Sedimentological Criteria for Distinguishing Stacked Dune-trough Muds from Muds in Inclined Heterolithic Strata in the Subsurface – Insights from McMurray Formation Outcrops and Modern Analogues*

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Abstract

Both dune-trough (also known as dune-bottomset) mud deposits and muds in inclined heterolithic stratification (IHS; Thomas et al., 1987) are deposited in the same depositional systems including fluvial, tidal, and tidally influenced fluvial systems. Although their geometries and structures are fundamentally different, these two deposits are hard to distinguish in core (Figure 1).

Introduction

Dune-trough mud deposits are documented in both inter- (Fenies et al., 1999) and subtidal (Allen, 1991) zones of tidal and tidally influenced depositional systems. In inter-tidal systems mm – cm scale dune-trough muds are deposited slowly from suspension in small pools (up to a couple of m^2 scale (Fenies et al., 1999) where between fluvial flood events and during the slack water periods of tide cycles water is entrapped in the troughs of sand dunes (Figure 2 and Figure 3). In sub-tidal depositional systems, turbidity is much higher and may reach 10-100 grams/liter (Allen, 1991) which allows for deposition of dune-trough muds which may exceed thicknesses of 0.1 m. Dune-trough muds are of limited lateral extent (up to several meters), (sub) horizontal, and bounded by thicker, steeply dipping clean sand foresets (bundles) of overlying and underlying beds. Mud strata within IHS deposits can be laterally extensive (up to several hundreds of meters (Strobl et al., 1997), from few mm (if product of daily tidal cycles) to > 0.1 m thick (if product of seasonal cycles (Jablonski, 2012), variably bioturbated, with inclined depositional dips (commonly 4-12 degrees), and bounded by thicker, continuous sand strata (Thomas et al. 1987; Table 1). In the rock record both dune-trough muds and muds in IHS are commonly interbedded.

Dune-trough muds and muds in IHS are characterized by low-permeability (< 0.2 Darcy), whilst sands above and below these muds are characterized by high permeabilities (> 2 Darcy). Since mud strata in IHS can be continuous (tens to hundred meters) these muds are of concern for reservoir developments as potential barriers for fluid flow (Strobl, 2012), whereas dune-trough muds are discontinuous and thus may present only minor baffles for fluid flow. Thus, distinguishing stacked dune-trough mud deposits from IHS in the subsurface may be important for reservoir development risk assessments.

Recent observations from McMurray Formation outcrops and cores suggest that stacked cross-beds with preserved dune-trough muds may easily be misinterpreted as inclined heterolithic strata (IHS) (Figure 4). The aim of this paper is to document differences and address challenges related to subsurface interpretation, as well as to propose tools for distinguishing them in subsurface data.

Data and Interpretation

Our detailed outcrop logs and sketches are from a recent road cut exposure in the Abasand area and from the McMurray Formation Type Section, both located in the vicinity of Fort McMurray, Alberta, Canada.

The first exposure is part of the lowest of three interpreted stacked channel deposits in a series of Abasand outcrops. Each stacked channel deposit is 15-25 meters thick. The outcrop of interest is approximately 8 m high and 50 m long. It is comprised of stacked planar and trough cross-bedded sand deposits. Individual bed thickness ranges from 0.25-0.75 m. Unlike many other exposures of cross-bedded sand in the McMurray Fm., this outcrop is characterized by preservation of 0.05-0.15 m thick mudstone layers occurring at the base of most cross-bed sets. Each mudstone layer is horizontal when it lies on the bottomset, but curves and thins upwards in the toeset, forming progressively more steeply dipping mud layers over short vertical distances, a phenomenon commonly seen in modern environments (Dalrymple, in review). Additionally, careful examination reveals that thick bottomset deposit is comprised of numerous thinly interlaminated mud layers (including clay, silt and very-fine grained sand), while the number of these layers decreases in toesets. The vertical frequency of mud layers is between 1 to 4 per meter (averaging 3 per meter); lateral extent is limited and ranges from < 1 m to a maximum of 3 m. All mud layers are bounded by steeply dipping clean sand foresets of overlying and underlying cross-beds. Interpreted dune-trough muds are bitumen free, while the surrounding sand is saturated by bitumen with an estimated Soil of 80%.

The second documented exposure is on McMurray Formation Type Section along the banks of the Athabasca River, 2 km north of the city of Fort McMurray. The outcrop is 60-80 m high and about 1.8 km long. Our investigation is focused on a very small portion of about 2 m^2 located at the base of an interpreted 35 m thick point-bar deposit. This exposure shows a (i) lateral transition from stacked planar tabular cross-stratified sand characterized by a few millimetres thick dune-trough mud bounded by a 0.15-0.25 m thick steeply dipping clean sand foresets into an interbedded sand and mud unit that looks like typical IHS. The thickness of mud increases laterally, locally exceeding 0.05 m. (ii) There is also a vertical change from stacked planar tabular cross-stratified sands to trough cross-bedded sands, characterized by preservation of relatively thick (up to 0.1 m) dune-trough muds. Like in the Abasand case, these dune-trough muds are horizontal and thicker in the bottomset, but curve and thin upward in the toeset, forming progressively steepening mud layers over short vertical distances (Figure 4).

Considering that the cross-beds and preserved discontinuous mudstone layers (both at Abasand and the Type Section) are at the base of interpreted large-scale point bar, coupled by strong evidence to support a tidal influence within the studied outcrops and particularly within the genetically related overlying IHS units, an inter-tidal origin of mud-drapes can be excluded, leaving the sub-tidal interpretation as the most plausible. A sub-tidal interpretation is also in the line with Allen's (1991) suggestion that decimeter thick muds can be accumulated in the troughs of the cross-beds in sub-tidal environment due to high turbidity (10-100 grams/liter suspended-sediment concentration). This contrasts with the order of magnitude lower suspended sediment concentration of mud (2-3 grams/liter) in the inter-tidal zones. The lateral transition from stacked cross-beds with no muds at the base to stacked cross-beds with thick (up to 0.1 m) muds at the base over distances on less than 1 m can be explained to be due to changes from spring to intermediate tides (Fennies et al., 1999); and reduced number of mud-silt couplets in toesets comparing with bottomset muds as a function of spring – neap cycles, inferring that preserved mud layers are result of multiple rather than a single event.

In both studied locations, the interbedded sand and mud are characterized by several centimeters thick (up to 0.2 m), non-bioturbated mudstone bounded by up to 0.2 m thick sand. Mud layers are comprised of multiple mud laminae whose number progressively decreases in the toesets, perhaps as a result of neap-spring cyclicity superimposed on the slower forward migration of a large to very large dunes; and are gradationally overlain by sand without mud layers. The overlying sand typically is comprised of high angle foresets or unidirectionally ripple-laminated, but often appears to be structureless (in outcrops due weathering and in cores due to core expansion).

The strong similarity between stacked dune-trough mud deposits observed at two studied locations and muds in IHS, which includes the high and regular frequency of parallel mud beds and same and/or very similar structures in sands above and below mudstone layers, presents a potential issue for distinguishing these two deposits in core studies. The criteria for distinguishing in a narrow core may include: (i) if present, the high-angle foresets in overlying sands are more likely an indication of dune-trough mud deposition; (ii) depositional dips (when FMI available), being inclined and unidirectional in IHS and (sub) horizontal and scattered in stacked dune-trough muds; (iii) when described in a broader geological context, the lower series of mud layer above the channel-base contact in the core is very likely a trough mud deposit, whereas those that are higher in the core are less certain, and/or more likely IHS; (iv) an upward transition over a short vertical distance from flat-lying mud layers to progressively more steeply dipping mud layers likely indicates the upward increase in slope from the bottomsets to the toesets (Figure 4) and sometimes even into the foresets of the dune (i.e. Figure 1 boxes 3-5 clearly shows the upward increase in dip) characteristic of dune-trough deposits, versus lack of this phenomena and rather constant dips of muds within the IHS; and (v) a lateral change in a number of thinly interbedded mud-silt layers (from numerous in bottomsets to less numerous in toesets) is diagnostic of dune-trough muds whereas a consistent number of thinly interbedded mud layers is more likely to be indicative of IHS deposition.

Conclusions

Visually, and particularly based on the same or a very similar frequency of interbedded sand and mud layers, stacked dune-trough mud deposits and muds in IHS look strikingly similar. Since the former are not, and the latter are, of concern for reservoir developments, the importance of distinguishing between the two in the subsurface is paramount. However, this is not an easy task, particularly using narrow cores. Thus, particular attention is needed to observe the subtle differences and details, some of which are emerging sedimentological concepts. The emerging concepts have been raised by integrating the presented outcrop study with recent findings in modern environments (BITE Consortium, unpublished data) and comparing it with data from narrow cores. The concepts for distinguishing dune-trough mud deposits and muds in IHS include a combination of sedimentological criteria such as presence and/or absence of high-angle foresets in overlying strata; (sub) horizontal, scattered versus inclined, unidirectional sand-mud contacts; occurrence at the lower versus higher parts of the channel; lateral steepening and thinning over short distances versus constant inclination and thickness of mud layers; and lateral change in a number of thinly interbedded mud-silt layers versus the rather constant number of thinly interbedded mud-silt layers (Table 2).

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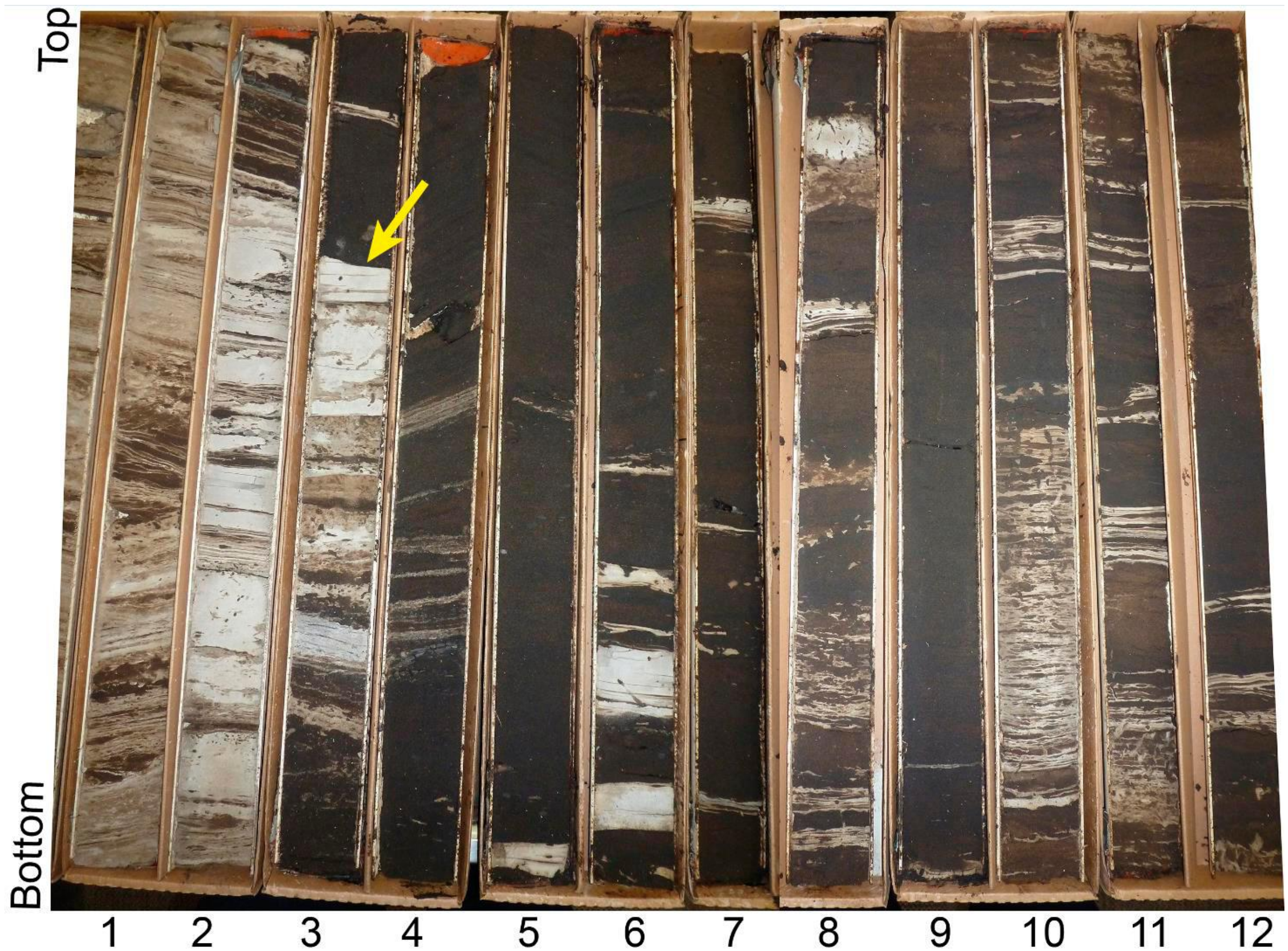

Figure 1. A selected core interval from well 100/02-35-89-9W4, located about 1.5 km behind the Type Section. Tubes 1, 2, and 3 (to the contact indicated by yellow arrow) are interpreted as muddy IHS strata of the underlying point-bar deposit; the top of tube 3 and tubes 4-7 are characterized by interbedded sand and mud. The sand shows steep angle foresets (bundles) and up top 5 cm thick muds. This unit could easily be interpreted as IHS. Correlation with the base of the large-scale channel in outcrop suggests that these muds are discontinuous dune-trough muds. Tubes 8-12 display variably bioturbated muds of HIS. Thin (mm scale) muds and are likely products of daily depositional cycles. Thicker muds are most likely the product of seasonal changes. Each core barrel/tube is 0.75 long and 0.08 m wide. The yellow arrow points to interpreted base of large scale point-bar deposit. Note: the core is not oriented.

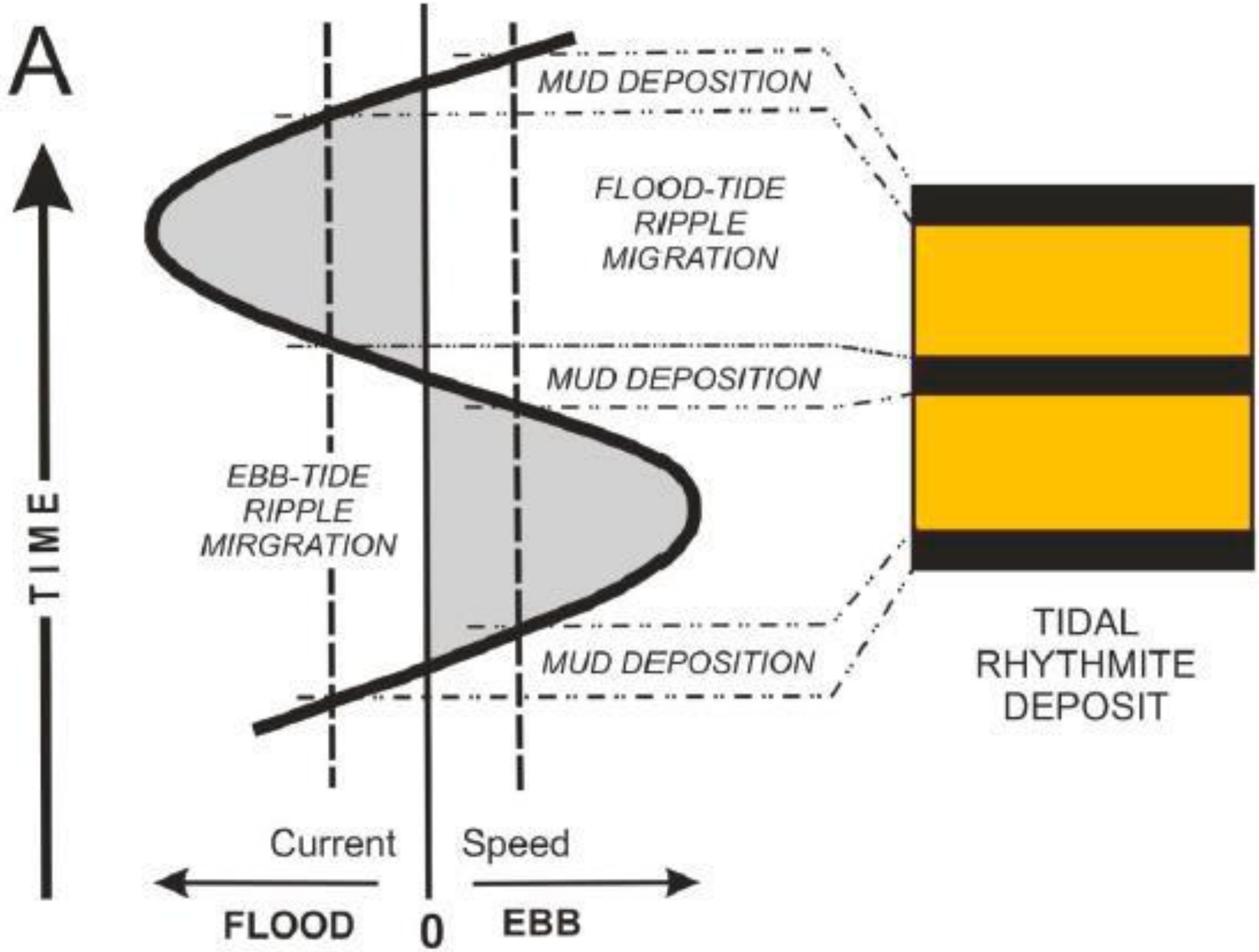

Figure 2. Tidal-current speed variation over a tidal-cycle (left) with the corresponding tidal-rhymite deposit (right). In this simplified symmetric tide example, three individual mud layers (black) are formed during the slack water intervals when the tidal current speed approaches zero. This is the interpreted depositional model for the formation of individual mud layers within the dune troughs. Variation in grain size is likely caused by trough deposition during flood and ebb tide and by overprinting of neap-spring variation. Modified from Dalrymple, (2010).

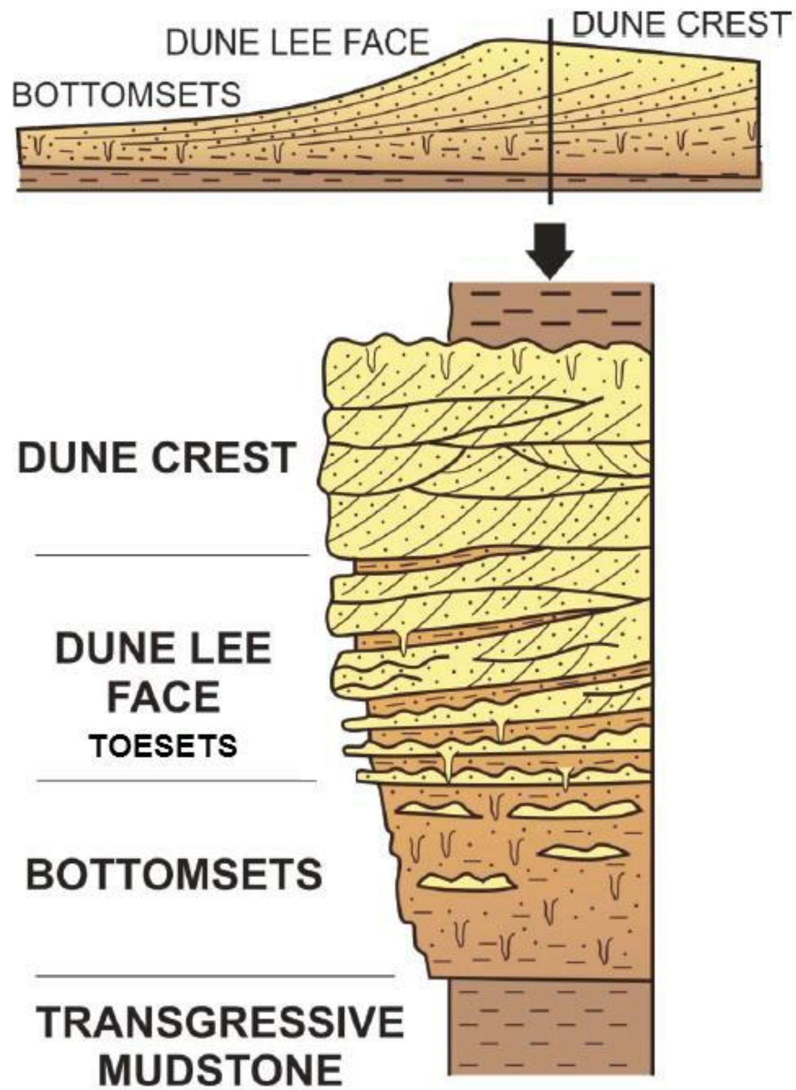

Figure 3. Schematic vertical succession of a dune highlighting the different depositional components of a dune. (Sub)horizontal dune-trough muds would be found in the bottomset region of a dune, while in the toeset area of a dune, these dune-trough muds would thin upwards and steepen. These inclined toeset muds may be mistaken for IHS deposition, and careful observation is necessary to correctly identify the origin of the deposit (see text). Amalgamation of multiple slack water muds may cause the dune-trough mud within the bottomset to be significantly thick (>.1 m). Alternatively, sub-tidal dunes in areas of high turbidity (and corresponding high suspended sediment concentration) will also have thicker accumulations of this dune-trough mud. Figure modified from Dalrymple, (2010).

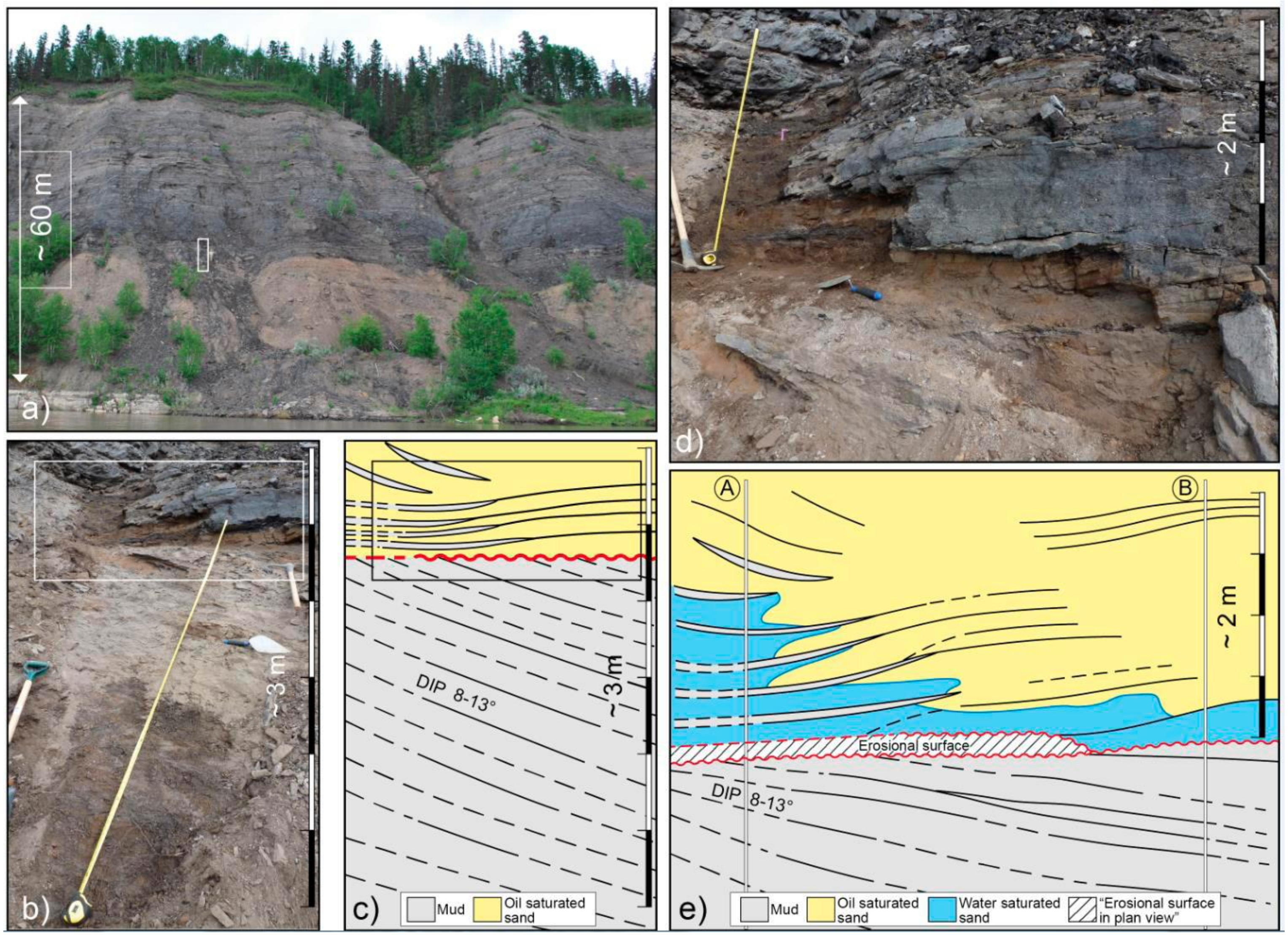

Figure 4. Dune-trough mud deposits at the base of an interpreted large-scale point bar. **a)** The McMurray Formation type section, located in vicinity of the Fort McMurray, Canada. **b)** Close-up view along the erosional contact of the point bar and underlying mud-dominated inclined heterolithic strata, interpreted as abandoned channel fill deposits. **c)** Schematic interpretation of b. **d)** A close-up view of depositional beds immediately above the major erosional surface (channel base). Note how from right to left the thin (mm scale) silt dune-troughs evolve into thicker (up to 5 cm) mud deposits. **e)** Interpretation of d, showing oil-water contacts. The A and B locations represent placement of hypothetical wells.

Sedimentological Criteria for Distinguishing DTM from Muds in IHS in Outcrops and Modern Analogues		Dune-trough Muds		Muds in IHS	
		inter-tidal	sub-tidal	daily cycles	seasonal cycles
lateral extent		several meters	several meters	hundreds of meters	hundreds of meters
thickness (m)	from	0.001	0.010	0.001	0.010
	to	0.02	0.10	0.02	0.20
	changes over short distances	yes	yes	no	no
Bioturbation Index		low	low	0 - high	0 - high
Depositional Dips		~ 0	~ 0	4 to 12	4 to 12
mud layer underlined by		sand	sand	sand	sand
mud layer overlined by		sand	sand	sand	sand
permeability of mud layer		< 0.2 Darcy	< 0.2 Darcy	< 0.2 Darcy	< 0.2 Darcy
laminated (comprised on multiple mud-silt couplets)		yes	yes	yes	yes
even # of laminae (mud-silt couplets) in mud layer		no	no	yes	yes
constant dip of laminae within mud layer		no	no	yes	yes
frequency of parallel mud beds per meter		2 o 5	2 o 5	2 o 5	2 o 5
Implications to Reservoir Developments					
barriers / baffles for fluid flow		**baffles**	**baffles**	**barriers**	**barriers**

Table 1. Comparison of sedimentological characterization criteria of dune-trough muds and muds in IHS as observed in outcrop and modern analogues. The green coloured characteristics are strikingly similar, the yellow are sometimes similar, and the red are diagnostic criteria for distinguishing the two.

Key Sedimentological Criteria for Distinguishing DTM from Muds in IHS in Cores	Dune-trough Muds	Muds in IHS
high-angle foresets in sand below and above	yes	no
depositional dips	~ 0	4 to 12 degrees
occur at base of channel	yes	rarely
upward transition over a short vertical distance from flat to progressively more steeply dipping mud layers	yes	no
lateral change in a number of thinly interbedded mud-silt layers	yes	no

Table 2. A summary key of sedimentological criteria for distinguishing dune-trough muds from IHS muds in narrow cores.