Reservoir Facies of the Dodsland Viking Trend

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Abstract

The Viking Formation, comprising the Dodsland trend of west-central Saskatchewan, consists of three stacked erosionally truncated deltaic successions (Viking 1 to 3 in ascending order). The uppermost erosional surface is a regional unconformity, the top of Viking erosional surface, which progressively bevels Viking stata from south to north. Erosional truncation, along the northern margin of the reservoir, has removed the entire Dodsland Viking reservoir assemblage (i.e. Viking units 1 to 3). Preservation of higher stratigraphic layers progressively from north to south, below the Viking top (VE 4) erosional surface, imparts an apparent southward imbrication of stratigraphic elements.

Deltaic sediments, comprising each of the stratigraphic layers making up the reservoir trend, consist of both constructive and destructive elements. Constructive elements, forming the bases of each coarsening upward deltaic cycle, consist of prodelta mudstones that grade upwards to distal delta front thinly interbedded sandstones and mudstones. Destructive elements consist of two facies that record different shelf processes (i.e. wave reworking of delta front sediments to form offshore bars and shoreface erosion of delta top sediments creating both ravinement surfaces and subsequently mantling these with lower shoreface sediments). Wave reworking of proximal delta front sediments, along the northern edges of Viking 1 and 2 depositional successions, created linear bars (i.e. shallow shelf shoals facies). These highly bioturbated, poorly sorted sandstones to muddy sandstones form east west trending, south facing asymmetric ridges that constitute the main reservoir facies along the Dodsland trend. Immediately south of the asymmetric bars erosional shoreline retreat by storm wave activity supplied delta top sediment to the lower shoreface. The resultant transgressive sheet of interbedded mudstones and fine grained to pebbly sandstones is generally a few decimetres thick. Along the southern margin of the Dodsland reservoir trend this heterolithic assemblage thickens in the Viking 1 to form two, metre thick, paralleling bands of sediment (i.e. shelf sand ridges).

Thin prodelta mudstones, at the bases of deltaic layers, form horizontal permeability barriers segregating the Dodsland reservoir into three flow units. Distal delta front thinly interbedded sandstones and mudstone have low to moderate horizontal permeability (generally less than ten millidarcies). Vertical permeability is low due to interbedding with mudstones and storage capacity is low due a low net to gross pay ratio. Shoal facies reservoir sands have relatively high horizontal permeability (tens of millidarcies to over one hundred millidarcies), moderate vertical permeability (single millidarcies to a few tens of millidarcies) and high storage capacity. Amalgamation of sand through repeated storm wave reworking coupled with intense bioturbation with both horizontal and

vertical burrows produced a relatively homogeneous reservoir with a high net to gross pay ratio. Lower shoreface transgressive sands have moderate to high horizontal permeability (tens to over one hundred millidarcies) but low vertical permeability (due to interbedding with mudstones) and low storage capacity due to their thinness.

Introduction

The Dodsland Viking reservoir trend, initially discovered in the early 1950's consists, of a number of initially isolated pools that, through subsequent drilling, have merged to define one large oil pool with several gas accumulations (Fig. 1). The oil-bearing portion of the reservoir has received renewed interest with the introduction of multistage fracture technology combined with horizontal well drilling. Since 2007 over 2000 horizontal wells have targeted the reservoir, adding over 135,000 cubic metres (850,000 barrels) of monthly oil production, for a combined total of approximately 3 million cubic metres (19 million barrels) of cumulative production.

The Dodsland trend is an east-northeast – west-southwest trending reservoir (Fig. 1) that overlies the northern rim of the Williston Basin, the Kindersley arch of Christopher (1964, 1984a). The pool is conventionally trapped by structural roll over along the up dip edge of Mississippian strata (Reasoner and Hunt, 1954). Trapping was both enhanced and modified by both early stage and late stage dissolution of Devonian evaporites (ibid.)

The Early Albian Viking reservoir is a shaly-sandstone consisting of thinly interbedded sandstones and shales with permeabilities in sandstones ranging from single millidarcies to over 100 millidarcies. Sandstones are fine to medium grained occasionally grading to coarse grained and pebbly.

Stratigraphy

Mudstones, frequently bentonitic, provide reliable correlation horizons. The base of the reservoir is defined as the top of a bentonitic mudstone can be readily correlated, on well logs throughout the reservoir trend (Fig. 2). Along the northern margin of the trend an additional sand layer (Viking B) occurs subjacent to the Viking Base mudstone (Figs. 2). This stratigraphic unit, not discussed in this paper, forms the main reservoir of the Kerrobert, Plenty and Prairiedale pools immediately north of the Dodsland trend. Within the Viking Formation, of the Dodsland reservoir trend, two additional mudstone horizons allow subdivision of the reservoir into three sedimentary packages Viking 1 to 3 in ascending order (Fig. 2). The stratigraphic assemblage forms an apparently southward-imbricated package of strata (Evans, 1970) with successive sedimentary units thickening and then thinning towards the south. The basal Viking unit, Viking 1 demonstrates a slight secondary thickening along the southern margin of the Dodsland reservoir trend (Fig 2).

The tops of the Viking units are interpreted as erosional surfaces (Pozzobon and Walker 1990, Thomas, 2007 and Tong, Chi, and Pederson 2005) marked by chert pebble conglomerates. The uppermost erosional surface is equivalent to the regional E4 unconformity of Boreen and Walker, 1991.

Reservoir Facies

General

The lower two Viking units, Viking 1 and 2 are the main reservoir units for the Dodsland trend. Through the main portion of the reservoir these sedimentary cycles are organized into overall coarsening upward depositional successions (Fig. 2, Viking 2 wells 15-20-30-25W3M and 3-32-30-25W3M, Viking 1 well 11-18-31-25W3M). Each cycle begins with a mudstone, often bentonitic, that grade upward through thinly interbedded fine-grained sandstone-and mudstone to dominantly massive sandstones with occasional thin mudstones. Within each cycle sands increase in frequency from 10 to 30 % of the interval thickness at the base of the cycles to 50 to 80% at the top. Sandstone bed thickness increases from a few millimetres to a few centimeters. This is accompanied by an increase in grain size from very fine grained to medium grained. In addition upper sands are poorly sorted with granule lamina and scattered pebbles.

Accompanying the up section increase in sand content and grain size, for Viking 1 and 2, is an increase in bioturbation index from 1-3 to 4-5. The contact between weakly bioturbated and strongly bioturbated intervals is generally sharp and frequently marked by a zone of sideritization. On well logs, in addition to the “tight” streak, the contact is discernable as a subtle increase in porosity (Fig. 2 horizon 2a wells 15-20 -30-25W3M, 3-32-30-25W3M and 13-4-31-25W3, horizon 1a well 11-18-31-25W3). The character of the ichnofauna changes with the increase in intensity of bioturbation, from a distal *Cruziana* ichnofauna to a proximal *Cruziana* ichnofauna.

Facies A: Mudstone facies

Medium grey mudstones are generally massive with occasional thin siltstone or fine-grained sandstone interbeds. Bioturbation intensity is low (0-1) although the lack of grain-size variation precludes certainty. Bentonitic mudstone layers up to several centimetres occur frequently in the mudstones. Occasional siltstone laminae occur at the tops of horizons and are gradational into overlying facies

Distribution

Thin mudstone horizons are laterally persistent and provide the framework for stratigraphic subdivision in the Dodsland pool (see Evans 1970). Mudstones occur a the base of depositional succession Viking 1-3 and are continuous to the south with mudstones forming the bases of Thomson’s (2007) stratigraphic units VM 1to 3. Although the mudstones are continuous to the south they terminate at the top of the Viking Formation against mudstones of the Westgate Formation along northern portion of the Dodsland trend (Fig. 2).

Facies B: Thinly interbedded mudstone - sandstone

Facies B consists of thinly interbedded sandstones and mudstones (i.e. ribbon sands). Sandstone beds are generally sharp based with normal grading, although reverse grading does occur (Fig. 3). Sands are laminated often wave ripple cross-laminated and frequently display combined flow structures (Fig 3). Load cast are relatively common while convolute lamination occurs rarely (Fig 4). Bioturbation index is essentially bimodal with zones of very low bioturbation (Figs. 3, 4) and zones of moderate bioturbation. *Helminthopsis* and *Planolites* typify the ichnofauna, while generally small forms of *Teichichnus* are uncommon and *Paleophycus, Asterosoma* and *Zoophycus* occur rarely. Carbonaceous debris and coal intraclasts are a minor component of the facies.

Distribution

Facies B overlies and is frequently gradational over a short interval of thinly interbedded mudstone and siltstone Facies A. Facies B is in turn overlain by facies C along the main portion of the Dodsland trend. Along the southern margin of the reservoir trend Facies C and is overlain by facies D. Facies B in reservoir units Viking 1 and 2 terminate abruptly beneath the top of Viking (E 4) erosional surface (Fig 2, Fig 5 Viking 2a to Viking 1 interval). Facies B is the uppermost stratal layer for Viking 3 depositional succession along the Dodsland trend.

Facies C: Highly bioturbated sandstone to muddy sandstone

Facies C is marked by an often-dramatic increase in the bioturbation index, relative to Facies B, resulting in near homogenization of strata, although rare occurrences of thinly interbedded mudstone and sandstone indicate precursor sediments (Fig.6). Most sedimentary structures have been destroyed by bioturbation but, where present, sands are laminated to ripple cross laminated similar to facie B. Grain size increases upward within the facies from fine grained to medium grained and, near the top, granule lamina occur along with and scattered pebbles (Fig 7). Sorting decreases up section with increase in grain size. Intermixed mudstone decreases proportionately up-section from approximately 50% to 10-20%. Carbonaceous debris and small coal clasts (up to a few centimetres) are common accessories particularly towards the tops of the sand. *Inoceramus* sp. shells occur infrequently in the muddier potions of the facies but, where present, can be abundant. Pozzobon and Walker (1990) recorded glauconite from this facies in the Eureka pool.

Bioturbation index in Facies C is generally high (i.e. 4-5) with a proximal *Cruziana* ichnofauna characterized by robust forms of: T*eichichnus*, *Paleophycus*, *Schaubcylindrichus*, *Asterosoma* and rarely *Skolithos*, *Zoophycus, Rhyzocorallium* and *Rossalia* (Figs 6 and 7.)

Distribution

The highly bioturbated sand rich portions of Viking 1 and 2 form the main reservoir bodies of the Dodsland Viking trend (Fig. 5). The units can be mapped using well logs (i.e. low gamma ray signature, high resistivity, high spontaneous potential and relatively high porosity) (Fig 9). The reservoir zones, up to seven metres thick, form elongate trends over 80 kilometres in length by three to six kilometres in width. The zones are asymmetric with steep south facing margins and gradually sloping north margins. The zones thin and broaden from west to east. This is accompanied by a decrease in grain size as well as a proportionate increase in mudstone. The Viking1 Facies C reservoir is best developed along the northern margin of the Dodsland Viking trend while the Viking 2 Facies C reservoir occurs through the middle part of the trend (Fig.).

Facies D Coarse grained sand to pebbly conglomerate

This facies is highly variable and in some instances absent. Where present the zone is generally thin (centimetre to decimeter thick). It is typically marked by an increase in grain size, although were Facies D overlies Facies C the contact is occasionally marked by a decrease in grain size (Fig. 7). The basal contact is sharp and in some instances bored by a *Glossifungites* ichnofauna. The upper contact is gradational into overlying mudstones (Facies A).

Where thin the facies consists of scattered pebbles at the top of Facies C (Fig. 9). Where well developed the zone consists of a heterolithic assemblage of thinly bedded pebble conglomerates, pebbly sandstones, granular sandstones, and fine-grained sandstones interbedded with thin mudstones (Fig. 10). This assemblage forms an overall fining upward succession gradational into overlying mudstones. Bed thickness is a few centimetres to several centimetres. In contrast to Facies C sandstones are generally well sorted. Wave ripples and combined flow structures occur in fine-grained sandstones. Bioturbation is typically low although some beds are moderately bioturbated. *Planolites* is sparse throughout the facies while *Helminthopsis* can be abundant in fine sandstone intervals. *Skolithos* occurs rarely.

Distribution

Facies D caps each of the Viking depositional successions although it is thin or absent over the main reservoir build-ups (i.e. Facies C). On wire line logs Facies D can be identified as clean gamma ray spikes (Fig 2, Fig 5). Facies D is best developed, at the Viking 1 level, south of the main reservoir trend (i.e. the main reservoir units of the Avon Hill and Whiteside pools) were it forms two low relief, paralleling bed forms (Fig. 5, 8). Development at the Viking 2 level is discontinuous along the southern margin of the main reservoir development. Facies D is poorly developed at the Viking 3 level.

Facies Interpretation

Facies A

Mudstones, frequently bentonitic, occasionally silty, record suspension fallout of fine sediments below storm wave base. Siltier layers record periodic high-energy events. Mudstone-siltstone deposition may reflect either increased water depth or sedimentation distal to sediment source. Mudstone horizons not only provide reliable marker horizons within the Dodsland pool areas but can also be correlated regionally (Thomas, 2007). The lateral persistence of these thin (few meter thick) beds indicates that they are marine flooding surfaces.

Facies B

Subtle coarsening upward log motifs on well logs reflect the moderately bioturbated thinly interbedded sandstone and mudstone intervals that overlie the mudstone marker horizons (Viking 3 well 11-17-30-25, Viking 2, below the 2a marker, wells 15-20-30-25 to 13-4-31-25W3M, Viking 1, below the 1a marker, well 11-18-31-25W3M, FIGS. 2). Wave and combined flow structures within the fine sand indicate deposition of sands within storm wave base while mudstones interbeds record fair weather fall out of suspended sediments. The sharp bases of sandstone beds indicate that sediment input was accompanied by lowering of wave base during storm events (i.e. tempestites). The occurrence of load casts and convolute lamination imply rapid sedimentation onto uncompacted muds. Moderate to weak bioturbation of the interval by small form of the distal *Cruziana* ichnofauna indicates a slightly stressed depositional environment (MacEachern and Bann, 2008). Interbedding of moderately bioturbated intervals with weakly to non-bioturbated intervals (lam-scram) indicates periodic short-lived highly stressful events accompanying storm deposition. These short lived stressful conditions indicate dramatic short lived changes in physicochemical conditions, most likely caused by flood induced hyperpycnal flow that introduces fresh water above the sediment water interface, inhibiting colonization by organisms (ibid. p. 89) The occurrence of carbonaceous detritus and small coal clasts in the sediments is consistent with periodic freshwater influx.

The coarsening upward depositional successions record building of a sediment source into the area. The occurrence of moderately stressed deposition combined with episodic rapid, highly stressed, sedimentation from a freshwater source points to deltaic sedimentation on a fluvial and storm dominated deltas. Within the context of deltaic sedimentation the thinly interbedded mudstone sandstone facies deposited below storm wave base represent distal delta front sedimentation. Underlying mudstones within this context represent prodelta mudstones.

Facies C

The increase in bioturbation levels of the upper portions of depositional successions 1 and 2 indicate protracted sedimentation. Prolonged exposure on the ocean floor would allow for colonization and intense reworking by organisms. The occurrence of glauconite, in highly bioturbated sands, is consistent with protracted sedimentation. The occurrence of thin fine-grained sandstone beds with combined flow or wave formed sedimentary structures, as a minor component of the highly bioturbated facies, indicates sedimentation occurred within storm wave base. The robust nature of the ichnofauna, with forms typical of open marine conditions (i.e. *Asterosoma*, *Helminthopsis*), indicates sedimentation under normal marine condition. This contrasts with the slightly stressed depositional conditions of underlying strata. The occurrence of normal marine sedimentation above slightly stressed distal delta front sediments is at odds with a normal progradational succession for a mixed fluvial-storm dominated delta. Rather than increasing bed thickness with approaching sediment source and increase in sedimentation rates, bed thickness appears to have remained relatively constant and sedimentation became protracted. Similarly ichnofaunal diversity increases and size increases indicating a reduction in levels of physiochemical stress. The highly bioturbated tops of depositional successions are interpreted as a due to insitu reworking of sediments on the sea floor by prolonged wave activity. The higher sand content and coarser grain size of this facies, relative to underlying sediments, indicates reworking of more proximal deltaic source than underlying distal delta front sediments; most likely proximal delta front sediments, although scattered pebbles and coal intraclasts indicate some reworking of delta top sediments.

The reworked tops of deltaic cycles 1 and 2 are similar in form and dimensions to inner shelf shoals in the Gulf of Mexico (Penland, Suter and Boyd, 1986, Penland Boyd and Suter, 1988). In particular they are similar in dimensions to Ship shoal that is up to 7 metres thick, 50 kilometres in length and from 5 to 12 kilometres in width. The shoal is asymmetric with a steep shoreward face and gradual seaward edge. The shoal facies is highly bioturbated with robust forms while the underlying progradational delta front sediments have a small ichnofauna. Ship shoal differs from the reworked portions of Viking 1 and 2 in preservation of underlying progradational elements (distributaries and delta front sediments) and early delta destruction facies (i.e. tidal inlets and lagoonal sediments). This probably reflects higher accommodation space associated with the Mississippi delta.

Facies D

The occurrence of wave formed structures in the "conglomeratic" zones indicates deposition above wave base whereas mudstones interbeds record suspension fallout of muds below wave base. The sandstone-mudstone couplets are interpreted as tempestites deposited within storm wave base but below fair-weather wave base. The gradational contact with overlying mudstones implies emplacement during transgression. The coarse nature of these sediments indicates reworking and re-sedimentation of primarily delta top sediments. The erosional base to the sedimentary packages combined with overlying wave formed sedimentary structures is interpreted as a wave ravinement surface formed during the destructive phase of delta cycles. Sediment eroded from the delta top by storm events, during transgression, was in part re-deposited on the lower shoreface forming a thin fining upward succession of lower shoreface sediments above the wave ravinement surface.

Summary

The lower portions of depositional cycles (Facies A and B), recording progradation of sediments into the area under slightly stressed depositional conditions, are interpreted as the constructive phases of delta growth. Overlying highly bioturbated, reworked portion of deltas and lower shoreface sediments overlying wave ravinement surfaces represent the destructive phase of deltaic cycles. Proximal delta front sediment and delta top sediments were cannibalized and reworked on the shelf by wave activity. Primarily proximal delta front sediments were reworked and redistributed to by transgressive submergence (Penland Boyd and Suter, 1988) to form shallow shelf shoals while delta tops sediments where re-sediment on the lower shoreface by principally wave activity during erosional shoreline retreat.

Stratigraphic Architecture

The southward imbrication of Viking units 1-3 is interpreted as reflecting differential preservation of strata beneath a regional erosion surface (the top of Viking - VE 4 erosional surface). Progressive truncation of strata is illustrated by successive removal from north to south of major stratigraphic horizons (i.e. Viking Units 3-1, Figs 3, 5.) and also progressive truncation of layers comprising deltaic cycles. Figure 8 illustrates the subcrop of Viking units 3 to 1 against the erosional surface. There is an absence of lateral facies change approaching stratal terminations as would be expected through depositional thinning. Regional marine mudstone horizons also terminate abruptly at the top of the Viking sand. Given that the top of the Viking is a well-established erosional surface throughout western Canada as well as in the Dodsland reservoir the progressive loss of strata is interpreted as evidence of erosional bevelling. Increasing thickness of Viking strata from north to south indicates increased accommodation space to the south resulting in preservation of progressively higher stratigraphic horizons.

Using the base of Viking sand (top of Viking 1 flooding surface) as datum illustrates a gradual thickening of the Viking succession from north to south (Figs. 3, 5). Evidence that these units formed a positive feature on the sea floor during burial is given by thinning of overlying marine sediments above the main part of the reservoir (Figs. 3, 5 interval from Viking top to Viking sandstone). Stratigraphic thinning of overlying strata provides additional evidence of the offshore bar character of the main sand developments for Viking units 1 and 2 (see, Martinsen, 2003).

Discussion

The Viking Formation reservoir forming the Dodsland trend consists of three-stacked deltaic unit that overlie the northern up-dip margin of the Williston basin. Trapping is due to a combination of structural roll along the northern rim of the basin (the Kindersley arch of Christopher 1964) coupled with erosional truncation of Viking reservoir units 3-1. Both early and late stage Devonian evaporate dissolution has modified original structural (Reasoner and Hunt, 1954). Monoclinal flexure of the Kindersley arch, down to the south, resulted in increased accommodation space preserving uppermost Viking strata, from erosional bevelling during the post Viking, Westgate transgression.

Reservoir units of the Viking Dodsland trend are the preserved roots of top truncated deltas (see Battacharya and Willis, 2001). Only the prodelta and distal delta front portions of the constructive phase of delta growth are preserved as the basal parts of coarsening upward depositional successions. Delta front and delta top sediments were reworked into linear offshore bars (inner shelf shoals) or, landward of these, re-deposited on the lower shoreface during the destructive phase of delta cycles. The preserved expressions of Viking deltas, forming the Dodsland trend, bear little resemblance to their original delta form. Rather they are erosional, reworked remnants of deltas (see Martinsen, 2003). The thinness of Viking deltaic sediments forming the trend as well as lack of preservation of uppermost deltaic facies reflects the extremely limited accommodation space available in the basin.

Distal delta front thinly interbedded fine-grained sands and shales (Facies B) have generally less than ten millidarcies of permeability. Vertical permeabilities are low due to interbedding with continuous mudstones. Hydrocarbon storage is generally low due to net pay to gross pay. The reworked Viking “bar’ facies sandstones and muddy sandstones (Facies C) have high permeabilities ranging from tens to hundreds of millidarcies. Vertical permeability in these zones is moderate to good due to amalgamation of thin sands and homogenization by vertical and horizontally burrowing organisms. The high net to gross pay ratio, of this portion of the reservoir, yields high hydrocarbon storage capacity. Transgressive lower shoreface sediments (Facies D) have high permeabilities (tens to hundreds of millidarcies) due to the coarse grained nature of these sediments but limited storage capacity due to their thinness and limited lateral extent. Vertical permeability is also limited due to the interbedding with mudstones. Continuous bentonitic mudstones (marine flooding events) form vertical permeability barriers that compartmentalise the reservoir into three flow units although the thinness of the mudstones allows induced fractures to breach these barriers to flow.

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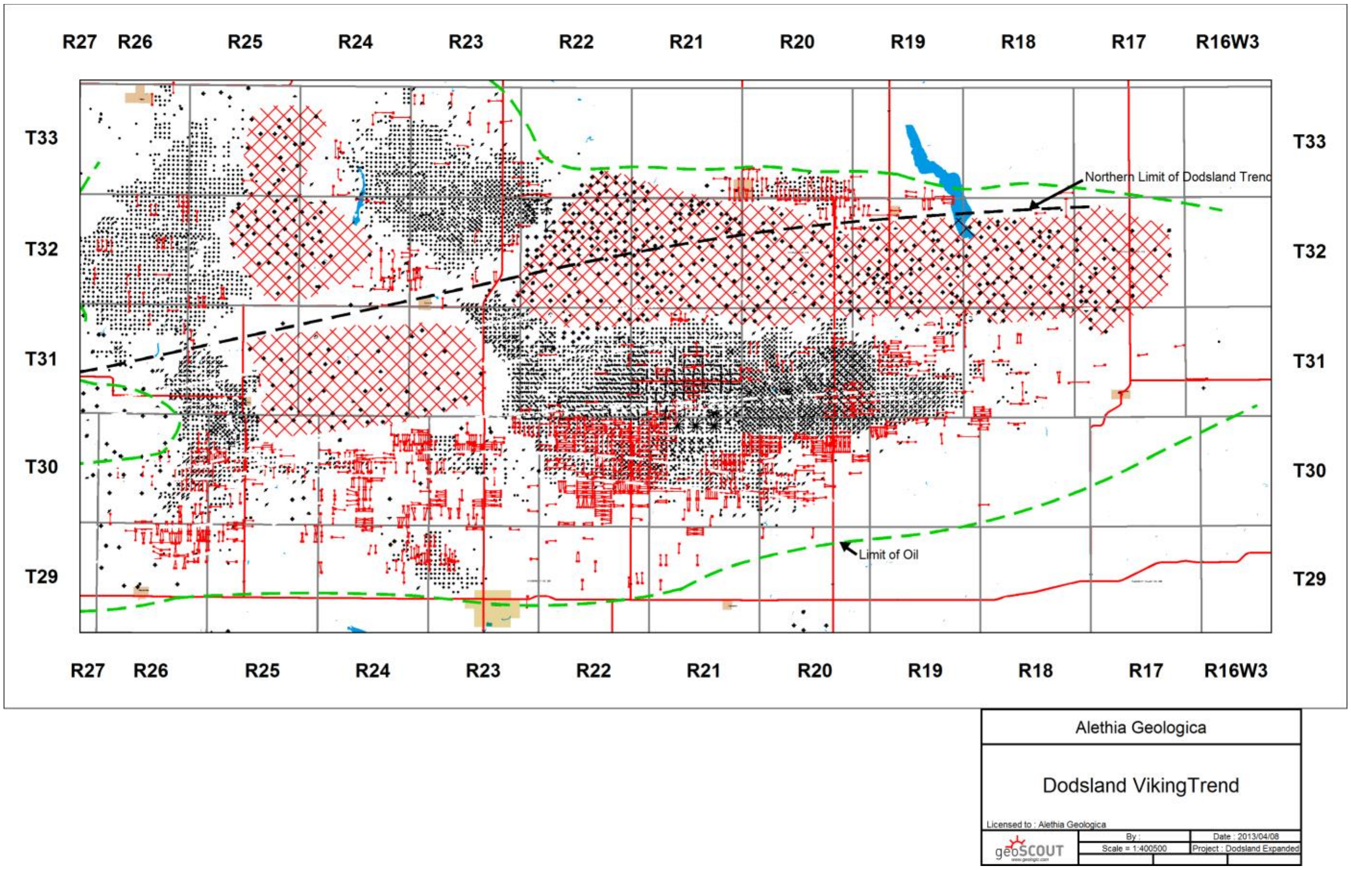

Figure 1: Dodsland Viking Trend: gas accumulations are crosshatched in red.

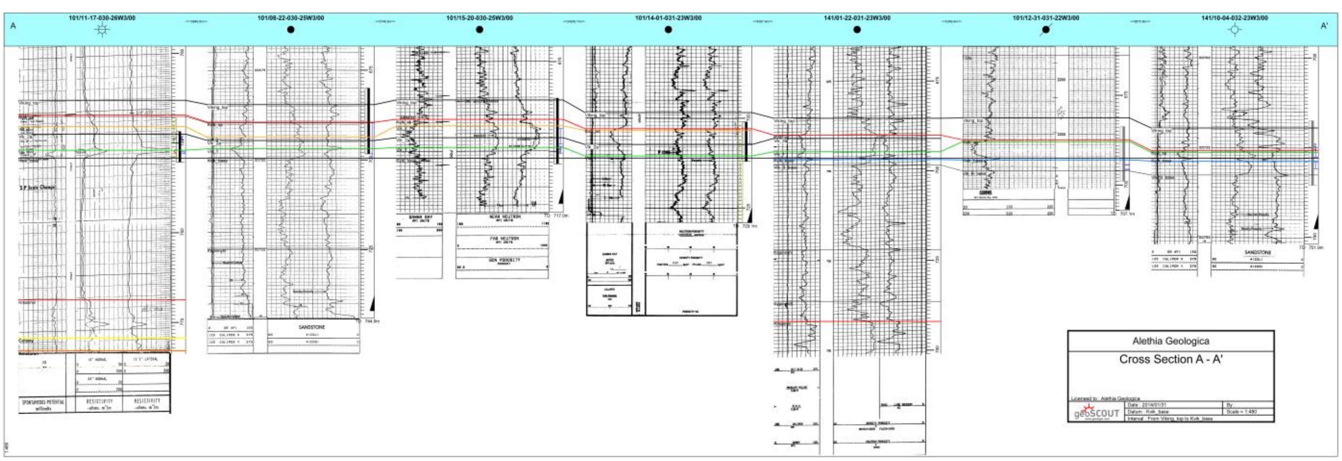

Figure 2: Viking Formation south to north cross-section A to A'; datum is the Viking Base. Top of Viking sand – red, top of Viking 2 – orange, Top of Viking 1 – green, Base of Viking - Black

Figure 3: Facies C, Thinly interbedded sandstone and mudstone. Fine-grained sandstone interbeds displaying sharp, erosional bases and gradational tops. Sandstones are well laminated and display combined flow structures. Viking reservoir unit 3, well 8-22-30-25W3M

Fig. 4: Facies B, Thinly interbedded sandstone and mudstone displaying various sizes of load casts. Viking 3 reservoir unit, well 101/ 8-22- 30-25W3M

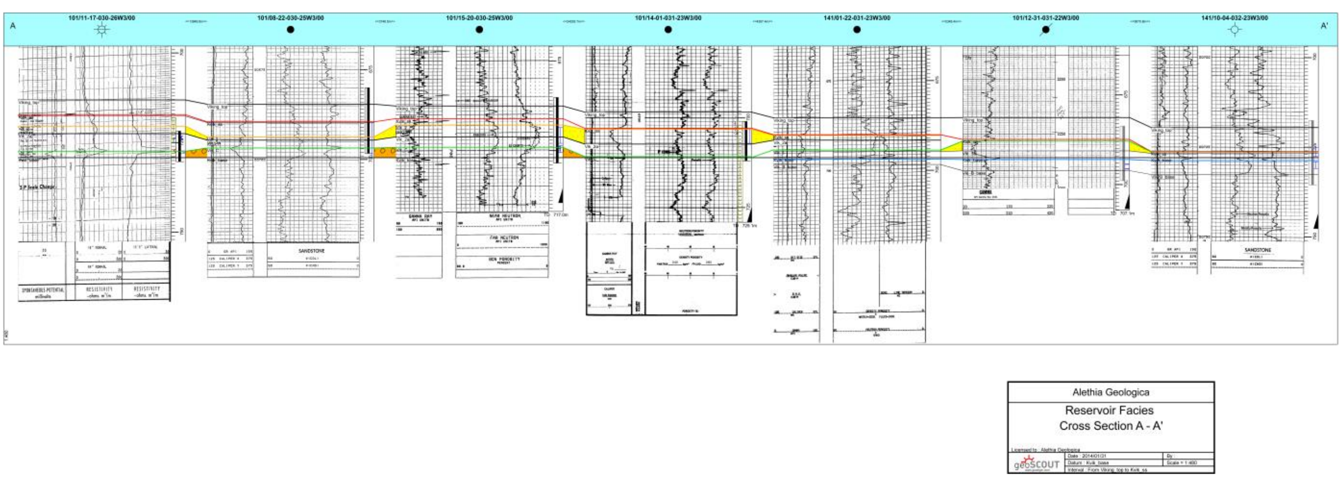

Figure 5: Stratigraphic cross-section A-A' with reservoir facies marked, Facies C yellow, Facies D tan.

Figure 6: Facies C, highly bioturbated sandstone with primary bedding destroyed. Note the robust Teichichnus burrows. Viking 1 reservoir unit, well 101/12-31- 31-22W3M

Figure 7: Facies D/Facies C Highly bioturbated medium grained sand of Facies C containing a large rounded chert clast abruptly overlain by a thin, fine-grained sandstone of Facies D at the base of a mudstone (Facies A). Contact between Viking 2 and 3, well 15-20-30-25W3M.

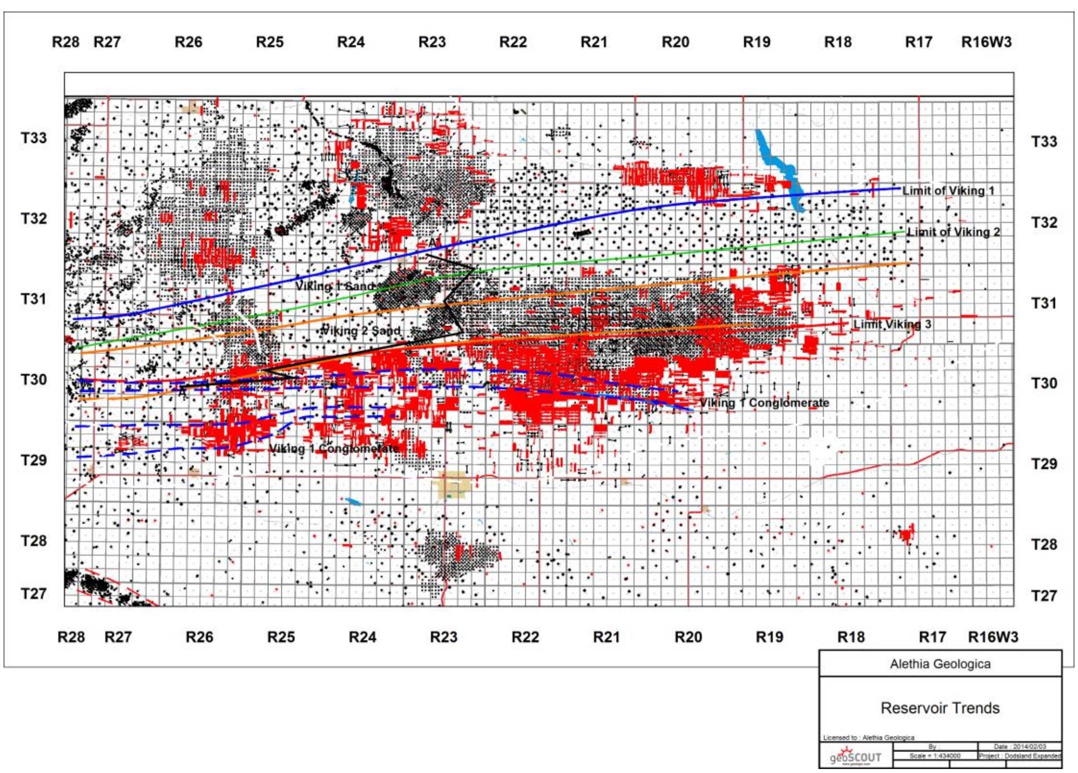

Figure 8 Dodsland reservoir trends and subcrop map

Figure 9: Highly bioturbated medium grained sandstone with scattered pebbles (Facies C) overlain by pebbles marking the base of Facies D. Contact between Viking 2 and 3 well 15-20?

Figure 10 Facies D: Moderately well sorted granular to coarse-grained sandstone partially cemented with siderite. Viking 1 well 6-17 30-26W3M.