Sedimentological Reappraisal of Mass-Flow Sandstones, Fulmar Formation Play, UK Central North Sea*

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Abstract

Mass-flow sandstones in the Upper Jurassic Fulmar Formation play represent secondary reservoir targets in the Central North Sea. However, their origin, character and distribution are still poorly understood. This study uses a process-based sedimentological analysis of cores, integrated with wireline log data to understand depositional processes that led to the emplacement of these mass-flow sandstones. Ten major sedimentary facies types (1-10) were identified. The sedimentary facies types, grouped into seven facies associations (T1 – T5; D1 and H1) represent deposition within a submarine fan – lobe setting. The two main depositional models, constrained by interpreted facies associations are turbidity current flows ponded in topographic lows; and hyperpycnal flows deposited as poorly confined to unconfined sheets. These models are only applicable on a sub-regional (field-wide) scale reflecting complex spatial and temporal variations. The results of this study emphasize the need for a rigorous sedimentological reappraisal of the extensive core database of the Central North Sea, to better constrain depositional models.

Introduction

The Upper Jurassic Fulmar Formation play represents an important play in the Jurassic petroleum system over much of the Central North Sea (CNS), and the reservoirs are predominantly shallow marine sandstones (Johnson et al., 1986; Fraser et al., 2002). However, the play also contains mass-flow sandstones, whose origin, character and distribution are still poorly understood (Kuhn et al., 2003; Sansom, 2010; Erratt et al., 2010; Wonham et al., 2014). Recent discoveries (e.g. Kessog and Jackdaw) contain reservoirs in these mass-flow sandstones, which demonstrate that there may be significant untapped potential to extend the Fulmar play. Therefore, an understanding of the origin, character and distribution of these mass-flow sandstones will be invaluable as a predictive tool for their exploration within the Fulmar play.

Most sedimentological studies on the Fulmar Formation have concentrated on the widespread, volumetrically more significant shallow marine (shoreface) deposits (Johnson et al., 1986; Stockbridge and Gray, 1991; Price et al., 1993; Howell et al., 1996; Gowland, 1996; Wonham et al., 2014). By comparison, little has been done on the mass-flow deposits (Robinson, 1990; Howell and Flint, 1996; Carruthers et al., 1996). This paper aims to characterize the sedimentology of the mass-flow sandstone reservoir facies within the Upper Jurassic Fulmar Formation play and synthesize models for their deposition.

Geologic Setting

The study area is approximately 70 km by 30 km in dimension, bounded to the north by the Forties-Montrose High, to the west by the West Central Shelf, to the south by the Mid North Sea High, and to the east by both the Jaeren High and the Norwegian sector of the CNS (Figure 1). The tectono-stratigraphic evolution of the CNS is here summarised in three phases

Phase 1: Mid-Paleozoic to Triassic

Early Devonian Caledonide Orogeny led to the development of a NE-SW Caledonide trend and a NW-SE Tornquist trend (Jones et al., 1999). Subsequently, Early Permian intra-continental rifting led to the formation of the Northern Permian Basin, whose inherited structural grain controlled the evolution of the CNS. The Rotliegendes Formation was deposited during the syn-rift phase, followed by the post rift Zechstein evaporite sequence. The Triassic is characterised by major salt movement and formation of minibasins where Lower Triassic Smith Bank Formation and Skagerrak formation accumulated (Hodgson et al., 1992).

Phase 2: Jurassic to earliest Cretaceous

The main rifting event in the CNS occurred in the Late Jurassic, creating fault-bounded basins and reactivating salt movement. Salt withdrawal and rifting were both spatially and temporally variable, such that sediments of the Fulmar Formation and lateral equivalents were deposited across varied and complex basin-floor topography (Stewart et al., 1999; Fraser et al., 2002). The Fulmar Formation unconformably overlies the Pentland Formation or Triassic strata in places and passes upwards into the Heather and Kimmeridge Clay formations. This was the period of deposition of pulses of mass-flow sandstones, commonly encased in shaly layers. A ‘Late Cimmerian (Base Cretaceous) Unconformity’ developed as the crest of rotated fault blocks were eroded, and post-rift thermal subsidence was initiated in the latest Jurassic/earliest Cretaceous.

Phase 3: Cretaceous to Tertiary

Regional post-rift thermal subsidence set in, marked by the deposition of the Cromer Knoll Group and overlying Upper Cretaceous Chalk Group (Johnson et al., 2005). Several Paleogene submarine fans were emplaced in the CNS as the Scottish Highs were uplifted, succeeded by neritic sequences of Neogene age (Wakefield et al., 1992). A Late Campanian and Tertiary (Alpine Orogeny) inversion occurred, causing reverse movement on basement fault, uplift and remobilisation of salt (Rattey and Hayward, 1993).

Results and Discussion

1. Facies analysis

A process-based sedimentological study of 404 m of cores from 12 wells was undertaken to understand the depositional processes and paleo-environment of mass-flow sandstones in the CNS. Ten main sedimentary facies were recognized. The result of this is summarized in Figure 2. Furthermore, facies were grouped into seven genetically related facies associations (FA) to aid depositional element interpretation.

FA T1: Poorly confined channel turbidite

This association represents the most abundant, reservoir-grade facies within the studied cores. It is dominated by amalgamated, massive, well to moderately sorted, fine to medium grained sandstones deposited by high-density turbidity currents (Facies 1a), which corresponds to Facies S3 of Lowe (1982). Individual beds are typically amalgamated into composite thickly bedded units exceeding 4 m in thickness. Sand content is very high. Subordinate facies include associated Facies 2, Facies 3 and occasionally, Facies 6. The lack or rarity of erosive bases, lag conglomerates and multiple internal scours, favours a proximal fan setting, in which sand was deposited in poorly confined channels.

FA T2: Channel-lobe transition turbidite

This association is dominated by ripple-laminated, fine-grained sandstone that are usually draped by mud or plant material, and interpreted to be deposited by low-density turbidity currents (Facies 3). Subordinate facies include Facies 4 and 5, and probably represent a continuum from a proximal to a distal setting. . It is typically a few decimetres thick. It is interpreted as deposited in a proximal-distal lobe transition setting

FA T3: Distal lobe/fan fringe turbidite

This association is dominated by very thinly-bedded, slightly rippled top, fine grained sandstone, interspersed within thick to very thick (several metres thick) mudstone caps (Facies 5). Subordinate facies include Facies 7 and 8. Ptygmatically folded sand injectites are common and sand content is very low. It is interpreted as deposited in a distal lobe/fan fringe setting - the most distal equivalent of association T2.

FA T4: Oxygenated basin mudstones

This association consists mainly of grey, bioturbated siltstones and mudstones (Facies 7). Bioturbation is typically intense as to give deposits a mottled appearance. It is commonly associated with Facies 6 and 8. It is interpreted to reflect deposition from hemipelagic settling, but within oxygenated bottom water conditions. Oxygenation may be caused by periods of increased water circulation or input of oxygenated water and organisms transported by mass-flow (Ravnås and Steel, 1997).

FA T5: Anoxic basin shale

This association consists mainly of mid-grey to dark-grey, fissile laminated, non-bioturbated mudstones/shales (Facies 8). Subordinate facies include occasionally interbedded Facies 7. Rare macrofossil casts occur. Intense fracturing was indicated by slickensides in the claystones. It is interpreted to be deposited by hemipelagic settling in anoxic to very low oxygen bottom water conditions.

FA D1: Collapsed channel debrite

This association consists of large, contorted, plastically deformed clasts within a muddy to sandy matrix, typically larger than the scale of a core diameter (Facies 9), ranging in thickness from tens of cm to 2 m. En masse ‘freezing’ of poorly sorted, matrix-supported conglomerates less than 1 m thick with a relatively high relief erosive relief (Facies 10), also occur. It is interpreted as deposited in the most proximal reaches of the feeder submarine channel close to the source area, or resulted from collapse of levee and channel margin, poorly consolidated sediment, and redeposited within channels.

FA H1: Poorly channelized hyperpycnite

The dominant facies is massive, moderately sorted, fine to medium-grained sandstone with abundant carbonaceous material (Facies 1b). The observed vertical facies succession starts from a 2.5 m thick, sharp-based, subtle inversely graded Facies 1b at the base, into a 0.3 m thick ripple-laminated unit with slightly coarser grains, which passes upwards into a 0.9 m thick planar parallel-laminated, medium-grained sandstone with slight bioturbation. This is overlain by another ripple-laminated sandstone unit (0.4 m thick), with finer grains, and a bioturbated unit (0.6 m thick) at the top. Hydrodynamically, this reflects a waxing-waning current flow typical of hyperpycnal flows (Mulder et al., 2003).

2. Well-log analysis

An attempt was made to calibrate core-defined facies associations to distinct well-log signatures. Most associations show no clear difference in signatures and on cross-plots. There could be several reasons for this, including but not restricted to: [i] wireline logs are indirect measurements of rock properties based on physical quantities thus, rocks with differing depositional significance can have similar properties sampled by wireline logs, hence are non-diagnostic; [ii] Some facies associations are thin (< 2 m thick) and probably below log resolution. Thus, a coarse well-log facies scheme was applied, distinguishing sand-prone mass-flow facies from mud-prone mass-flow facies and adjacent shoreface and/or fluvial successions.

Jeremiah and Nicholson (1999) published a named sequence stratigraphic template from one wells available for this study (well 23/26b-15), which formed the basis of correlating time-equivalent sequences in the northern part of the study area (Figure 3). The lack of biostratigraphic data precludes detailed sequence stratigraphic analysis. From the correlation, it is observable that back stepping of the shoreface Fulmar Formation (yellow shade) was coeval with emplacement of laterally restricted mass-flow sandstones (orange shade) above the Middle to Late Oxfordian sequence boundary (SJU 310). Mass-flow sandstones also become more common post Middle Kimmeridgian, illustrating varying controls on the emplacement of mass-flow sandstones in time and space.

3. Depositional model

Complex spatial and temporal variations in rifting and salt withdrawal/dissolution during the evolution of the Jurassic Central North Sea mean that it is difficult to develop a basin-wide depositional model for the emplacement of mass-flow sandstones. In this study, we show that specific processes were active at different parts of the basin during the Late Jurassic. Two main depositional processes are modelled, constrained by interpreted facies associations (Figure 4 and Figure 5). They are: [i] turbidity current flows ponded in topographic lows e.g. hanging walls of basin bounding faults, in the southern part of the study area (Figure 4); and [ii] hyperpycnal flows deposited as poorly confined to unconfined sheets, possibly deflected around growing salt walls, in the northern part of the study area (Figure 5). The emplacement of mass-flow sandstones is most likely related to periods of increased rifting, location of rifting block and intensity of rifting, which is thought to be spatially variable throughout the CNS.

Conclusion and Recommendation

Detailed, process-based sedimentological analysis of core data integrated with wireline-log data for the Upper Jurassic Fulmar Formation play, as an aid to understanding the origin of the mass-flow sandstones, and therefore better predict reservoir facies distribution and character has been carried out.

Sedimentological analysis of cores identified ten main sedimentary facies types (1 – 10) within the mass-flow deposits, which reflect a range of mass-flow processes. The identified sedimentary facies were grouped into seven facies associations (T1 – T5; D1 and H1) that reflect deposition within a submarine channel – lobe setting. Many of the core-defined facies associations show no clear difference in wireline log character when calibrated to wireline log data, limiting extrapolation of facies association beyond where there is core control. Two main depositional models, constrained by recognised facies associations, are proposed, their occurrence linked to periods of increasing rifting.

It is recommended that additional core and well-log data be provided to validate conceptual models. High-resolution seismic data is required to understand the large-scale stratigraphic architecture of mass-flow sandstones and adjacent block structuration. This is necessary as these mass-flow sandstones are typically below the resolution of conventional seismic data. In addition, detailed petrographic and geochemical analysis should be carried out to better constrain provenance of mass-flow sandstones.

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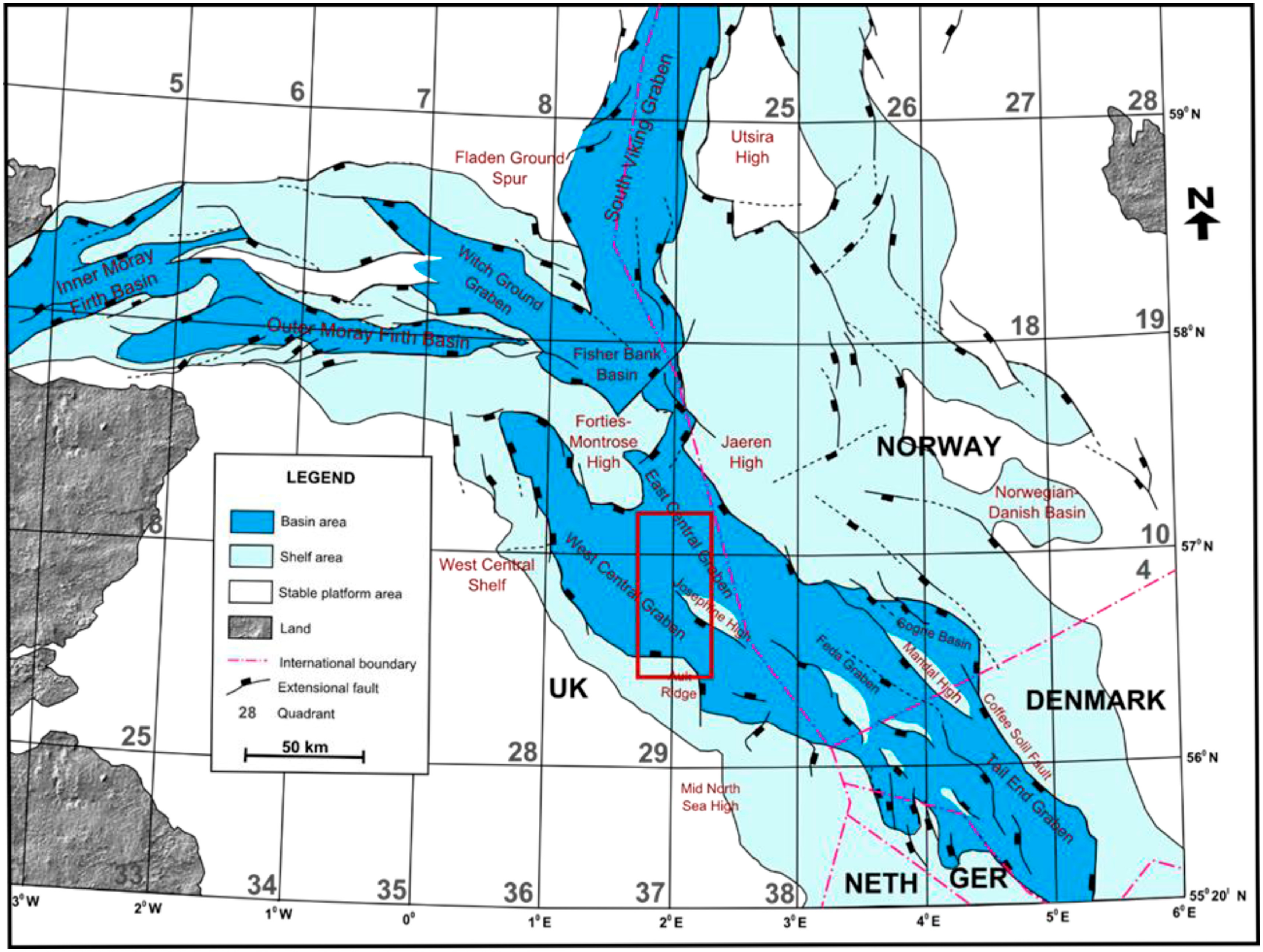
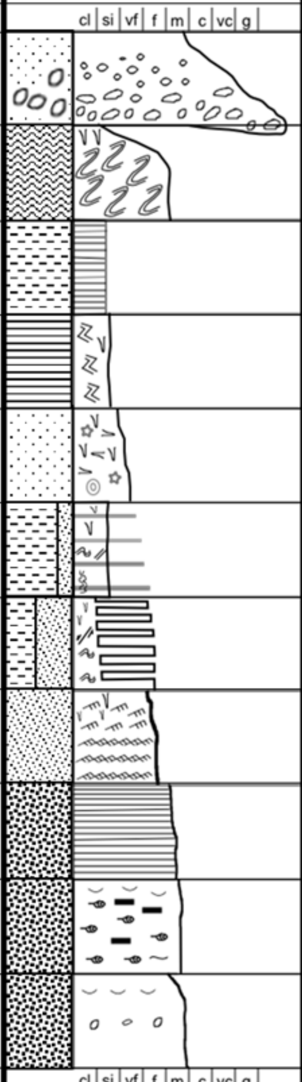


Figure 1. Main structural elements of the Jurassic Central North Sea (modified from Fraser et al., 2002). Outline of the study area is the red box shown within.



CODE	LITHOLOGY, GRAIN SIZE AND SEDIMENTARY STRUCTURES	FACIES NAME	FACIES DESCRIPTION	DEPOSITIONAL PROCESS
10		Matrix-supported conglomerate	Grey, poorly sorted, matrix-supported conglomerate. Clasts are sub-rounded to rounded, up to 3 cm in diameter; matrix is mud to sand-sized grains. Erosive contact with underlying facies.	Medium to high-density, cohesionless debris flow. Roundness of large clasts points to a sedimentary recycled origin. May also be deposited by erosive fluvial process.
9		Slump beds	Grey to brown, contorted and pervasively deformed mega slump beds, made up of unsorted mix of sandstone and mudstone. Bioturbation is common.	*En masse* 'freezing' of sandy to muddy, cohesive debris flow. Deformation may have occurred during transport of poorly lithified strata or during *en masse* deposition.
8		Non-bioturbated, fissile laminated mudstone	Mid- to dark-grey, sparsely to non-bioturbated, fissile laminated mudstone. Commonly fractured, resulting in observed slickensides. Pyrite is common.	Hemipelagic settling of background mud from basinal water. Anoxic bottom water conditions existed.
7		Bioturbated siltstone	Mid- to dark-grey, moderately to intensely mudstone or sandy siltstone, resulting in a mottled appearance.	Low energy, very dilute (low-density) turbidity current. Aerobic conditions existed which supported life.
6		Bioturbated sandstone	Creamy to brown, moderately to intensely bioturbated, silty to fine grained sandstone. Typical gradational contact with underlying facies. Concretions are common. Sand content varies.	Moderate to high-density turbidity current. Deposits were subsequently reworked by biogenic organisms
5		Very thin sandstone-striped mudstone	Mid- to dark-grey mudstone-dominated interval, with < 2 cm stripes of paler siltstone or fine sandstone. Sand lenses may have lower amplitude scoured base and rippled top. Sand content is relatively low	Dilute, very low-density turbidity current. Thick mudstone cap deposited by differential settling of flocs or by hemipelagic settling. Slow rate of deposition
4		Heterolithic sandstone-mudstone couplet	mm- to cm-scale alternation of dark grey mudstone and light-grey very fine to fine grained sandstone. Convolute structures are common. Clear smearing along fault planes occur.	Moderate to low energy, low-density turbidity current. Repeated cycles of break-up of flocs containing both mud and very fine sand causes interbedding.
3		Ripple-laminated sandstone	Light-grey to yellowish brown, moderate to well sorted, fine grained, ripple-laminated sandstone. Asymmetric current ripples and climbing ripples occur. Ripple wavelength < 4 cm, amplitude < 5 mm. Sparse to moderate bioturbation.	Low-density turbidity current. Main sediment support mechanism is fluid turbulence. Current ripples result from a unidirectional, low-velocity waning flow. Climbing current ripples indicate rapid deposition
2		Planar-laminated sandstone	Light-grey to brown, fine to medium grained planar parallel-laminated sandstone. Moderate sorting. Individual laminae are only a few mm thick and occasionally deformed. Sand content high (70-90%).	Relatively fast-flowing currents in the upper-stage plane-bed regime. Deposited from both low- and high-density turbidity currents (mixed-density?)
1b		Massive sandstone with abundant carbonaceous matter	Light-grey to brown, well to moderately sorted, fine to medium grained, massive sandstone similar in character to Facies 1a. Abundant carbonaceous (coaly) material. Subtle inverse grading.	Sustained, high-density turbidity current. Abundant carbonaceous material suggests direct connection to a dense river flow, typical of hyperpycnal flows.
1a		Clean, massive sandstone	Creamy or light-grey to brown, well to moderately sorted, fine to medium grained, amalgamated massive (structureless) sandstone. Subtle normal grading; sharp basal contact. Floating clasts and dish structures occur, but are uncommon. Negligible mud content.	Moderate to high energy, high-density turbidity current. Near-steady flow speed and/or sediment concentration resulted in very subtle graded bedding. Wide range of colour is likely due to varying mineralogy

Figure 2. Sedimentary facies characteristics and the interpreted depositional processes of cored intervals studied.

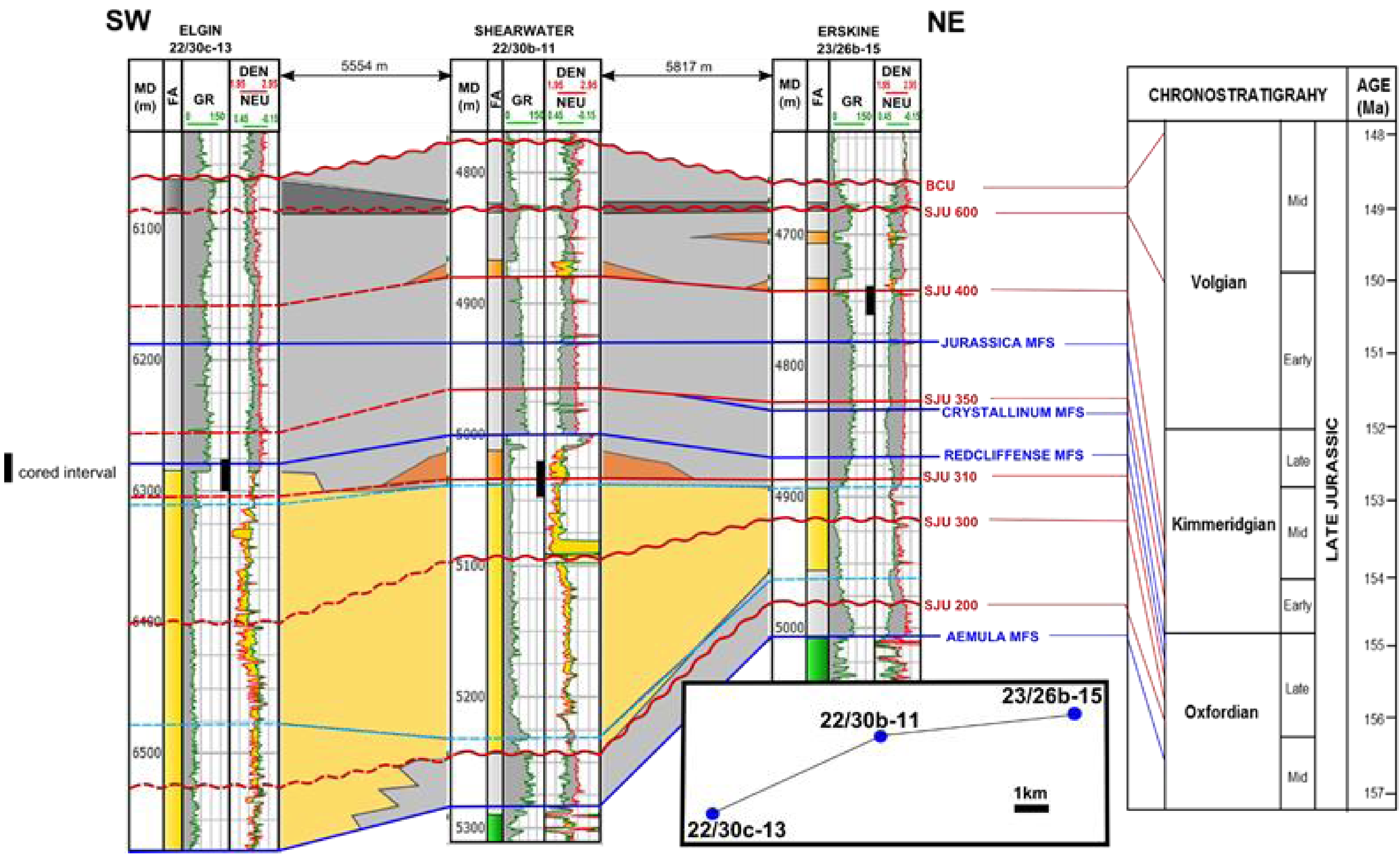


Figure 3. SW-NE well-correlation panel across the Elgin–Shearwater–Erskine fields. Correlation panel is flattened on the Mid-Kimmeridgian Jurassica MFS. Stratal surfaces are named after Jeremiah and Nicholson (1999).

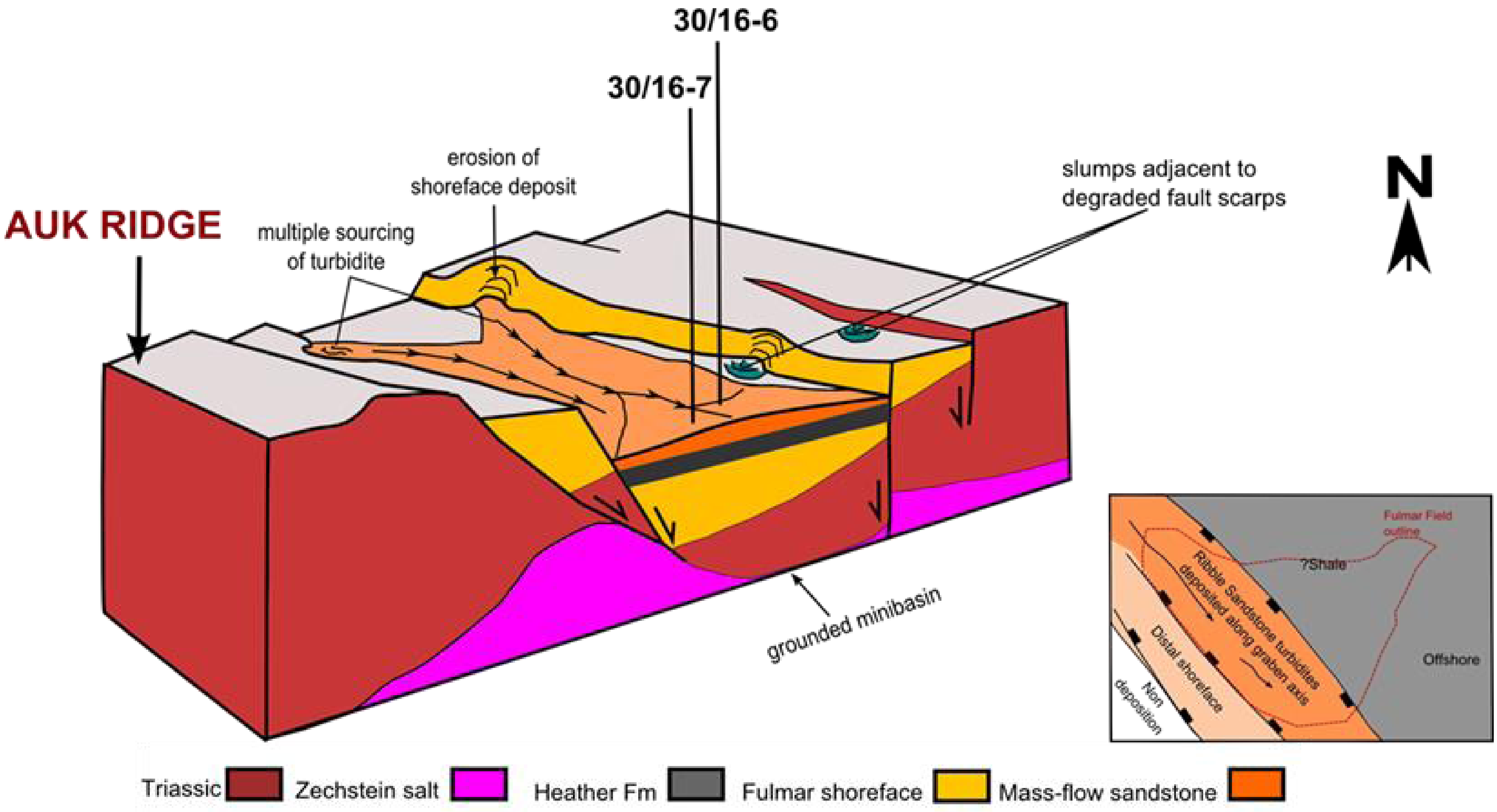


Figure 4. Conceptual model for turbidity currents sourced from adjacent shoreface rocks and ponded in hanging walls of bounding faults.

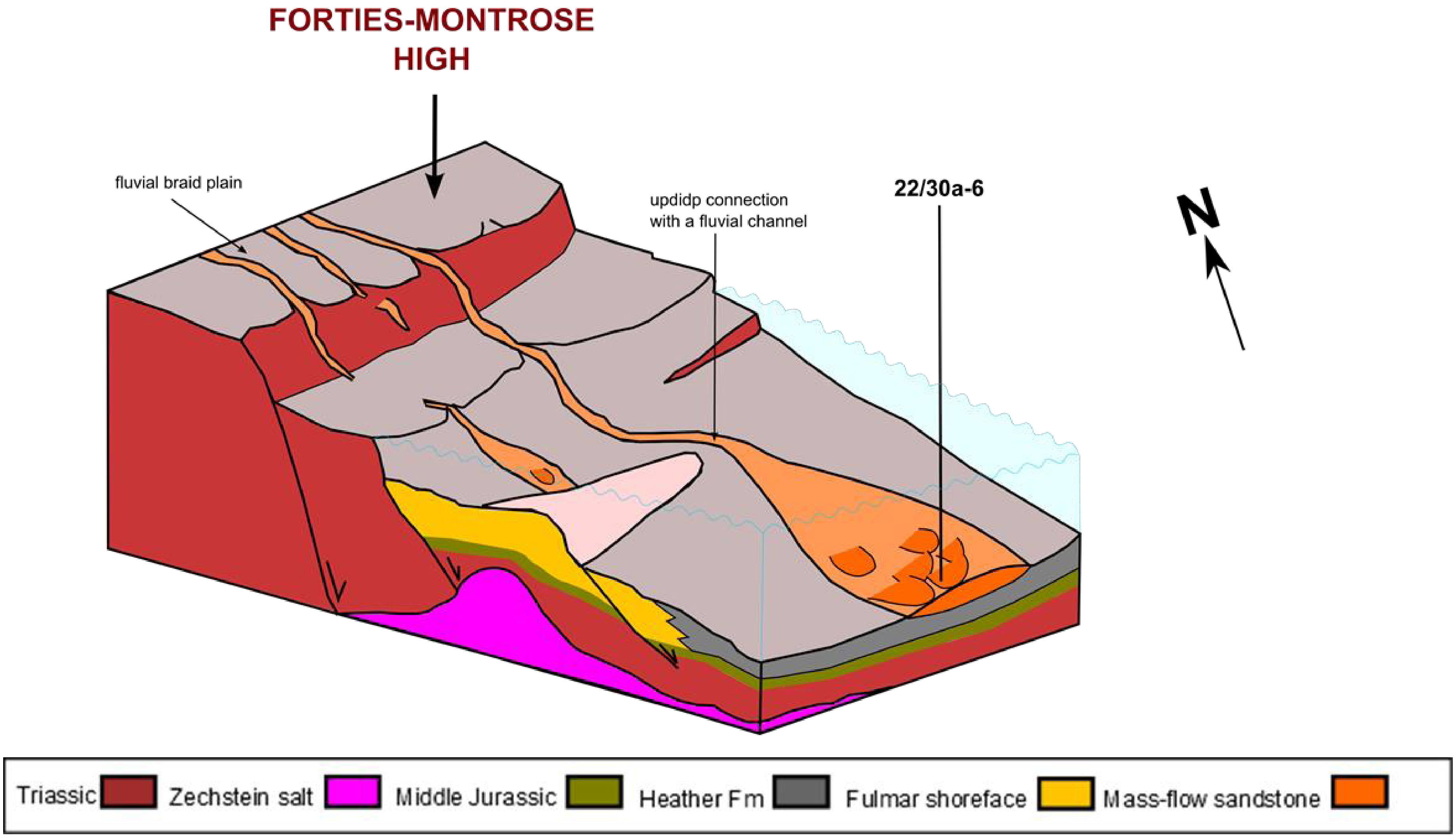


Figure 5. Conceptual model for a poorly confined hyperpycnal flow, deflected around growing salt wall.