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Anatomy of a Fluvial to Estuarine Valley Fill, North Cactus Lake McLaren Reservoir

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Filling of the north Cactus Lake post Waseca paleovalley, during McLaren sea level rise, resulted in a tiered sedimentary succession recording process change from fluvial to estuarine sedimentation. Sedimentary tiers record braided stream, meandering stream, tidally influenced fluvial and estuarine (i.e. within the zone of maximum turbidity) sedimentation. Sand on sand contacts between, the various sedimentary units, results in a reservoir in excess of 20m. Mud dominated late stage estuarine channels provide barriers to flow segmenting the valley fill into separate reservoirs. Baffles to fluid flow are thin mudstones deposited by tidal processes coupled with seasonal and/or annual variation in river discharge

Introduction

The North Cactus Lake McLaren reservoir (Sections 14 and 15, Township 36, Range 28W3M) contains 36 million barrels of 12 API oil (40,000 centipoise) of which 1 million barrels has been recovered using primrary techniques.

Theory

Landward portions of fluvial-estuarine valley fill successions, in tide dominated estuaries, record progressive increase in tidal influence and decrease in fluvial influence (Dalrymple and Choi 2007). Hydraulic energy overall decreases progressively from the fluvial zone to the turbidity maximum: as reflected in a reduction in the grain size and a concomitant decrease in the scale of sedimentary structures. Basal portions of valley fill deposits are predicted to be fluvial; either meandering stream or braided stream. (Fig. 1). These are overlain by tidally modulated fluvial sediments comprising alternate bars that form within the straight (landward) portion of estuaries. Evidence of saltwater intrusion, along the channel thalweg, maybe preserved as thin “flocculated” mudstones. Sedimentation within turbidity maximum is a zone of bedload convergence with the lowest hydraulic energy, within the fluvial-estuarine system., Settling of mud, on both point bar surfaces and at the base of the channels occurs during slack water period of tidal cycles (daily and spring-neap) and is augmented by periods of low fluvial flow. Flood and ebb currents, within the turbidity maximum, follow mutually evasive paths in this highly meandering portion of the channel. The turbidity maximum is a hostile environment for organisms; favouring opportunistic fauna (ichnogenera) often of diminutive size

Method

This study consists of an integration of core interpretation and well log correlation/interpretation of the North Cactus Lake McLaren reservoir. Five cores occur within the project area in addition to two cores on adjacent sections (Fig. 1). Logging of cores included documentation of: sedimentary structures, ichnology (including species identification and degree of bioturbation) gross lithology, and grainsize analysis. Well log correlation, within amalgamated sand reservoirs, involves recognition and correlation of subtle well log patterns.

Interpretation of depositional facies was an iterative process through integration of core interpretation and well log correlation. Stratigraphic units identified by characteristic well log profiles, albeit subtle, where tied to sedimentological features within core. From this an interpretation of the depositional processes responsible for the sedimentary horizon could be interpreted and a detailed sedimentological history of the reservoir constructed. Reservoir fluid contacts assisted in the identification and mapping of barriers within the reservoir

Example

North Cactus Lake McLaren Valley Fill reservoir

Tier 1 Braided Stream (?) (Fig. 2)

The basal valley fill unit, although not penetrated by core, is recognizable, on well logs, as a 4-6 m thick highly porous (i.e. 33% porosity) clean sand. The sand is distinct given its occurrence below a thick shale in well 4-14–36-28W3M. Tier 1 is confined to the deepest part of the valley.

Tier 2 Meandering Stream (Fig. 2)

Active Channel facies

The interpreted meandering stream sand, comprising the bulk of Tier 2, is characterized by large coal clasts (up to 6cm) occurring on foreset laminations. Planar tabular cross-beds (where recognizable), are up to 20 cm. thick. Sands are well sorted typically upper fine grained. Intraclasts are small rounded mudstones and occasional sideritized mudstones.

Abandonment facies

Meandering stream sands are laterally adjacent to abandoned channel mudstones encountered in wells 101/04-14 (well logs) and 102/02-16. Abandoned channel sediments are light grey silty mudstones with randomly oriented, abundant to sparse, carbonaceous debris.

Interpretation

Expansion of the valley during meandering stream sedimentation is evident by its distribution beyond the extent of Tier1. Locally sourced clasts occur within the sand and progressive down-cutting along the valley margin can also be demonstrated in closely spaced wells.

Tier 3 (Fig. 2)

Tier 3 consists of two layers.

Tidally influenced channel base

Along the centre of the valley (i.e. thalweg) the base of Tier 3 consists of thinly interbedded mudstones (2-6cm thick) and sandstones (decimetre scale). The slightly silty mudstones are structureless. The apparently massive sands are moderately well sorted, lower fine grained with silty and carbonaceous debris rich intervals. Zones of angular mudstone clasts are common.

Along the northern margin of the reservoir, the equivalent layer is a moderately sorted upper fine-grained sand with abundant comminuted carbonaceous debris. The sand is laminated with occasional high angle tabular cross-beds. Small grey mudstone intraclasts are present. On well logs the zone has a slight positive gamma ray deflection, reflecting the increase in clay and silt content relative to underlying and overlying sands.

Interpretation

The occurrence of thin structureless mudstones in the deepest, high energy, portion of the channel suggests that these are fluid muds formed by flocculation caused by salt-water intrusion into the estuary. Along the northern margin of the channel, presumably under slightly higher energy conditions, mudstones are eroded (i.e. mudstone intraclasts) although the presence of silt and carbonaceous debris record low flow conditions

Tidally influenced point bar

Sands, comprising the bulk of the interpreted point bar, are well sorted upper fine grained to lower medium grained although as the point bar accreted to the south, sand grade decreased to fine grained to very fine grained (i.e. wells 6-14, and 7-15). Point bar sands along the northern margin of the reservoir are blocky whereas wells along the southern margin they fine upward trend (fine grained grading to very fine grained (i.e. wells 6-14 and 7-15). Thin mudstones - siltstone interbeds occur along the southern margin of the reservoir.

Interpretation

Tidally influence point bar sands are deposited contemporaneously with channel base sands but accreted latterly form north to south, over-top of these sediments. Increasing tidal influence during growth of the bar is indicated by a reduction in grain size laterally, form north to south and the occurrence of thin mudstone-siltstone couplets are preferentially preserved along the southern margin of the point bar. Tidally influenced point bars occur in the straight portion of estuaries (i.e. landward of the turbidity maximum).

Tier 4 (Fig. 2)

Tier 4 consists of a channelized facies (IHS) and vertically accreted facies that stack on top of Tier 3 sands as well as along the margins of the valley.

Late Stage IHS filled channels

Well 2-16-36-38W3 is interpreted to intercept a late stage channel that truncates underlying valley fill sediments (i.e. Tiers 3 and 2). The heterolithic strata in well 2-16 consisting of two facies; a thin channel base sand, similar to the tidally influenced channel base facies, and an IHS facies. The inclined heterolithic facies is an 8m thick fining upwards succession comprised of small scale fining upwards cycles either: sandstone-siltstone-mudstone triplets (5cm to 1.25m thick) or siltstone-mudstone couplets, (5-10 cm. thick). Sands are laminated and occasionally rippled. Siltstones are finely interlaminated with mudstones, whereas dark grey carbonaceous mudstones are massive. Individual couplets or triplets represent neap spring cycles while interlaminated siltstone-mudstone record daily tidal periodicity.

The heterolithic character of the sediments in the 2-16 well indicates a stronger tidal influence than Tier 3 sands in sections 14 and15 and therefor later stage sedimentation. The reservoir sand in the 2-16 well are hydrodynamically separate from section 14-15 sands, given different oil water contacts (i.e. -56m SS, and -53m SS respectiively). IHS in well 2-16 is interpreted to occupy a late stage channel that truncates pre-existing strata at least to the current oil-water contacts. The western margin of the Cactus Lake reservoir is delineated by a late stage IHS filled channel that is gas charged to a level below the oil in section 14.

The high mud content of inclined heterolithic strata indicates sedimentation within the turbidity maximum at the lowest energy level within the estuary. Late stage channels also record splitting of ebb and flood currents into mutually evasive paths coupled with increased channel sinuosity.

Tidal flats

Tidal flat sediments, that cap the valley fill succession, consist of stacked fining upwards sands imparting a serrated profile on well logs (i.e. wells 7-15 and 5-14). In core tidal flat sands are finer than underlying sands (i.e. very fine grained becoming silty towards their tops. They are also evident by a reduction in saturation to below 60% in (wells 9-15 and 10-15) accompanied by a reduction in permeability to less than 4 Darcies (typically less than 2) versus 6 darcies. Mixed flat sediments consist lenticular bedded sand and silty mudstones that grade up to interlaminated siltstone and mudstone. Bioturbation is weak with a few forms of Planolites, Skolithos and Arenicolites. Mud flats are comprised of thin ss-sst-mst to sst-mst cycle that are deformed (brecciated at their top). Salt marsh sediments in the form of carbonaceous mudstones or thin coals cap fining up cycles.

Conclusions

Tiered sedimentary fill in paleovalleys is a common both at outcrop (e.g. Hayes et. al. 2018, Gardiner et. al.1995, Weigou et.al 2010) and in subsurface (e.g.Wood and Hopkins,1989, Mathison 1987) . It is also predicted both by estuarine depositional models (Dalrymple and Choi, 2010) and sequence stratigraphic models (Willis 1997). Interpreting process change in subsurface requires integrating core and well log data with theoretical data and ancient analogues. An understanding of the various processes that shaped the sedimentary record within valley fill successions can act as a predictive tool for the distribution and extend of barriers and baffles in reservoirs.

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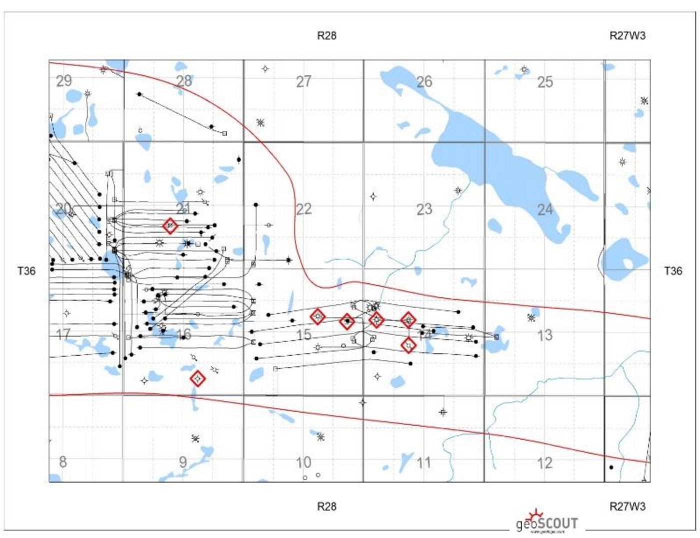

Fig. 1 North Cactus Lake McLaren reservoir sections 14 and 15 Rge. 36 Twp. 28W3. Core red diamonds.

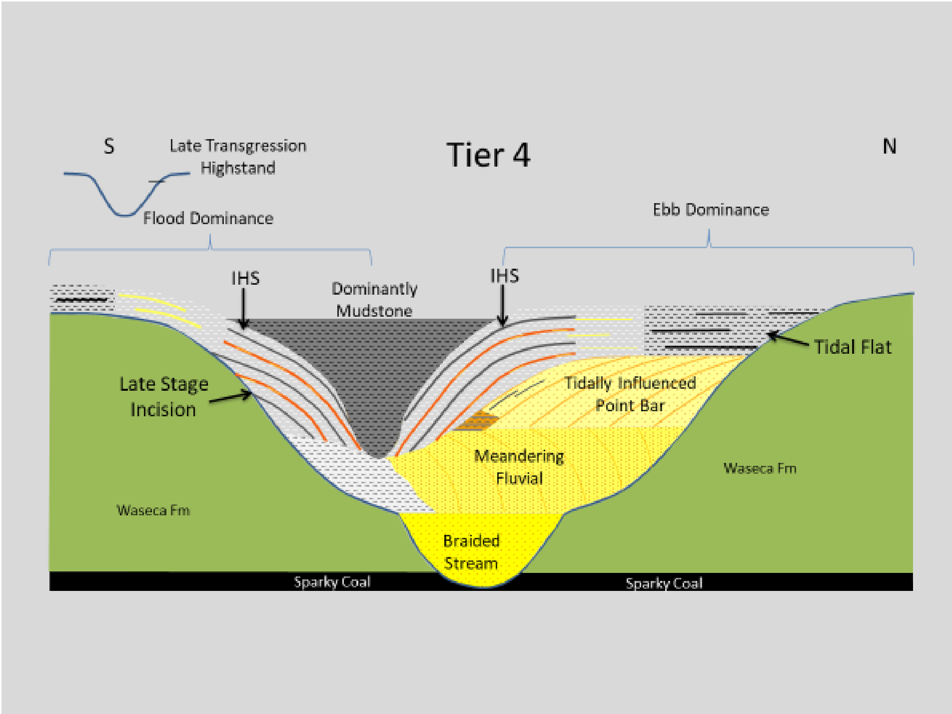

Figure 2 Schematic cross section through North Cactus Lake McLaren reservoir