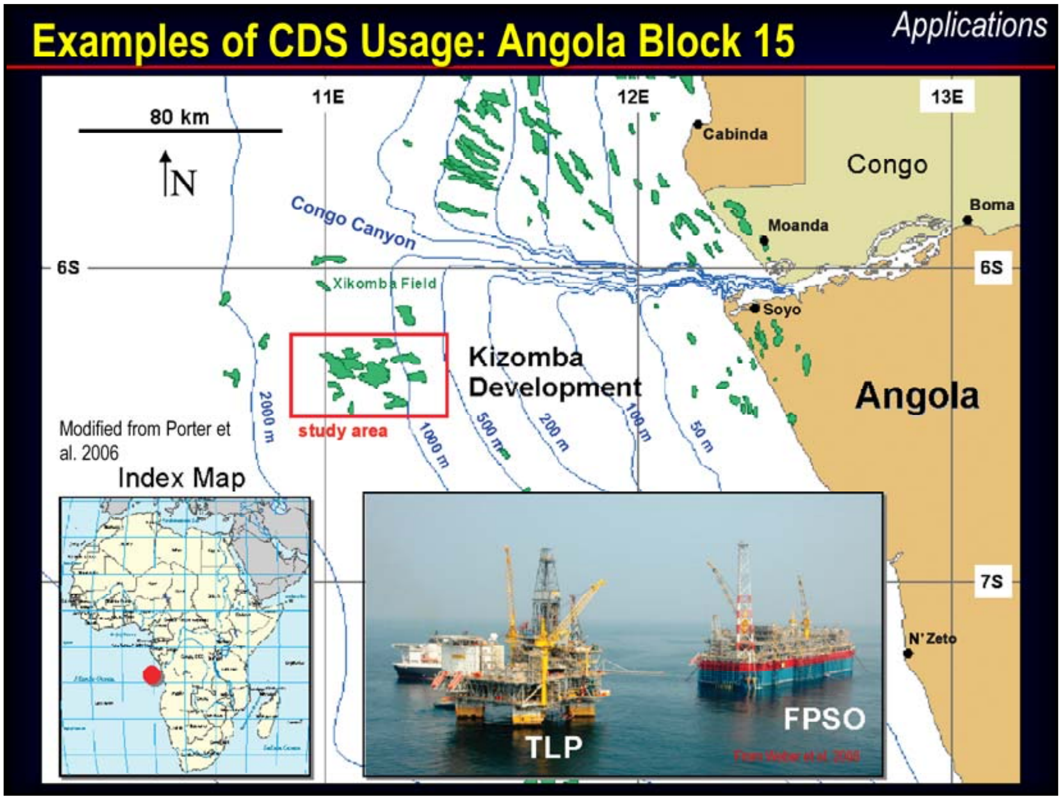
You combine physical stratigraphy surfaces and appropriate horizons to form the uniform alphanumerical designations, as exhibited in the “local chronostratigraphic designation” column. For instance, the candidate flooding surface above Sand E is within the shale package containing a fossil abundance peak and the Ser200. It is therefore named as Ser_200fs. Ser_200fs may also be a candidate for the Ser1 maximum flooding surface (Ser1_mfs) but further evidence may be required (e.g. a significant faunal peak, associated evidence of downlap on seismic tied to this surface). All physical surfaces compared with corresponding horizons are named in this manner. Also, one can interpolate between horizons such as in the case of Ser400fs, where the log data suggested a marine flooding event and it was between the Ser300 and 500 bioevents.

Sequence boundaries are treated a bit differently, as they tend to be associated age gaps and are designated from the oldest datums above and youngest below. In the case of the sb at the base of sand E, we observed erosion and truncation, called it a SB. The youngest below is Lan1_900fs and oldest above is Ser1_100fs so it is designated as Ser1_sb. At this point, Ser1 is tied to any global sea-level chart. It is just the first Seravallian SB recognized in the well, area or basin of interest. This is the local chronostratigraphy.

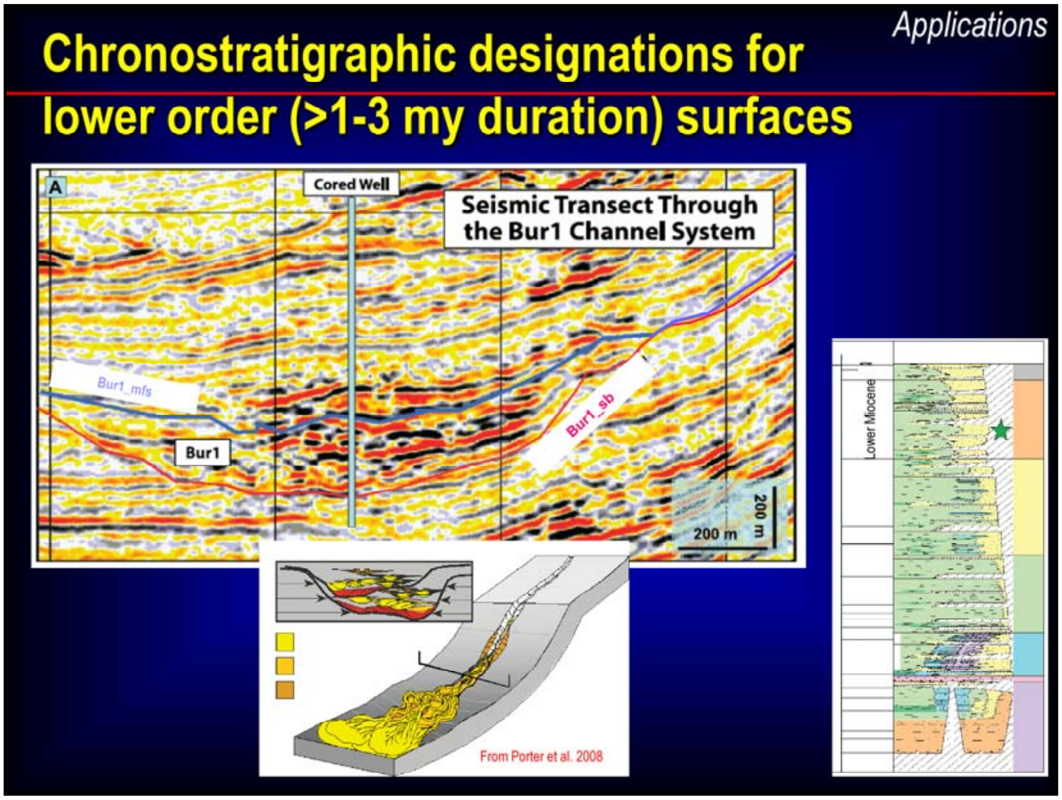
If one so chooses, and biostratigraphy and other age information is unequivocal, then a tie is made to regional or global charts. In this case, Ser1 is tied directly to the European Basins stratigraphy of De Graciansky et al 1998. However, not all SB’s and MFS do tie directly, for example the Ser4_sb does not directly to the more regional Ser4 sb as it is located below the Ser3_mfs and does not receive an asterisk like the other key markers. Of course, one should always avoid circular reasoning which would be the attempt to tie every major surface to a global chart especially when the data simply does not permit it.   And we have found lots of cases in lots of basins where you cannot tie to a global chart and use only a local chronostratigraphic designation.



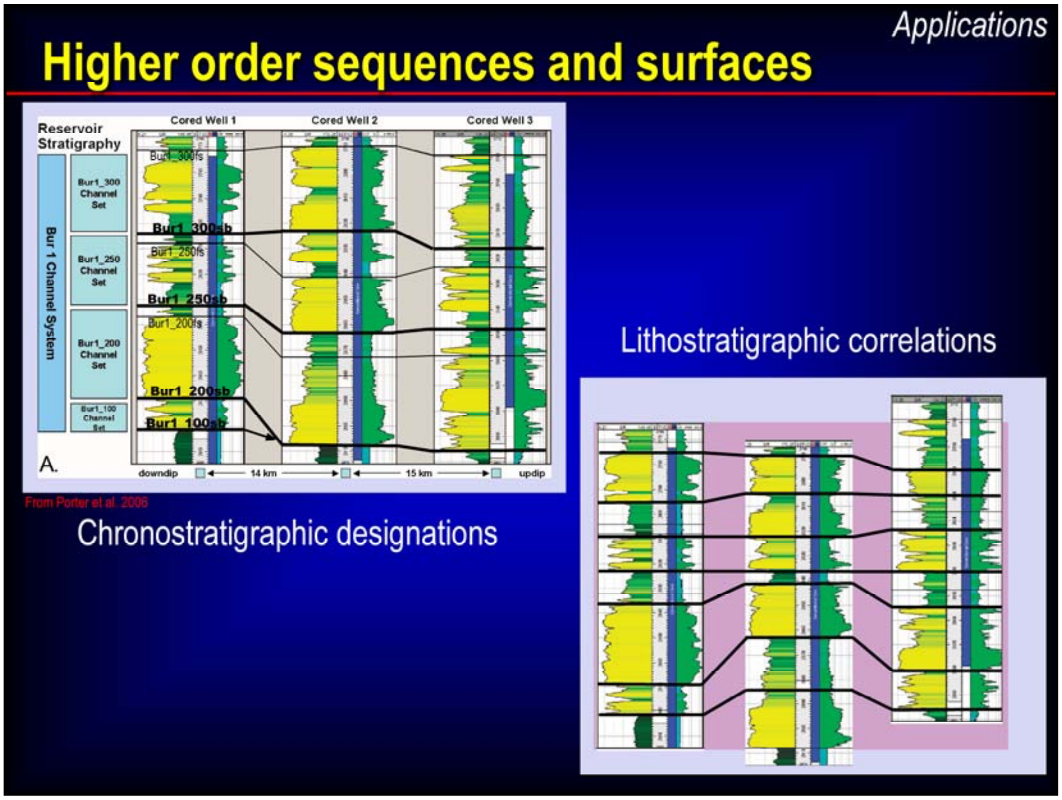
We have posted the chronostratigraphic designations for Phanerozoic sequences on AAPG search and discovery. This compilation also includes the coastal onlap curves for the Mesozoic and Cenozoic from SEPM SP 60 and the more recent Paleozoic curves from Haq and Schutter 2008. We use the most recent age recalibrations as well



Now, Any system for chronostratigraphic designation of sequence stratigraphic surfaces must be flexible enough to handle a range of sediments from non-marine to deep-marine, siliciclastics and carbonates, and Cambrian to Recent. I will attempt usage in the DW Miocene of West Africa, The Paleozoic of Kazakhstan, and Ferron Outcrop succession of Utah. First example is Angola Block 15 where we have produced hydrocarbons for nearly a decade now.

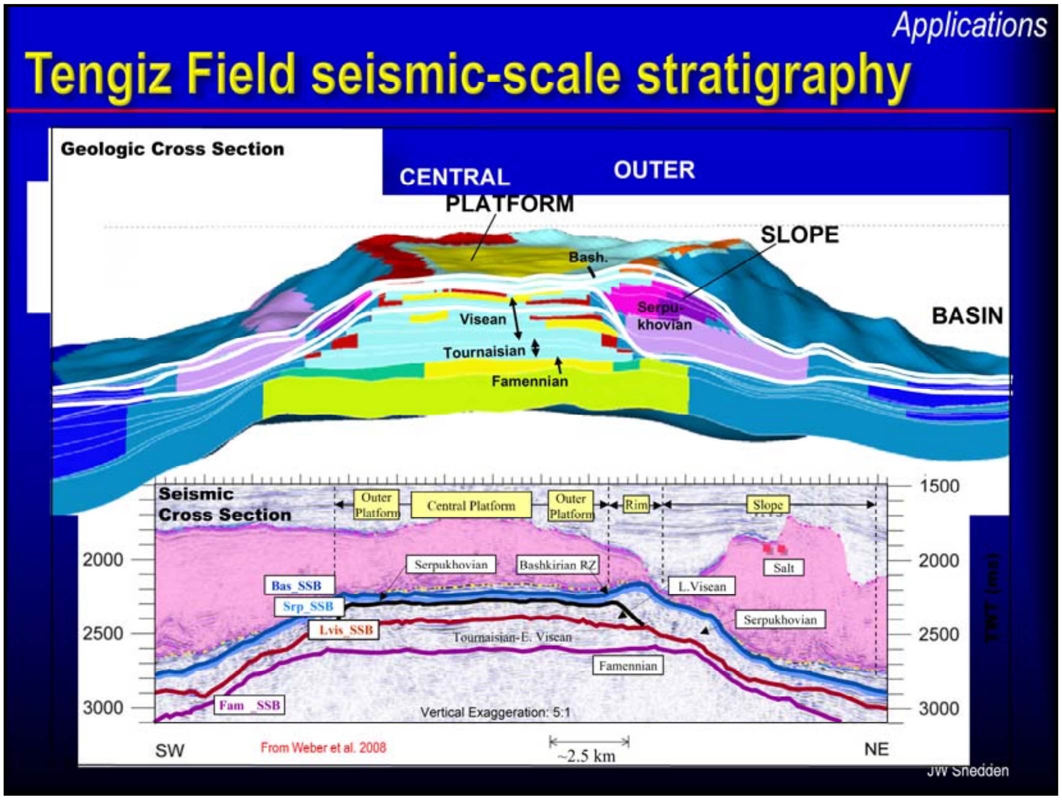


Sandstone reservoirs are dominantly of Miocene age, deposited in deepwater, highly-confined to weakly-confined channels and channel complexes. In this field example, physical observations from seismic interpretation and biostratigraphy identified two prominent markers, the Burdegalian-1 sb and maximum flooding surface.



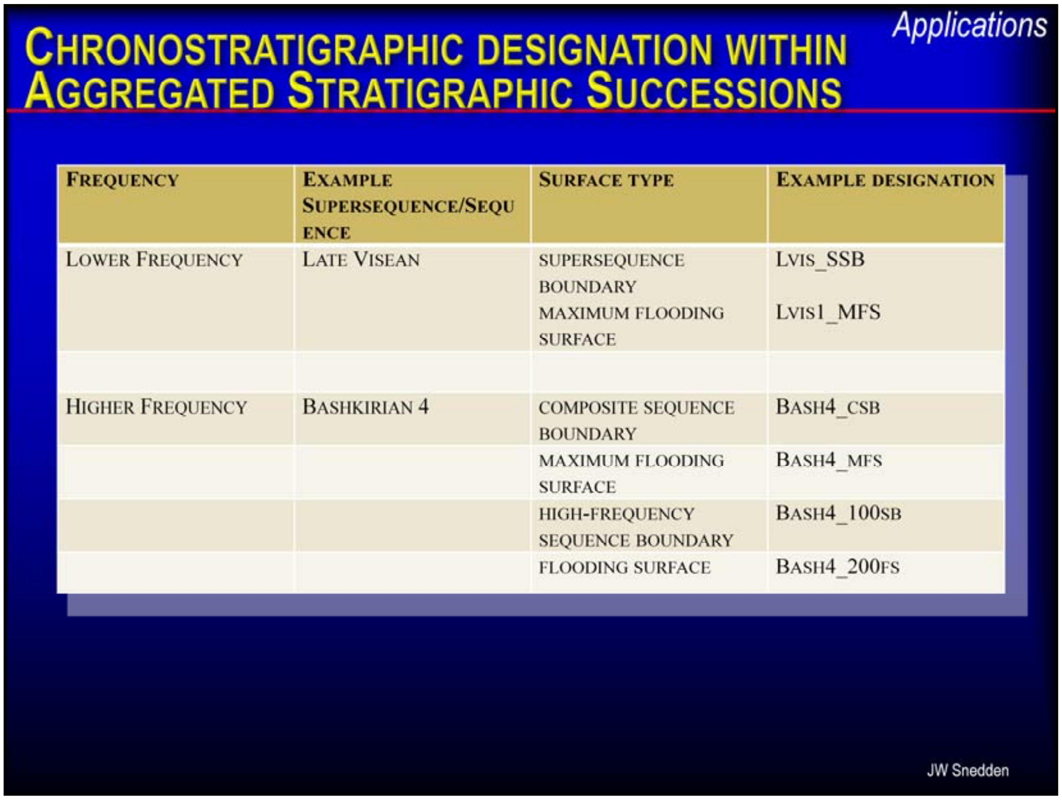
Higher frequency surfaces (Bur1_100sb, 250sb etc.) also were identified from borehole logs and high-resolution biostratigraphy and designated as such (Figure 5A). In this deepwater confined channel system, repeated channel incisions resulted in irregular distribution of sand-prone, axial channel-fill packages in both the horizontal and vertical dimensions, making stratigraphic relationships very difficult to track without a rigorous, disciplined approach to correlation.

The depositional architecture revealed by this approach contrasts sharply with more a lithostratigraphic correlation of the reservoirs (Figure 5B) which places similar lithofacies in lateral continuity. For example, the shale marker here (center) is not a through going shale in the chronostratigraphic correlation framework. This interpretation is supported by the well pressure decline trends and production history analyses (Porter et al., 2006)



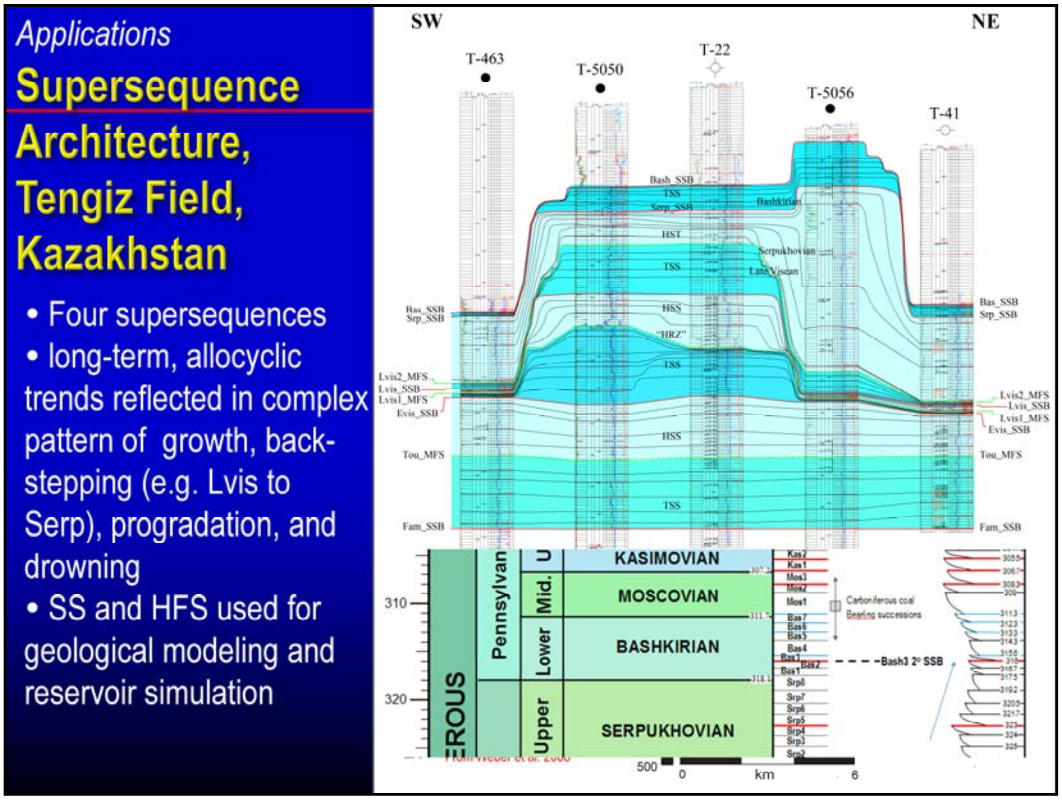
At the other end of the spectrum from the Miocene of deepwater West Africa are the Paleozoic carbonate reservoirs of Tengiz Field. The Paleozoic can be tough to work because of the long timeframes and poorer resolving power of the biostratigraphic and absolute age dating techniques. At Tengiz, Jim Weber of EM constructed a correlation framework starting at the supersequence level.

From seismic, the key boundaries he recognized are the Fammenian_ssb, Late Visean (Lvis), Serpukhovian (Serp_ssb), and Baskirian (Bash_ssb). This is a time span of about 18 my. But even from this low frequency correlation framework, one can observe the three phrases of the Carbonate platform growth history, from aggradation to backstep to progradation (point).



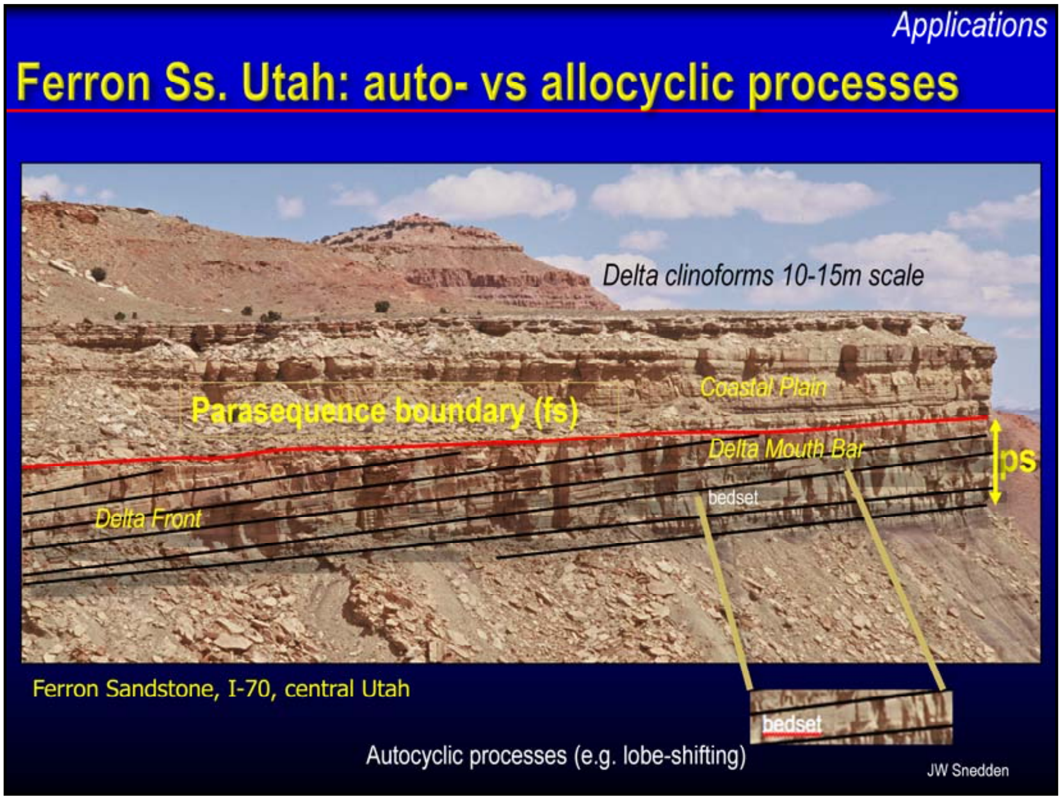
Frequency	Example Supersequence/Sequence	Surface type	Example designation
Lower Frequency	Late Visean	supersequence boundary maximum flooding surface	Lvis_SSB Lvis1_MFS
Higher Frequency	Bashkirian 4	composite sequence boundary	Bash4_csb
		maximum flooding surface	Bash4_mfs
		high-frequency sequence boundary	Bash4_100sb
		flooding surface	Bash4_200fs

This table shows an example of the designations using supersequences (ssb) for sb and mfs. From well logs, core and field data, Weber and the Tengiz team was able to subdivide the reservoirs into higher frequency composite sequences, including those bounded by the Bash4_csb and even sequence level, the Bash4_100sb.

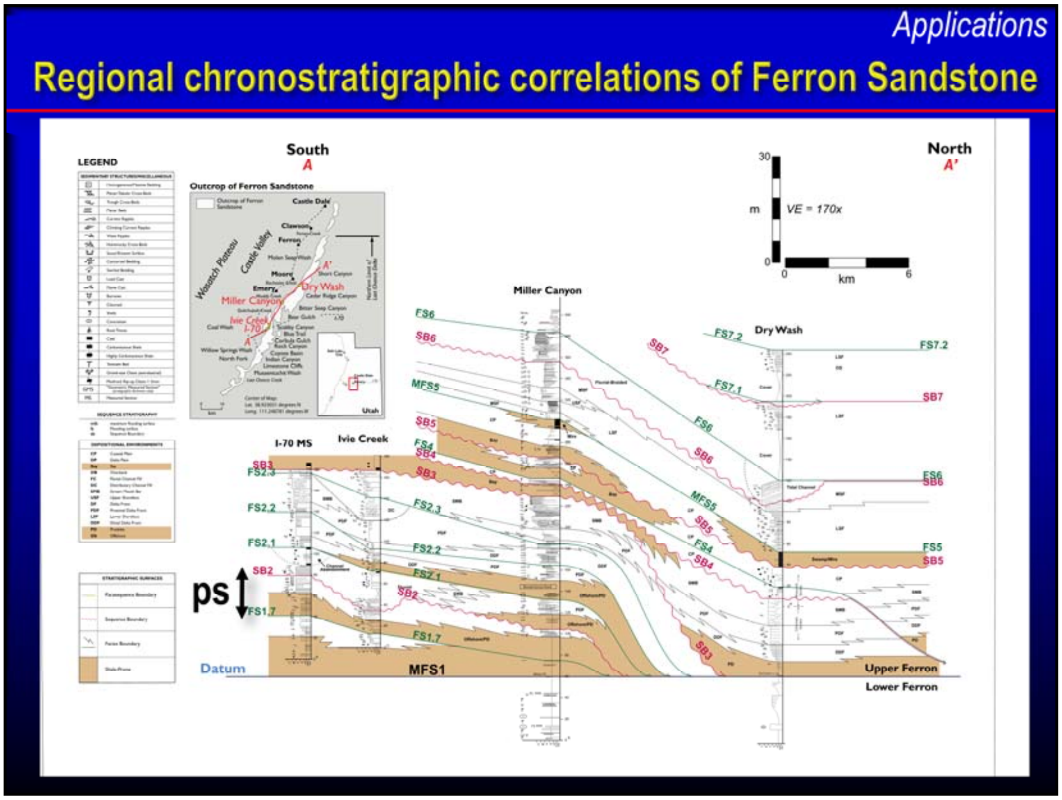


The carbonate growth history and reservoir architecture of the Tengiz field is clearly revealed when using chronostratigraphic correlations. Highstand supersequences are shown by light blue color and transgressive supersequences by dark blue. One cannot see what mirrors the seismic patterns: Backstepping of the carbonate platform from the Lvis_SSB (Late Visean) to the Srp_SSB (Serpukhovian) is followed by easterly progradation of the platform margin from Srp_SSB to the Bas_SSB.

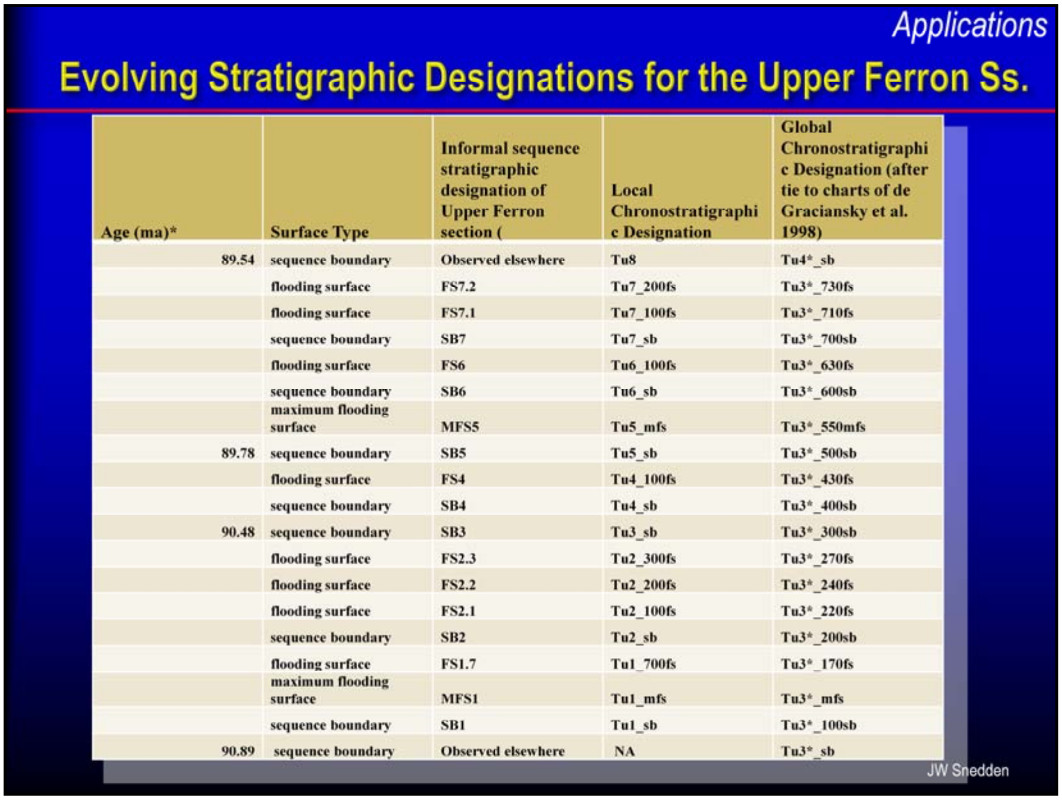
Note tthat Weber While Weber et al. (2008; in press) did not attempt ties to global charts (hence the lack of a * designation), one can still place the observed reservoir architecture in a context of possible allocyclic controls. For example, the outbuilding, progradation to aggradational pattern from Serp_SSB to Bash_SSB follows global patterns of sea-level fall in the Late Mississippian.



I am sure you are thinking, sure, this works with great industry data but what about outcrops where the data is not so good. We employed the same approach to correlation of four measured sections in the outcropping Upper Ferron Member of Utah, using published ammonite data for age-constraints. The Ferron is well known as a ancient marginal marine delta front to deltaic plain deposit. This is an outcrop along I-70 illustrating a single parasequence of 10-15m scale. Clearly the internal building blocks or elements of the parasquence are bedsets bounded by small scale clinoforms which are clearly formed by autocyclic processes by mouth bar progradation and lateral lobe shifting.



Early on, we defined sixteen surfaces (6 sequence boundaries, 10 flooding surfaces) and correlated these from paleo-landward to paleo-seaward locations, from I-70 to Dry wash to the NNE,   The outcrop I just showed along I-70 is shown here.



Applications

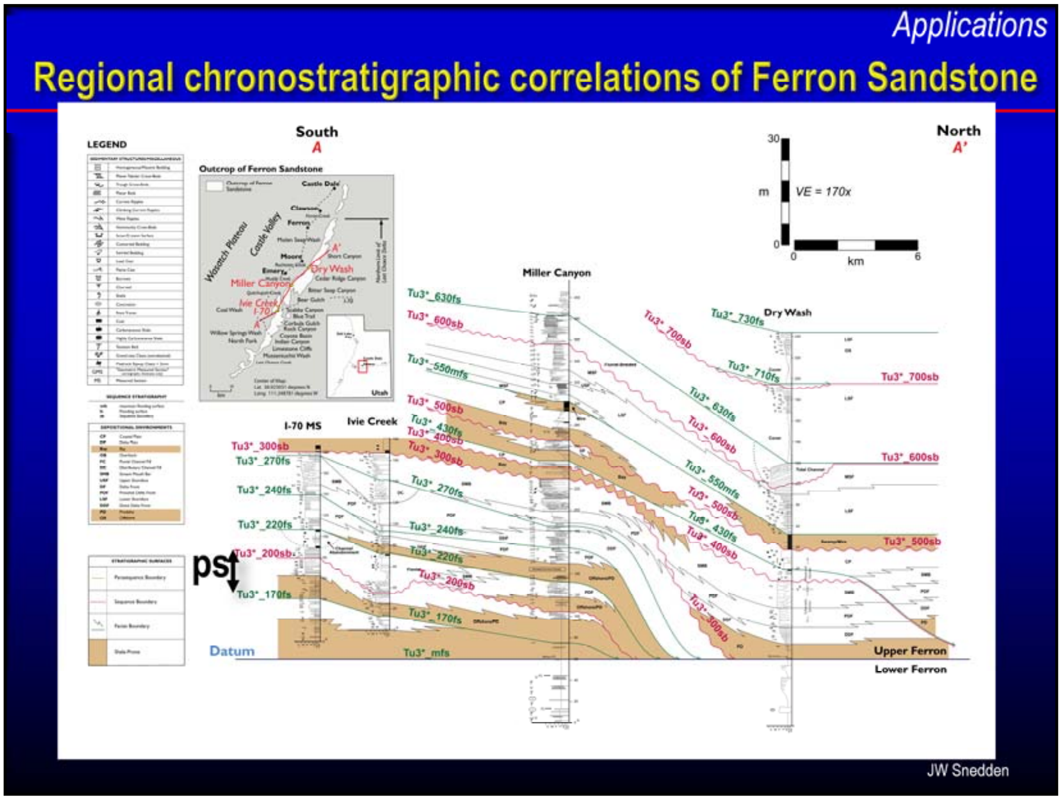
Evolving Stratigraphic Designations for the Upper Ferron Ss.

Age (ma)*	Surface Type	Informal sequence stratigraphic designation of Upper Ferron section (	Local Chronostratigraphic Designation	Global Chronostratigraphic Designation (after tie to charts of de Graciansky et al. 1998)
89.54	sequence boundary	Observed elsewhere	Tu8	Tu4*_sb
	flooding surface	FS7.2	Tu7_200fs	Tu3*_730fs
	flooding surface	FS7.1	Tu7_100fs	Tu3*_710fs
	sequence boundary	SB7	Tu7_sb	Tu3*_700sb
	flooding surface	FS6	Tu6_100fs	Tu3*_630fs
	sequence boundary	SB6	Tu6_sb	Tu3*_600sb
	maximum flooding surface	MFS5	Tu5_mfs	Tu3*_550mfs
89.78	sequence boundary	SB5	Tu5_sb	Tu3*_500sb
	flooding surface	FS4	Tu4_100fs	Tu3*_430fs
	sequence boundary	SB4	Tu4_sb	Tu3*_400sb
90.48	sequence boundary	SB3	Tu3_sb	Tu3*_300sb
	flooding surface	FS2.3	Tu2_300fs	Tu3*_270fs
	flooding surface	FS2.2	Tu2_200fs	Tu3*_240fs
	flooding surface	FS2.1	Tu2_100fs	Tu3*_220fs
	sequence boundary	SB2	Tu2_sb	Tu3*_200sb
	flooding surface	FS1.7	Tu1_700fs	Tu3*_170fs
	maximum flooding surface	MFS1	Tu1_mfs	Tu3*_mfs
	sequence boundary	SB1	Tu1_sb	Tu3*_100sb
90.89	sequence boundary	Observed elsewhere	NA	Tu3*_sb

JW Snedden

This table ilustrates the process of evolving the chronostratigraphic designations . Early on, in the field, we used a purely scheme, SB1, SB2, MFS5, etc. Of course, it is well known that the Ferron is Turonian so the next step was to define the local chronostratigraphic designations, so SB1 becomes Tu1_sb, that is the first sequence boundary in the Turonian.

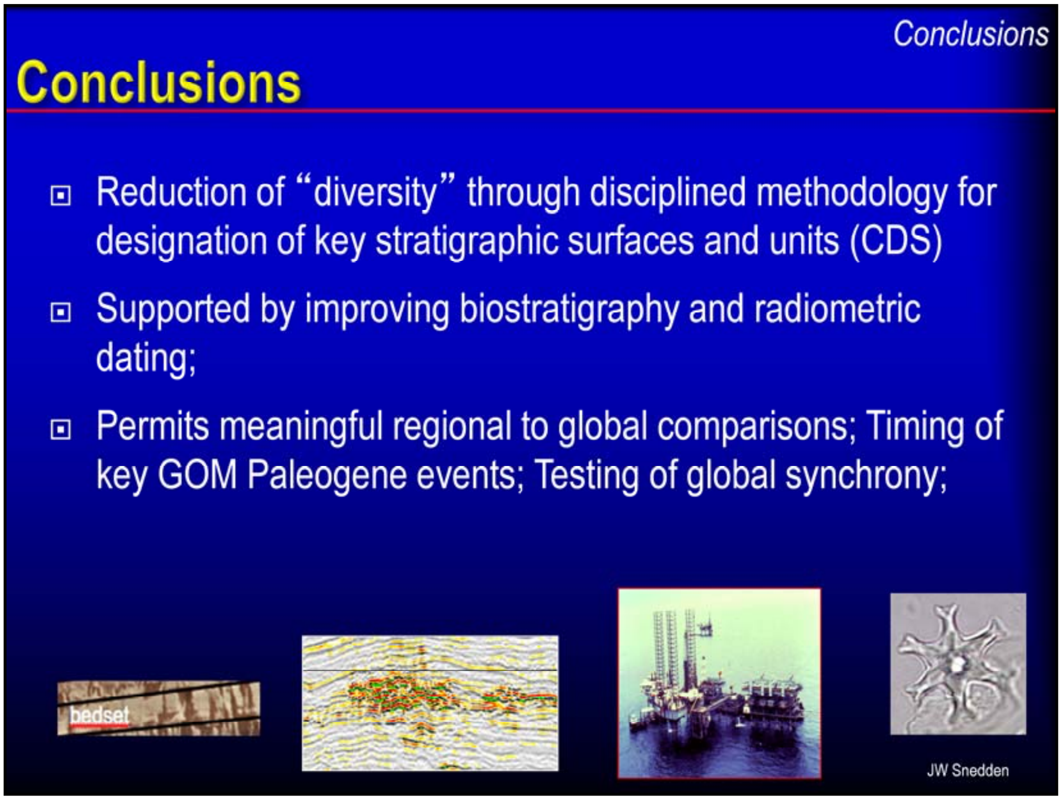
We then consulted published ammonite zonations and determined, after review, that the entire Upper Ferron is confined to the Turonian3 cycle as defined by de Graciansky et al. 1998. Thus the Upper Ferron is clearly high frequency, deposited in about 1.35 my, and thus we evolve the designations to denote the high frequency cycles. Tu1 becomes the Turonian-3 star _100sb. Indicating a tie to the Turonian-3 global sequence. Higher frequency flooding surfaces are designated as Tu3 star 170fs, etc.



Using the age-constraints provided by the European Basins sequence chronostratigraphy framework, the seven high frequency sequences identified in the outcrop section from the Tu3*_sb to Tu4*_sb span about 1.35 my, averaging about 192 ky in duration.

The presence of high frequency sequences is understandable, given the high sedimentation rates and high accommodation of the Ferron delta system. The steadily increasing accommodation of the Turonian matched the sediment supply, resulting in a rather thick deltaic succession.

We see similar patterns in the Paleozoic, Bashikiran to Muscovian succession of Germany, where a kilometer thick succession of Carboniferous delta plain deposits form the Carboniferous coal-bearing reservoirs of mines and CBM resources.



Read Conclusions