3D Seismic Reflection and Borehole Expression of Tectonically Controlled Deep-Marine Reservoirs: An Example from the Northern North Sea Hydrocarbon Province*

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Abstract

Deep-marine reservoirs form some of the most attractive targets in many mature and frontier basins. Determining the distribution and geometry of these reservoirs, especially within tectonically active settings, remains a major challenge, however, principally due to the complex interaction of a variety of extra- and intra-basinal controls (i.e., tectonics, climate, sea level, etc.). In this presentation I use 3D seismic reflection, well and core data to provide a regional synthesis of the subsurface expression of a series of tectonically controlled, deep-marine reservoirs that are developed along the western Norwegian margin. I outline the key controls on the deposition of these reservoirs and illustrate the key trapping styles.

Turbidite sandstones represent the best reservoirs; in core, individual beds are up to a few metres thick, but amalgamated units up to several tens of metres thick are common. Sandy-mudstone debrites are observed, but they are of poor reservoir quality and may form barriers or baffles to fluid flow. Synthetic seismograms indicate that sandstone-dominated deposits are expressed on seismic data as packages of high-amplitude reflections. Amplitude mapping indicates that 11 slope fans are recognisable and that these were fed by sediment routed through upper slope canyons incised into the eastern basin margin. These fans are either ponded behind or overstep intra-basin highs; the key trapping styles are: (i) stratigraphic, and related to up-dip pinch-out of the fans into slope mudstones; or (ii) structural, and related to differential compaction-related drape of fans across underlying fault blocks.

The areal extent of the onshore drainage catchments that supplied sediment to the fans has been estimated, based on scaling relationships derived from modern source-to-sink systems. The results of our study suggest that the Turonian fans were sourced by drainage catchments that were up to 2200 km² and which extended up to 140 km from the shoreline. The estimated inboard extent of the catchments correlates to the innermost structures of a large fault complex, which is thought to have defined the position of the regional drainage divide in this region since the Devonian. I suggest that increased sediment supply to the Turonian fan systems reflects tectonic rejuvenation of the landscape, rather than

eustatic sea-level or climate fluctuations. The duration of fan deposition is thus interpreted to reflect the “relaxation time” of the landscape following tectonic perturbation, and fan system retrogradation and final abandonment is interpreted to reflect the eventual depletion of the onshore sediment source. Future exploration success in tectonically controlled deep-marine reservoirs relies on a robust understanding of the seismic expression, sedimentology, stratigraphic architecture and trapping styles associated with turbidite systems deposited on bathymetrically-complex slopes. Furthermore, important insights into reservoir size and location can be gained by considering the complete “sediment routing system.”

Basins Research Group

Imperial College London

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Software: Schlumberger

Seismic data: CGGVeritas

Motivation I - Applied

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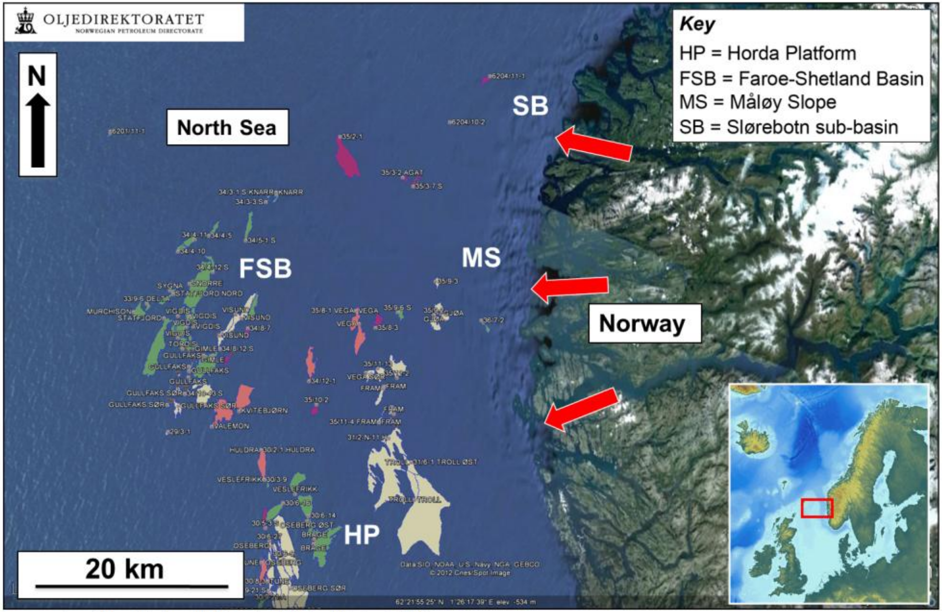

Image courtesy of GoogleEarth and the Norwegian Petroleum Directorate (NPD)

Motivation II - Conceptual

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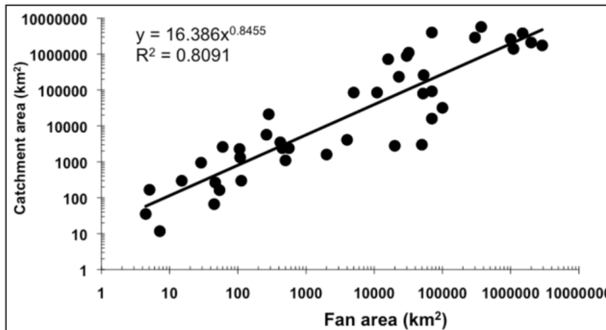
- Deep-water depositional systems controlled by auto- and allogeneic processes
- 'Source-to-sink' analysis of sediment routing segments
- Scaling relationships independent of geological time
- Gaps in ancient systems filled by data from modern systems
- Potential application to exploration for deep-water reservoirs…



Talk Outline

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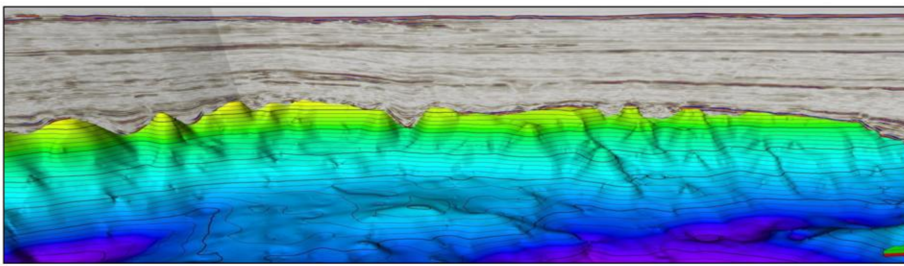
- **Part 1 -** Subsurface expression of deep-water reservoirs, offshore western Norway
- **Part 2 -** Controls on the evolution of deep-marine tectonically controlled depositional systems (‘S2S’ analysis)



Presenter’s notes: These data are relevant for understanding sediment routing and exploration potential in frontier basins. Determine the impact of local controls on sediment routing. Use scaling relationships from modern S2S systems to speculate on the nature and evolution of Late Cretaceous tectonics and topography along western Norway.

Geological Setting and Dataset

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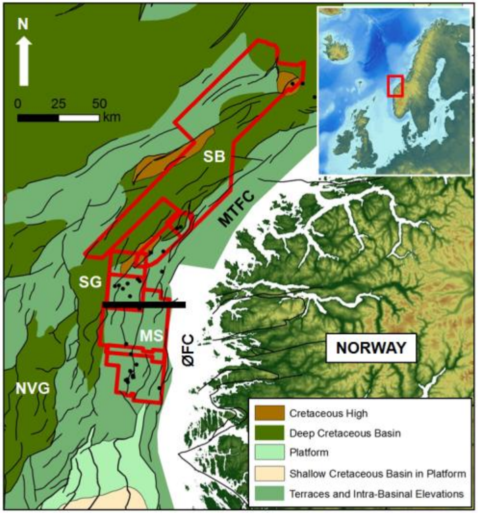
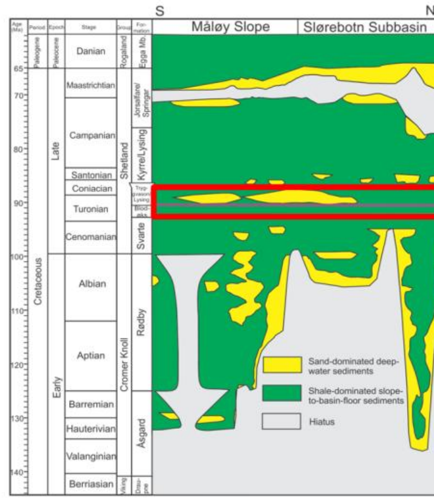
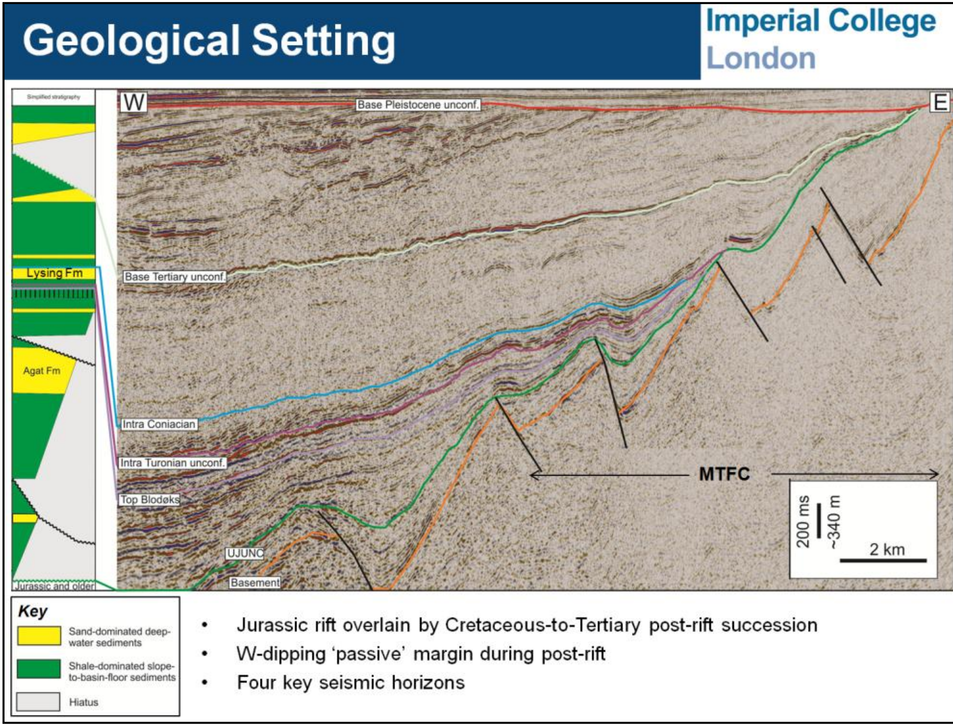




NVG=North Viking Graben; SG=Sogn Graben; SB=Slorebotn sub-basin; MS=Maloy Slope; OFC=Oygarden Fault Complex; MTFC=More-Trondelag Fault Complex

Presenter's notes: Study area is located in the eastern northern North Sea, offshore western Norway, with focus on the Måløy Slope and Slørebotn sub-basin, two Upper Cretaceous to Tertiary depocentres that were bound to the east by major, basement-involved fault zones (MTFC and OFZ). It is a good area to study S2S concepts: (i) dataset comprises five overlapping 3D seismic reflection surveys, infill 2D seismic data, seven boreholes containing wireline logs and completion reports, and two wells with core data; and (ii) the post-depositional tectono-stratigraphic history has been relatively simple.

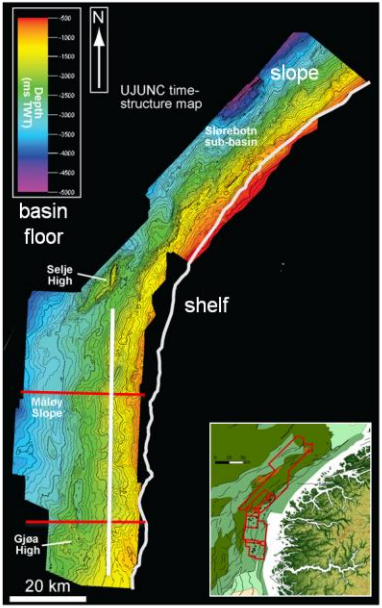
- Mud-dominated Cretaceous and Tertiary succession; regional sandstone delivery in the Early Cretaceous (not discussed here) and Late Cretaceous (Trygvasson and Lysing fms – the focus of this study).
- c. 3 Myr sediment pulse=3rd-order depositional system.
- MTFC=50 km wide, basement-involved, Ordo-Silurian origin, but reactivated and became a dominant basin-bounding structure during Jurassic and Cretaceous.
- OFC=Active from Cretaceous until relatively recently; superimposed on the NSDZ, an old, basement-involved, crustal lineament.

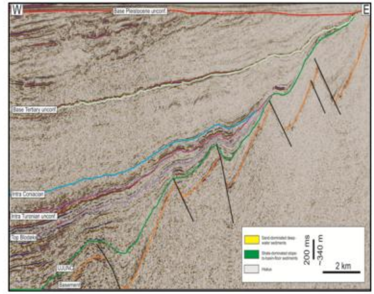


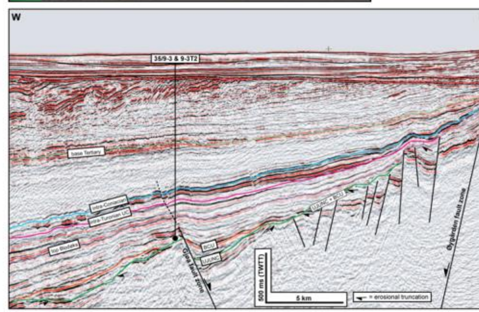
Presenter's notes: Jurassic-to-earliest Cretaceous rift overlain by Cretaceous to Tertiary post-rift. Overall west-dipping slope: Norwegian mainland in the east and the Sogn Graben in the west.

Four key seismic horizons: (1) UJUNC – defines Jurassic erosion and rift structure; (2) Blodaks – regionally mappable and correlatable in wells, and also defines Turonian basin-floor morphology; (3) intra-Turonian UC – defines onset of sand pulse; and (4) intra-Coniacian – defines end of sediment pulse.

Slope Morphology

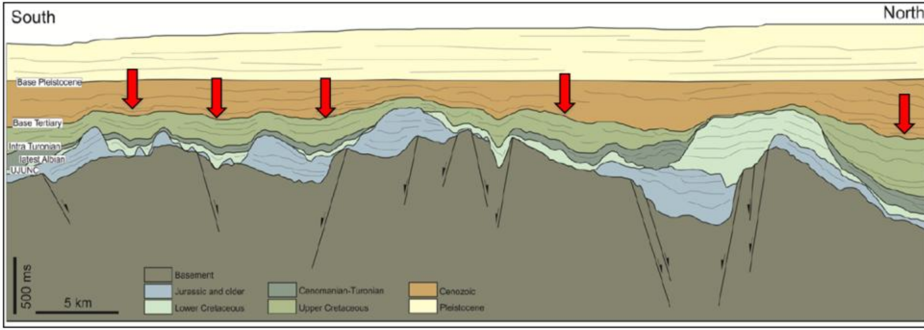


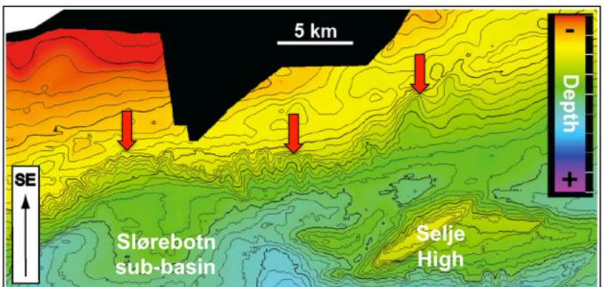




Presenter's notes: UJUNC provides regional overview of margin morphology; W-to-NW-dipping slope, onto which two major intra-basin highs are superimposed (i.e., SH and GH). Shelf is eroded, but likely fault-controlled. Marked along-strike variability in margin morphology; SB very faulted and steep (related to MTFZ), and MS relatively weakly faulted and gentle (N.B time data and no depth conversion/decompaction; thus 'steepness' is relative). Slope morphology affects sediment routing, deposition and stratigraphic architecture. Along the margin some 'rugosity' is observed (see next slide).

Upper Slope Canyons





- Upper slope canyons at basin margin
- Up to 10 km wide, 650 m deep and extend 10 km downslope
- Formed during the Late Jurassic and underfilled and re-incised during the Cretaceous

Presenter's notes: Upper canyons are developed along basin margin at the UJUNC level. Canyons are up to several kilometres wide, up to a few hundred metres deep and extend <10 km down-slope; they are defined updip by the OFC and inner fault of the MTFC, implying these structures controlled the palaeo-shelf edge and canyons development, although later erosion makes this uncertain. Some canyons appear to be fault controlled. Canyons locally incise into pre-Mesozoic, metamorphic basement. They are filled by latest Jurassic downdip (thereby confirming their age) and latest Cretaceous updip; interpreted to have formed during latest Jurassic and to have controlled sediment routing until they were filled in Late Cretaceous.

Upper Slope Canyons

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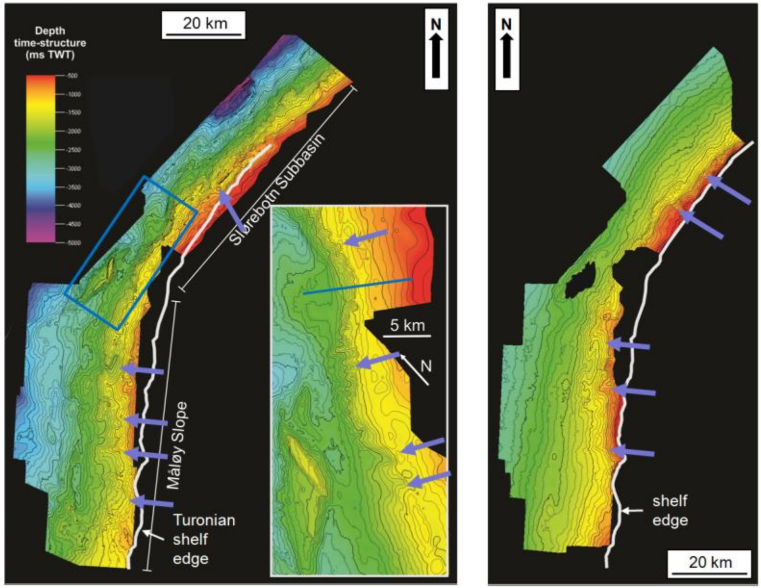
(i) Late Jurassic - canyon formation

(ii) Turonian - canyon re-incision



Stratigraphic Framework

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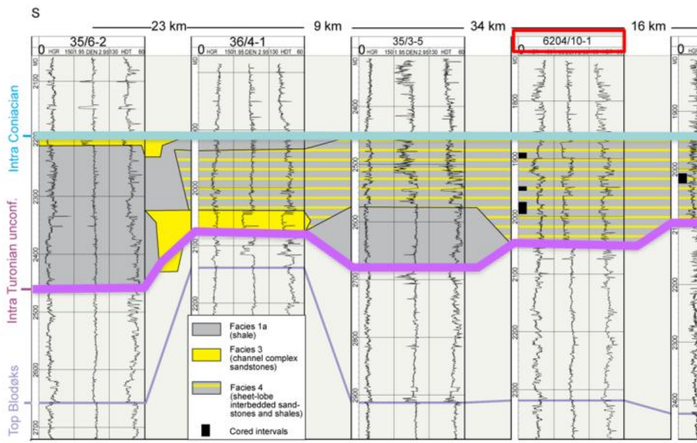

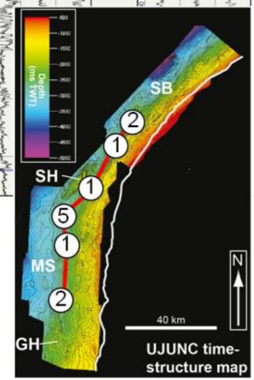

- Turonian sand 'pulse' in a 100-200 m thick deep-water succession
- Deposition during a 3 Myr period (late Turonian to early Coniacian)
- Amalgamated sandstones (+N:G) and heterolithic (-N:G) intervals

Presenter's notes: Stratigraphic correlation, datumed on the intra-Coniacian, indicating the regional (120 km along-strike) Turonian sand pulse (3 Myr) developed in a 100-200-m thick succession. Note correspondence between seismically mapped horizons and sandstone-bearing intervals in well.

Core Expression

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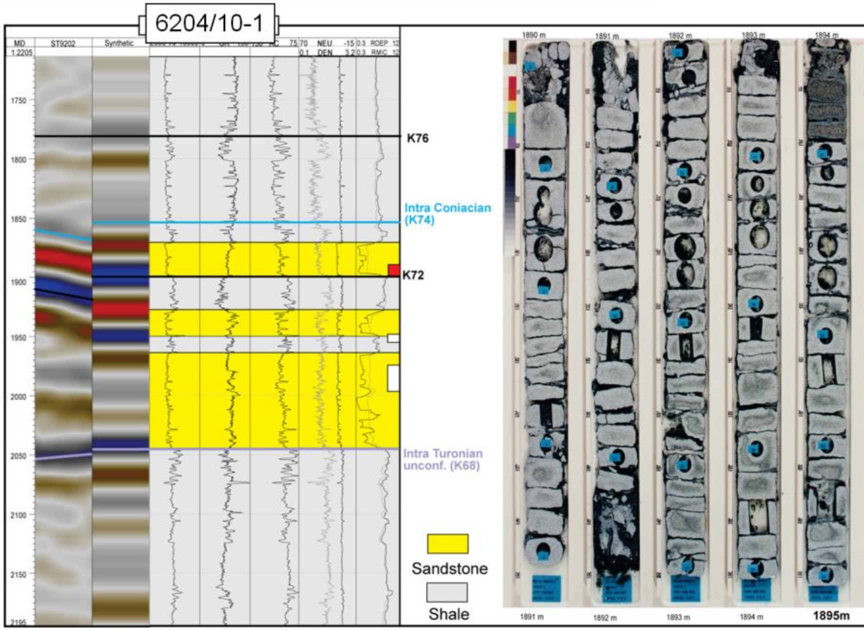

Presenter's notes: Reservoir quality is variable in the Upper Cretaceous succession. Mud-rich, fine-grained sandstones deposited by debris flows and clean, fine- to-medium-grained, glauconite-rich sandstone deposited by turbidity currents are both observed.

Seismic Expression

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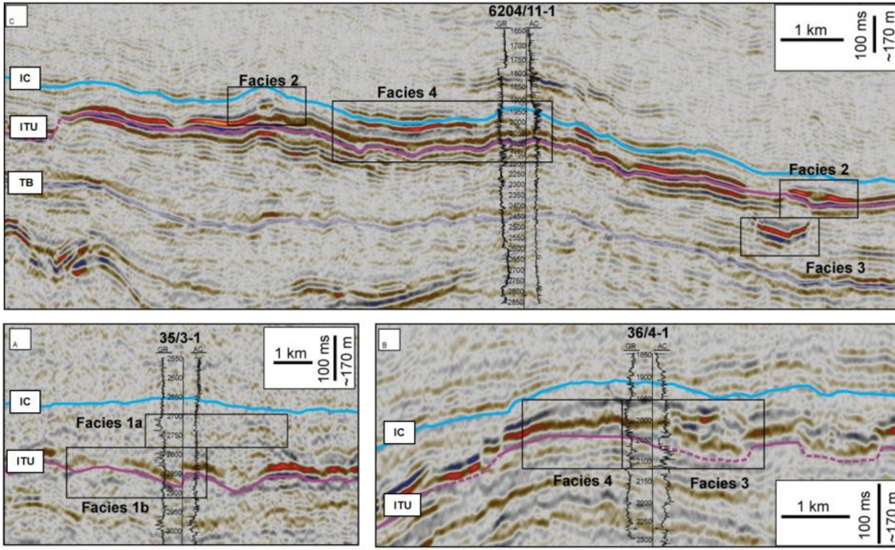

Four seismic facies: (i) low-amplitude sheets; (ii) high-amplitude sheets; (iii) high-amplitude channels; and (iv) stacked high-amplitude channels

Presenter's notes: Four main seismic facies are identified. Wireline and core data provide confidence in discriminating between sandstone- and mudstone-rich units. Still some uncertainty due to the limited vertical resolution of the available seismic reflection data (i.e., ca. 30-35 m).

Seismic Expression

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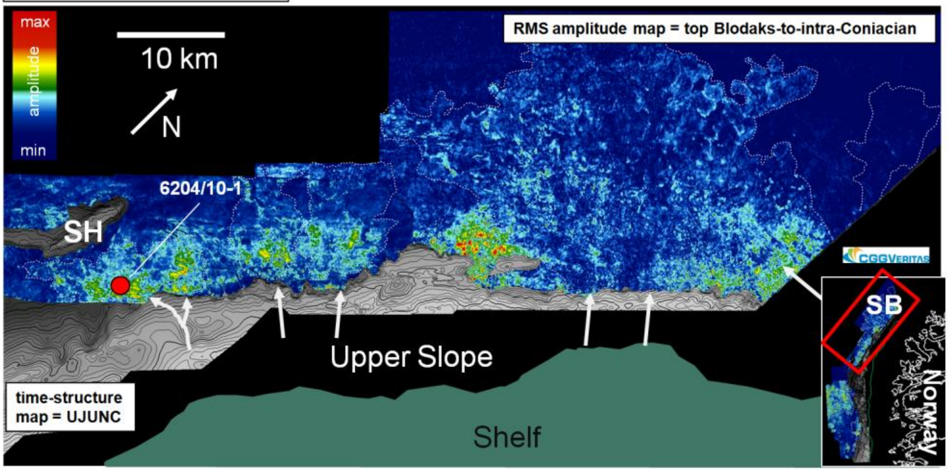
Sløreboth sub-basin



Presenter's notes: High amplitudes=sandstone-dominated; low-amplitudes=mudstone-dominated. 11 channel-lobe complexes identified, which are located basinward of upper slope canyons. Fan morphology is variable, depending on the degree of slope confinement; e.g., areally extensive fans on unconfined slopes in the north of the study area and areally restricted fans in the south of the study area updip of the Selje High.

Seismic Expression

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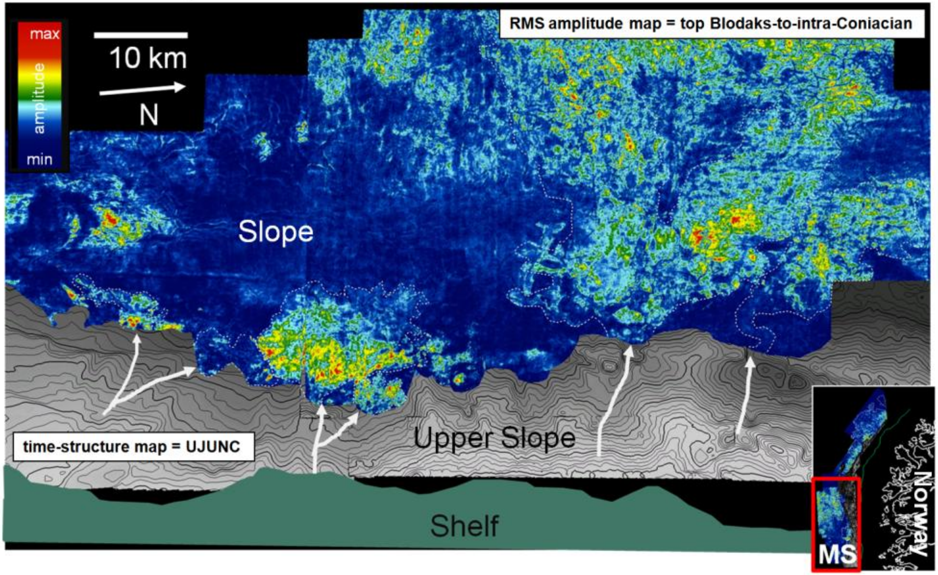
Måløy Slope



Late Cretaceous Palaeogeography

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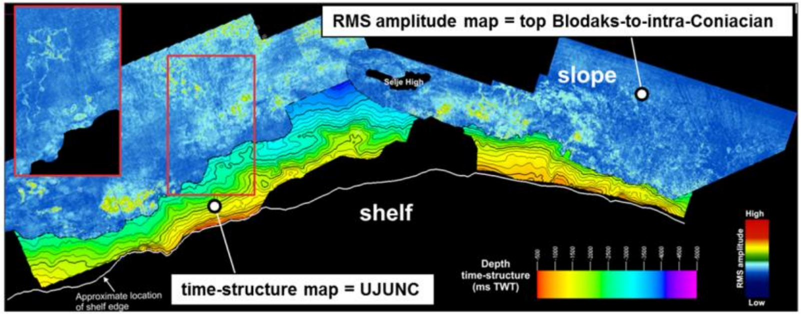

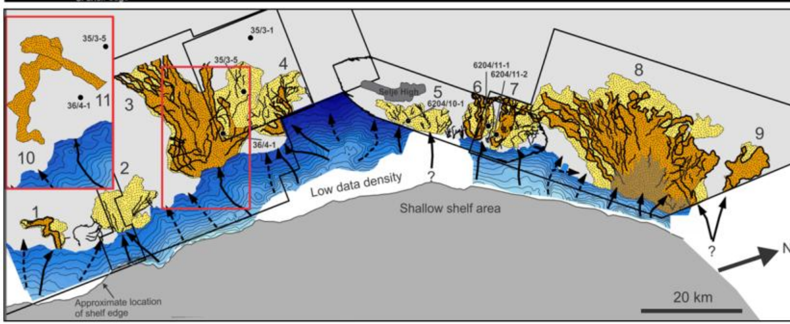

Fan System Dimensions

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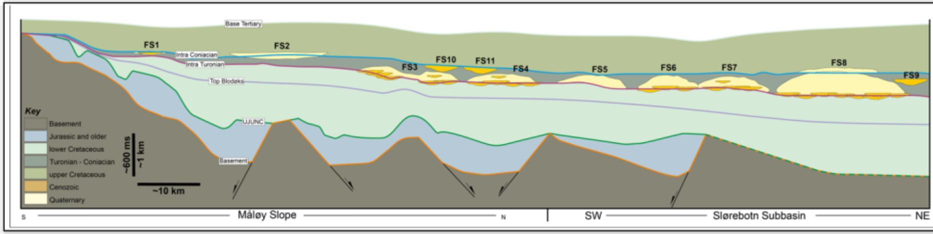
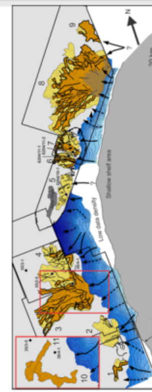


Fan (SF)	Fan area (km²)	Fan length (km)	Fan width (km)	Fan thickness (ms/m)	Aspect ratio	Fan outlet spacing (km)	Slope length (km)	Fan volume (km³)	Deposition rate (m/my)
1	27	11	6	60/102	59:1	14	11	1.4	17.3
2	76	13	12	70/119	101:1	23	10	8.7	38.4
3	386	27	21	120/204	103:1	11	13	84.8	73.2
4	109	14	8	100/170	47:1	34	8.5	8.0	24.4
5	59	7	13	130/221	59:1	10	6	7.9	44.8
6	45	9	6	90/153	39:1	11	8	6.2	45.6
7	66	11	7	100/170	41:1	31	10	10.8	54.3
8	587	24	38	300/510	75:1	-	4	216.2	122.8
9	-	-	-	-		-	-	-	-
10	55	18	4	50/85	47:1	-	-	-	-
11	30	15	5	50/85	59:1	-	-	-	-
MIN	*27*	*7*	*4*	*85*	*39:1*	*10*	*4*	*1*	*17*
MAX	*587*	*27*	*38*	*510*	*103:1*	*34*	*13*	*216*	*123*
AVG	*144*	*15*	*12*	*182*	*63:1*	*19*	*9*	*43*	*53*



Summary

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- Deep-water reservoir potential exists in the Upper Cretaceous succession offshore western Norway
- Deep-marine channels and lobes are expressed as amplitude anomalies
- Deep-marine system are developed outboard of and were fed through upper slope canyons
- **What can we infer about the onshore relief and nature of genetically-related drainage catchments?**
- **What controlled the discrete pulse of sediment to the Norwegian margin at this time?**

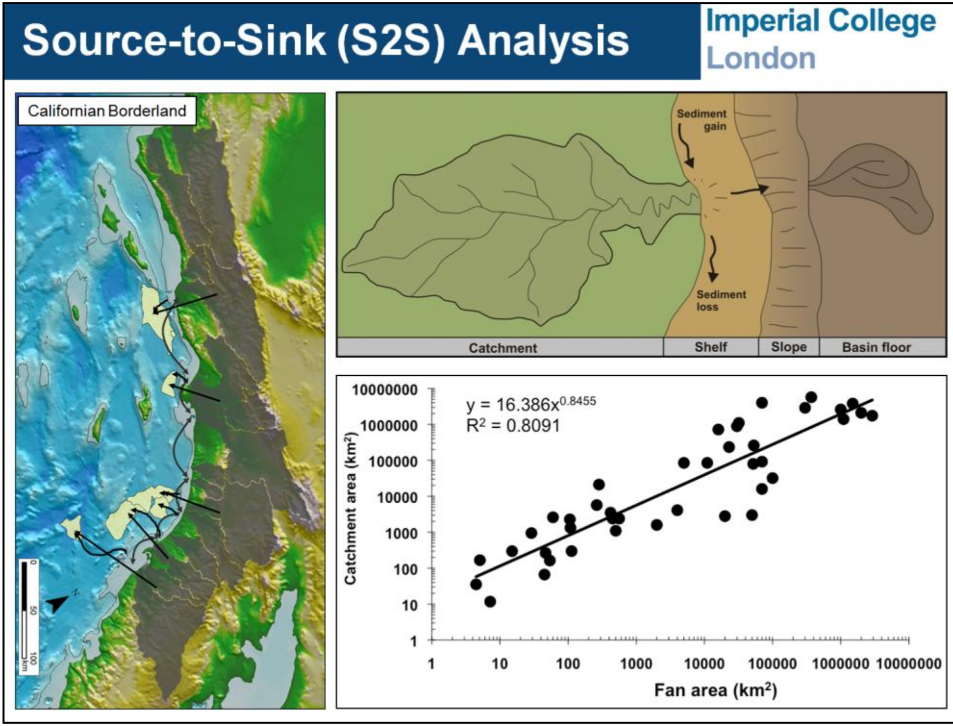
Presenter's notes:

Point 1 – Reservoir thickness of several tens of metres; reservoir quality variable.

Point 2 –Relationship between amplitude and lithology appears reliable; anomalies mappable using standard mapping techniques.

Point 3 – Canyons inherited from an earlier period of Late Jurassic incision.

Point 4 – Structural closures are robust and easily identifiable; stratigraphic traps are riskier due to confidence level in seismic delineation of pinch-out.



Presenter's notes: Intrinsic and extrinsic processes control timing, volume and calibre of sediment delivered to deep-water basins (e.g., margin relief, shelf processes, slope deformation, canyons, etc.).Isolating these in stratigraphic record is difficult due to buffering and filtering of signals. We are data-limited too; modern systems are rich in relatively short trimescale data (e.g., $<10^6$), but ancient systems have coarser resolution in terms of imaging and timing (e.g., $>10^6$). Links between ancient submarine fans and their drainage basins can be inferred from analyzing modern systems: (i) catchment spacing; (ii) fan area; and (iii) slope morphology. We aim to 'fill the gaps' in ancient systems and use modern relationships in a predictive sense. Small, high-gradient systems are more susceptiable to climatic or tectonic forcing, and signal more likely to be preserved.

S2S analysis includes all areas and processes involved in generating and transporting sediment in onshore catchments and depositing this in the deep-water realm. Improve understanding of how internal and external factors affect stratigraphy on various time scales. Preserved sedimentary units and system morphology may reveal complex responses between segments on short time scales. Crude estimates on system morphology, drainage extent, and response to long-term perturbations can be made in ancient systems.

Source-to-Sink (S2S) Analysis

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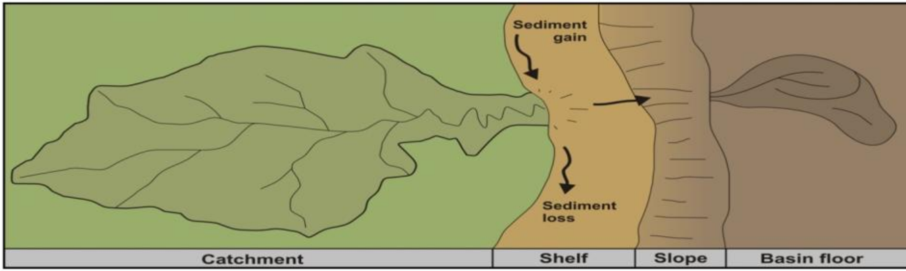

- **Key assumptions:**
  - **Fan size-based estimation –** *fan supplied from a single catchment (issues with longshore drift; trapping of sediment in paralic basins)*
  - **Slope length-based estimation –** *present slope reflects Late Cretaceous slope (issues with post-depositional deformation)*
  - **Catchment spacing-based estimation –** *catchment morphology and sediment dispersal influenced by active and extinct faults*

Catchment Prediction

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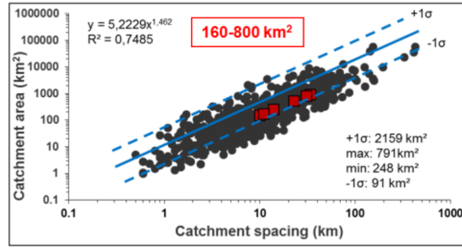
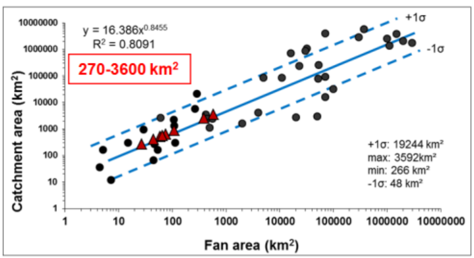
Upper Cretaceous data

Fan system (FS)	Fan outlet spacing (km)	Fan area (km²)	Slope length (km)
1	14	27	11
2	23	76	10
3	11	386	13
4	34	109	8,5
5	10	59	6
6	11	45	8
7	31	66	10
8	-	587	4

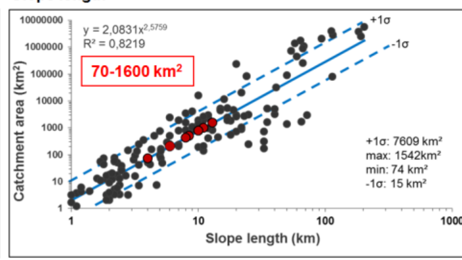
Outlet spacing



Fan area



Slope length



Presenter's notes: First-order estimates on drainage area can be derived from scaling relationships observed in modern systems. Data here from 29 modern systems along tectonically-active, predominantly extensional margins. Data presented in log-log space and fitted with a power-law regression equation to describe mean trend. We focus on eight systems for which we can confidently locate an apex and therefore point-source.

Catchment Prediction

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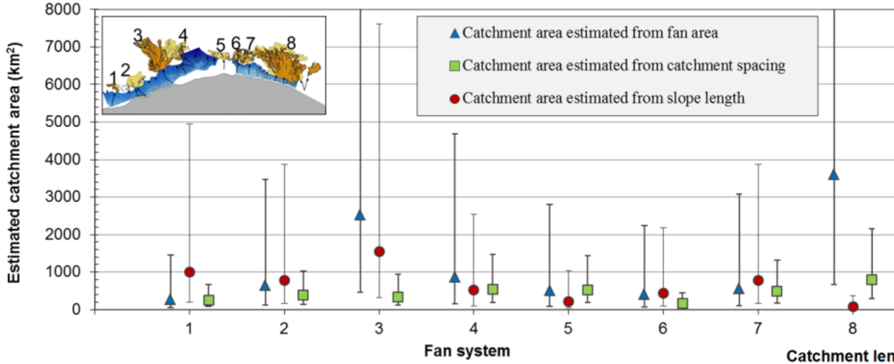
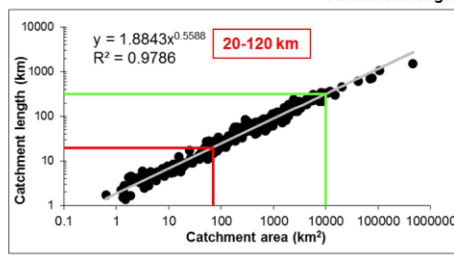
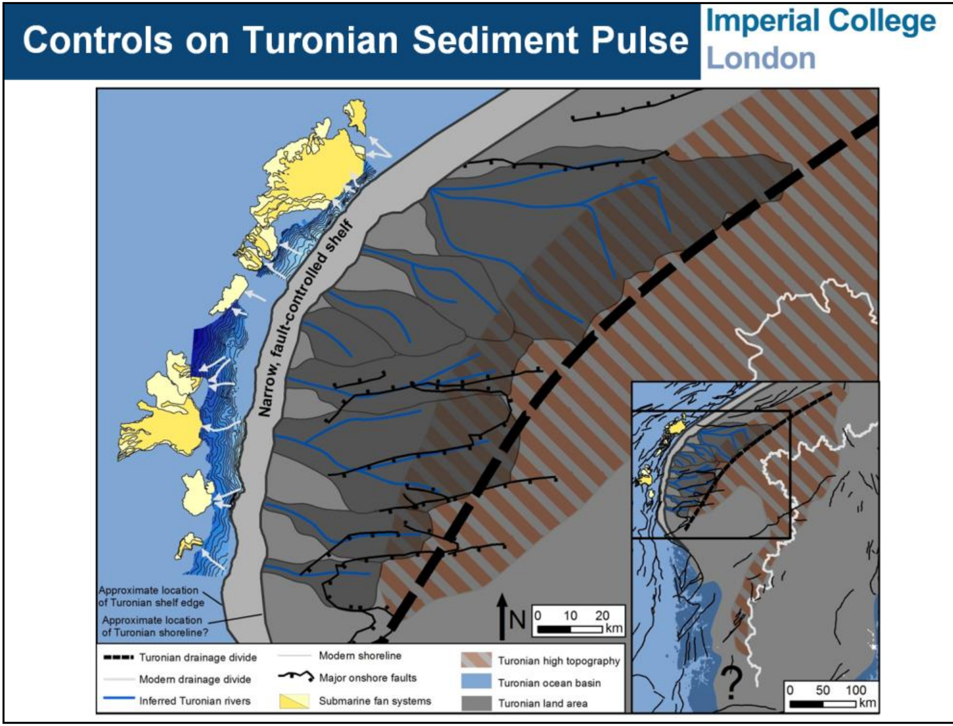


- **Independent** estimates of palaeo-catchment area = 300-3500 km^2
- Estimates are consistent and overlap within the uncertainties of one standard deviation

Catchment length





Presenter's notes: Based on: (i) modern patterns of drainage along active margins; (ii) positioning catchment outlet in vicinity of mapped submarine catchments that supplied sediment to the fan systems; and (iii) the estimated area and length of catchments (we construct a Late Cretaceous palaeo-landscape model for the western Norwegian margin). Estimated extent of catchments overlaps with major boundary faults systems of the MTFC. Is tectonics a valid mechanism to explain Turonian sediment pulse? We have already suggested that upper slope canyons may be related to tectonics.

Controls on Turonian Sediment Pulse

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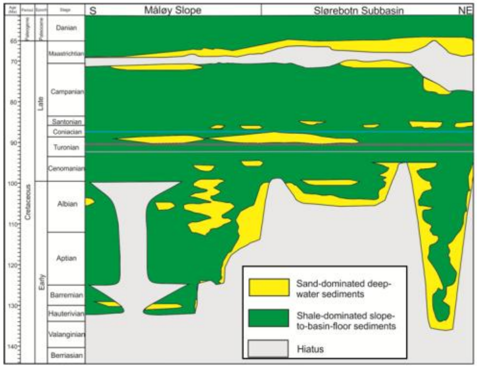

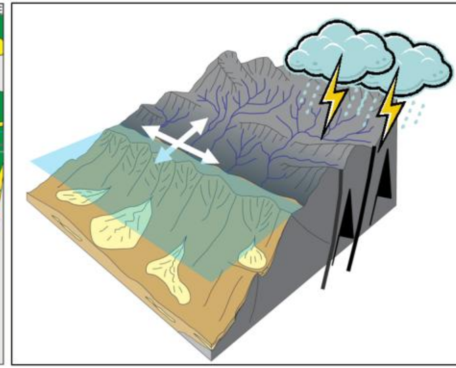

Possible drivers for 3 Myr-duration Turonian sediment pulse:

- Lateral shift of feeder system
- Climatically or eustatically driven changes in sediment flux
- Tectonically driven changes in sediment flux

Presenter's notes: High-frequency, occasionally large-magnitude climatic and eustatic variations during Cretaceous greenhouse conditions could be important and could have caused transit of deltas across narrow shelf; however, very little sandstone input into basin during 80 Myr period; thus, it is hard to conceive of sustained high-relief hinterland that yielded such little sediment, especially considering SL variations of several 10's of metres during greenhouse times on a narrow shelf. Tectonics appear to have driven canyon formation and overall stratigraphic architecture, thus appealing as a mechanism for sediment pulse; some evidence from fission track analysis, too.

Nature of the Turonian Sediment Pulse

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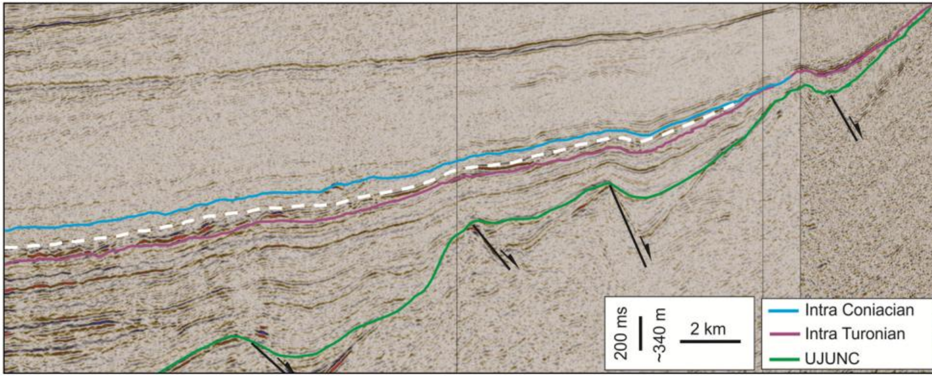
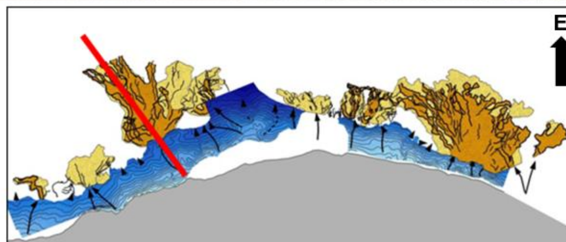


- Fan initiation occurs at the intra-Turonian reflection

- In some areas, backstepping and abandonment occur **below** the intra-Coniacian reflection



Nature of the Turonian Sediment Pulse

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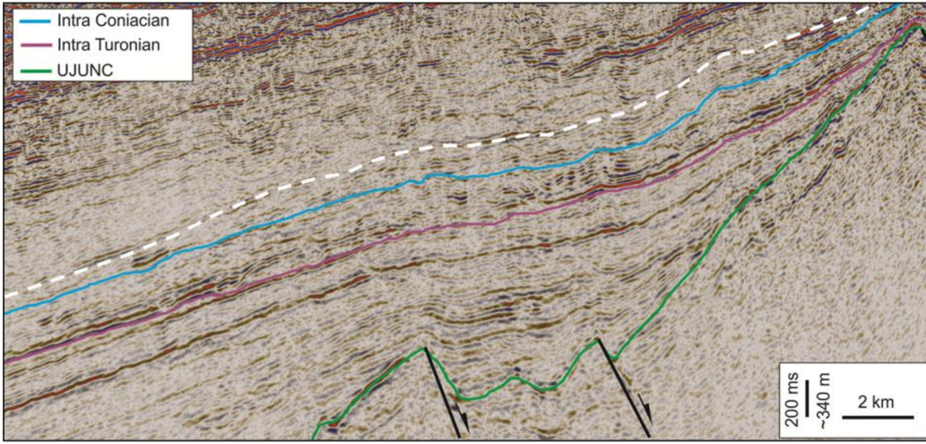
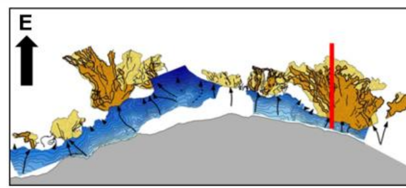


- ...in other areas, backstepping and abandonment occur **above** the intra-Coniacian reflection....
- Fan initiation was synchronous; fan abandonment was diachronous



Nature of the Turonian Sediment Pulse

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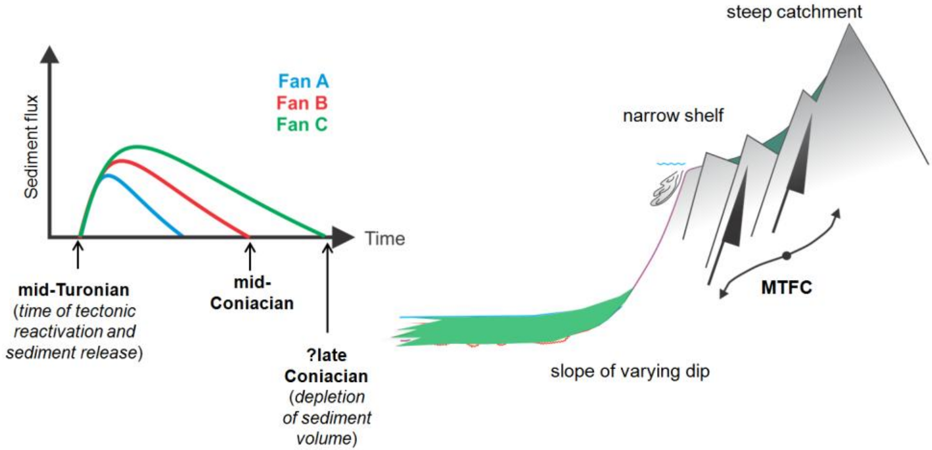

1. Synchronous initiation
2. Diachronous abandonment

Depletion of sediment released by fault-driven tectonic perturbation?

A Tectonic Control on Sediment Supply?

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- Short, steep mountainous catchments highly 'reactive'; instantaneous sediment production and transportation (i.e., no long-term intra-basin storage)
- Time-lag between tectonic uplift, sediment production and deposition
- Decrease in sandstone input reflects landscape 'relaxation'; diachroneity suggests along-strike variations in magnitude of tectonic uplift
- cf. tectonically controlled Ormen Lange system; hinterland uplift driven by plume migration

Presenter's notes:

1. Expected along tectonically active margins; processes can be augmented by other extra-basinal (e.g,. climate, eustacy) and intra-basinal (e.g., slope deformation) processes. 2. Provence data support derivation of material from the Caledonides rocks along the western Norwegian margin. 3. Mudstone above basal UC and canyon surface is suggestive of a S2S time-lag. 4. Difficult to constrain variability of onshore tectonics, although ongoing AFTA analysis of fault zones is providing some useful clues.

Conclusions and Implications

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- Late Cretaceous tectonic reactivation caused catchment rejuvenation and slope canyon incision

- Increased sediment flux resulted in deposition of 11 basin-margin fan systems

- Catchment adjustment following tectonic perturbation varied along-strike; fan abandonment diachronous

- Applications to exploration in frontier settings