PS Seismic Facies Classification of the Internal Architecture of Mass Transport Deposits: Implication for Reservoir Seal Competence*

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Abstract

Mass- transport deposits (MTDs) are important stratigraphic elements in many deepwater basins and they constitute a primary component of heterogeneous siliciclastic seal sequences in many of petroliferous basins around the world. Although 3D seismic characterization of MTDs has been carried out extensively from a number of case studies in a range of basins, no comprehensive scheme has been presented to classify their internal architecture in a manner that is directly mappable onto the problem of defining their potential as sealing sequences.

In this work, a qualitative object based seismic facies classification for MTDs is presented based on an extensive review of the internal 3D seismic architecture of MTDs from the Taranaki Basin, New Zealand and other published literatures. In order to ground truth, the classification scheme with lithology information and evaluate the leakage or seal potential, lessons learned from outcrop studies of MTDs are briefly highlighted. Three main types of deformation are recognized within MTDs consisting of (1) layered, (2) blocky, and (3) amorphous, based on five criteria including a) external geometry, b) internal reflection configuration, and inferred stress regime, c) reflection continuity, d) amplitude strength, and e) RMS amplitude and/or coherency pattern. It is observed that in many petroliferous basins, at least two of the three types of facies are developed in MTDs, and in some, the three types can be found distributed within a single MTD.

The seismic facies classes of MTDs would have significantly different implications for hydrocarbon potential. It is proposed in this project that the geometry of the internal seismic character of an MTD and the N/G play an important role in determining the sealing capacity i.e. whether the MTD leaks or not. The seismic facies classification for MTDs provides a seismic interpreter with a rapid analysis of the deposit whose aim is to come up with a risk map that can better inform exploration decision making.

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1. Project Rationale

It has been pointed out that the role of the Mass Transport Deposits (MTDs) in analogous hydrocarbon traps has been less explored. Although 3D seismic characterisation of MTDs has been carried out extensively from a number of case studies in a range of basins, no comprehensive scheme has been presented to classify their internal architecture in a manner that is directly mappable onto the problem of defining their potential as sealing sequences.

In order to assign risk levels to MTDs which are now being increasingly recognised as ubiquitous components of hydrocarbon seals, a three dimensional (3-D) architecture of the MTD must be defined including a description of heterogeneities on any observable scale, not merely those accessible from core or well data . Seismic data, however, have a resolution of at least several meters and do not provide direct information on the lithology which is critical in assigning a risk to seismic facies classes. In the absence of seismic calibration, prediction on MTD lithology heterogeneities can be based on exposed outcrops of MTDs provide good analogues to assess for such heterogeneities. In this project however, some scenarios were considered (high N/G, moderate N/G and low N/G) in order to make predictions about seal integrity of MTDs.

It is important to note that due to the resolution of seismic data and for the purpose of developing a seismic based classification, only MTDs which have thicknesses equal to or greater than 100 m are considered in the proposed classification.

2. Geological setting

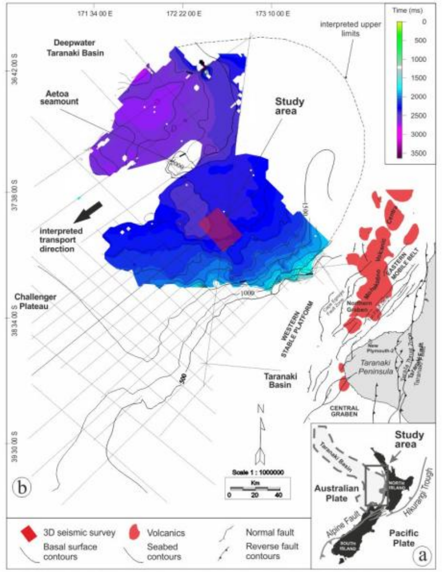


Fig. 2.1. (a) Map showing the study area along the western margin of New Zealand's North Island including relative location of Taranaki Basin, its northwestern deepwater extension and corresponding tectonic framework along Australian-Pacific plate boundary zone.(b) Structural domainsand principal tectonic and volcanic features of Taranaki Basin. (Modified King and Thrasher (1996) and Omeru 2014).

3. Stratigraphy

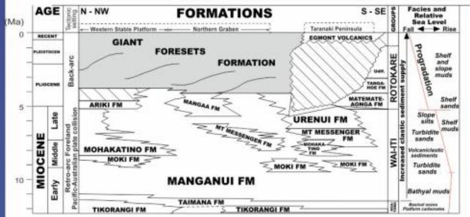


Figure 3.1. Miocene to Recent stratigraphy for the Taranaki Basin (Modified from King and Thrasher 1996). This is focused on the Pliocene to Pliestocene Giant Foreset Formation in the Western Stable Platform.

4. Data and Method

The data for this study is the Romney 3D survey (Fig. 1) located on the southern lobe of MTD and which images an area measuring 590 km 2. The 3D seismic data was provided by Anadarko Petroleum Corporation as a 16-bit scale and clipped volume because it included multiple prospects and leads. The data was processed to post-stack time-migration (PSTM), zero-phased, and Automatic Gain Control (AGC) was applied. The data was migrated using Kirchhoff pre-stack migration and bending ray post-stack migration to generate a 12.5 m by 12.5 m grid with a 4 ms sampling interval and was displayed every 4-inlines and cross-lines giving it a bin-size of 50 m which corresponds to the maximum horizontal resolution. The data is displayed using SEG-Normal polarity where an increase in acoustic impedance is represented by a peak (positive amplitude-red on seismic sections). The main frequency of the 3D seismic data is 50 Hz, yielding a vertical resolution of approximately 9 m which equals one quarter of the wavelength at the dominant frequency assuming a sediment velocity of 1800 ms-1.

The classification workflow consists of three steps:
1) The basal shear and top surfaces (upper and lower limits) should be mapped.

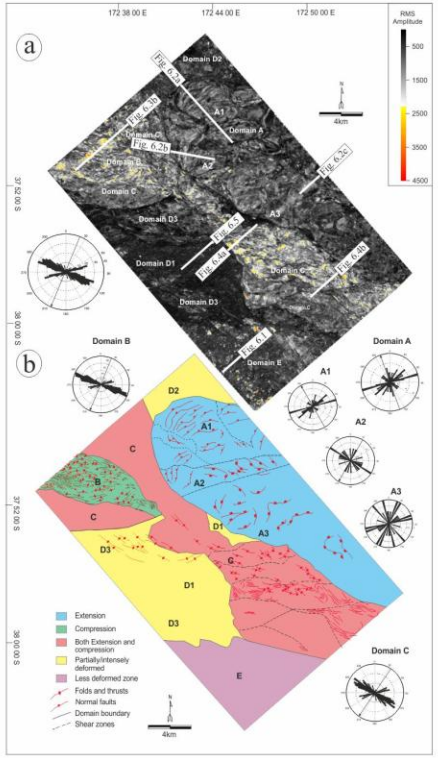
2) If the MTD is greater than 100 m in thickness then it is best to divide the deposit iso-proportionally in windows and calculate the Root Mean Square (RMS) amplitude for each window to unravel the MTD morphology by looking at patterns and colour.

3) Pattern recognition techniques are employed to interpret the RMS amplitude map. Traces which are close together in term of seismic attribute will stand in the same group of seismic facies . It is essential for an interpreter to iterate between section and plan views during the interpretation of the MTD interval, which is a critical step in the seismic interpretation .

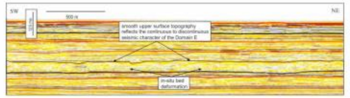
5. Overview of MTD seismic facies classes

Facies	Mechanism	Cross sectional seismic expression (internal configuration; continuity; external geometry; amplitude strength)	Plan-view appearance (RMS amplitude or coherence or time slice patterns; amplitude strength)	Spatial distribution within MTDs	Seismic examples
Layered		Wavy, parallel to subparallel; continuous to discontinuous sheet; flat basal and upper surfaces; transparent, moderate to high	low to moderate amplitude blocky pattern or featureless light colored on coh. slice	Occur anywhere within MTDs from up-dip extensional domain to down-dip contractional domain	Figure 6.1
Blocky	Extensional	Discrete units of stratal reflections separated by normal or listric faults; generally flat basal surfaces and irregular upper surfaces; moderate to high	Moderate to high amplitude; Thick elongated ridges	Usually found in the up-dip extensional domain (headwall) but can also be observed in the translational or toe domains	Figure 6.2
	Contractional	Discrete units of imbricated thrusts or folded reflections; generally flat basal surfaces and irregular upper surfaces; moderate to high	Thin elongate ridges with fold hinges corresponding to long axis; moderate to high amplitude	Usually found in the down-dip contractional domain (toe) or in the translational or toe domains	Figure 6.3
	Hybrid	Imbricated thrusted or folded reflections cross-cut by faults or vice versa; generally flat basal surfaces and irregular upper surfaces; moderate to high	Complex planform geometry; moderate to high	Usually found in the translational domain	Figure 6.4
Amorphous	Incomplete Deformation	Localised packages of coherent reflections (blocks) within chaotic matrix; flat basal and upper surfaces; low to transparent	Isolated irregular shaped high amplitude geometric feature within dark and mottled texture	Found anywhere within an MTD but usually in the translational domain	Figure 6.5
	Complete Deformation	Total loss of seismic character; low to transparent	Dark amplitude or low coherency	Usually found anywhere within an MTD	Figure 6.6

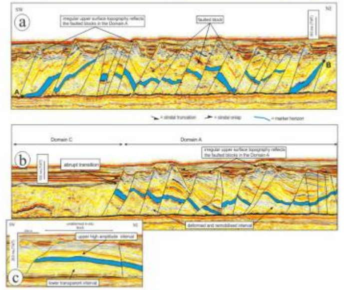
6. Internal architecture



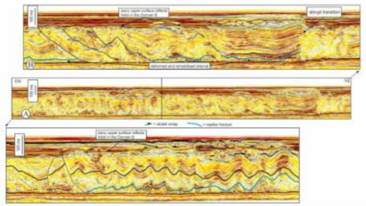
6.1. Layered



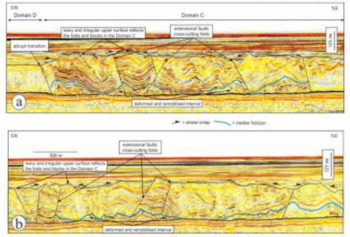
6.2. Blocky (Extentional)



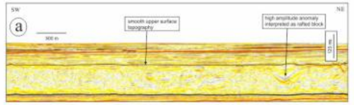
6.3. Blocky (Contractional)



6.4. Blocky (Hybrid)



6.5. Amorphous



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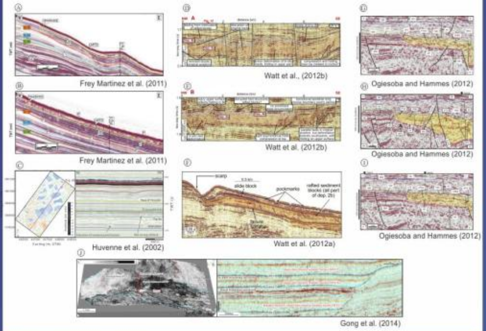
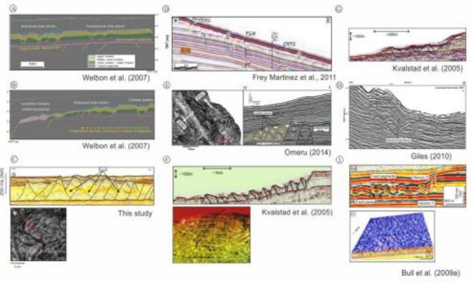
7. Seismic example from other basins

Layered

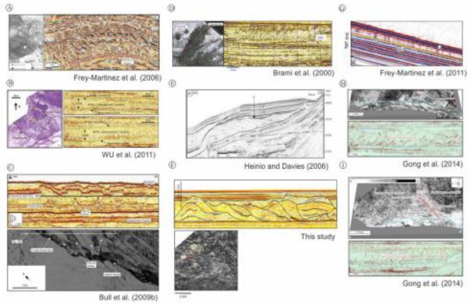


Blocky

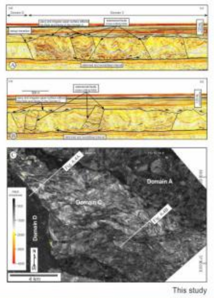
Extentional



Contractional

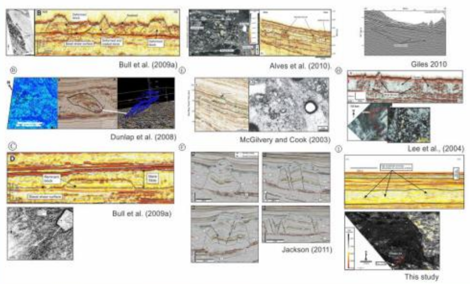


Hybrid

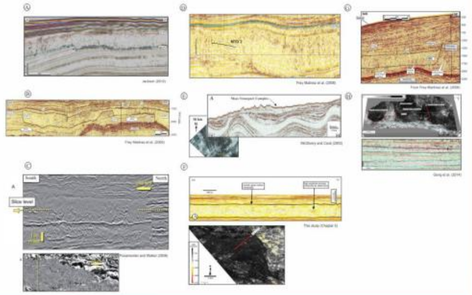


Amorphous

Incomplete deformation



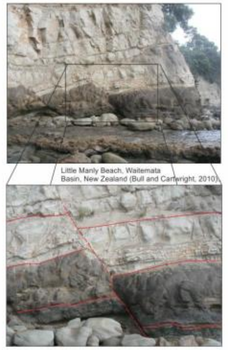
Complete deformation



8. Outcrop analogue

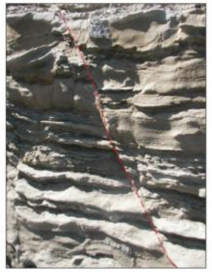
Below the internal detachment surface, the sandstone and siltstone beds have retained some coherency whereas beds above it are more highly contorted and more tightly folded from the Taranaki Basin, northern New Zealand..

Notice some coherencywithin the MTD from the Taranaki Basin, northern New Zealand.



Little Manly Beach, Waitemata Basin, New Zealand (Bull and Cartwright, 2010).

Here we see extensional faults bounding huge rotated blocks, typical of headwall regions of MTDs. Miocene Waitemata Basin, northern New Zealand.

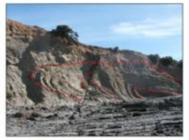


Minor extension fault with decimeter throw. Would these compromise the seal, at least locally, and offer migration paths upwards through an otherwise flat lying and probably decimetre throws locally sealing unit?

Little Manly Beach, Waitemata Basin, New Zealand (Bull and Cartwright, 2010).

Here we see huge (seismic scale) complex MTD from Antarctica. Note the thrust out recumbent fold (black arrow).

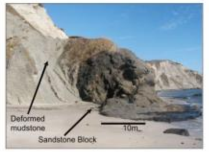
Middle Miocene Gordo megabed mass-transport deposit in the Tabernas Basin, southern Spain (Posamentier and Martisen 2011)



Two extensional faults overprint already existing recumbent fold stucture from Gull Island Formation, Ireland (Posamentier and Martisen 2011)

A classic example of a thrust fault overprinting a recumbent fold fashion (from Posamentier and Martisen 2011).

Examples of floating blocks can be seen in a number of localities in the peninsular. Here, an elliptical shaped megaclast or block of sandstone appears stranded within a low N/G interval. But closer inspection should reveal that this clast might in fact be a detached recumbent fold, with two noses giving the appearance of an ellipsoid. Block is 10m wide.



Here is another example of a relatively rigid block of volcano-clastic sandstone entrained in a deformed mudstone matrix.

Large slump resulting in almost complete disruption of bedding, Carboniferous Bude Sandstones at Efford, southwest England (from Posamentier and Walker 2006).

Here we see an MTD involving stratified blocks in the Upper Cretaceous Great Valley Sequence, Lake Berryessa, California (from Posamentier and Martisen 2011).

(from Posamentier and Martisen 2011)

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9. Implication for Reservoir Seal Competence

9.1 Net to Gross of MTD

The relative degree of risk associated with MTD seals of the three main seismic classes of MTDs are discussed in this section considering a variety of geological circumstances (e.g range of layer geometries and connectivity in low N/G versus high N/G systems) as observed from outcrop. However, we first considered, two

Firstly, the seal quality critically depends on N/G of the MTD. This is determined by the provenance or staging area of the mass-transport deposits. For example, a sand-rich MTD like the example from the Gordo Megabed Spain (Fig. 9.2) would prove to be high risk seal compared to the mud-rich MTD of the Ross slide (Fig. 9.1) whose thorough disaggregation renders any limited sand layers completely unconnected and hence would constitute a high quality seal.
Slope derived MTDs will likely be mud rich because the slopes are commonly the site of predominantly mud deposition while shelf-edge derived MTDs or those involving basin floor sediments may be sand rich (Lucente and Pini, 2003; Dykstra et al. 2011; Posamentier and Martisen 2011).

Secondly, the incorporation of strata below the main detachment during MTD translation may be important in determining the seal characteristics of the MTD.

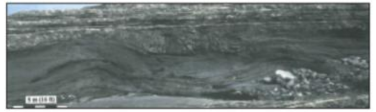


Figure 9.1. Mud-rich MTD from the Ross Slide, SE Ireland would constitute an excellent seal (from Lien et al., 2007).

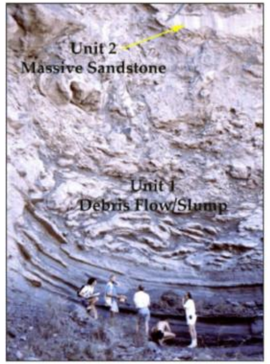
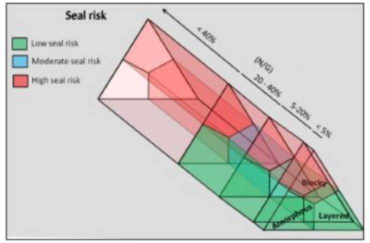


Figure 9.2. Sand-rich MTD from the Gordo Megabed, SE Spain would constitute a poor seal (from Cossey, 2006). important factors from a seal quality perspective.

9.3 Schematic seal risk diagram

Based on outcrop observation of MTDs a seal risk diagram for the proposed MTD classes has been created (Fig. 10.16). Given a low N/G system, the blocky unit will constitute the highest seal risk. However, as N/G increases, all three classes of MTD will constitute high risk seals..



9.2 Pervasive structures within MTD

The layered facies does not represent high risk due to the semi-continuous and continuous beds within the MTD and the consequent lack of cross-stratal flow routes will engender this with good sealing potential. However the presence of through-going faults transecting this unit might prove render the unit as high risk as evidenced in figure 9.3. The seemingly tight fault zones are infilled with mineralised veins. In addition the sand-rich layered unit will represent high risk seal since leakage can occur via the pore network over geologic time.

The seal risk associated with the extensional blocky facies would depend on the preservation of the original stratigraphy of a remnant block, height of block and the presence of internal or fault bounded fault as opposed to the variability in net-to-gross values. However, the extensional blocky units will become high seal risk with an increased net-to-gross because possible migration pathway might occur via permeable beds without any faulting.
In reality, most of the normal faults that define the extensional blocky class will not represent a threat to the integrity of the seal because any significant vertical stress would generally keep the low angle fault surfaces tightly closed to fluid flow with a commensurately low static vertical permeability. Therefore, only dilation under high pore fluid pressure (probably from the underlying reservoir) would open them up and increase permeability along the fault zone, and this would be a mechanical seal failure involving reactivation.

The seal risk associated with the folded structures comprising the contractional blocky unit probably mainly depends on the extent and character of numerous sub seismic faults and fractures on the crest of folds which could possibly act to connect permeable sandy carrier beds of the fold limbs. However this leakage mechanism requires that the sub-seismic faults do not form clay smear or cataclastic seals against the leaky strata (Ingram & Urai, 1999). Evidence for leakage through crestal faults is visible in outcrops example (Fig. 9.4) and it is thought that the carbonate concretions aligned parallel to the axis of a recumbent fold indicated persistent migration of formation fluids (Sporli & Rowland, 2007).

The seal risk associated with the thrusted structures in the contractional blocky facies will be the headwall dipping thrust faults that might act as migration conduit for hydrocarbon. Just like in the extensional blocky facies, these thrust faults are expected to be closed because confining stress but would probably dilate under high pore fluid pressure, thus acting as a conduit for leakage.
In addition, thrusted units sometimes comprise a succession of thrusted, deepwater turbidite deposits that have largely remained intact extending from the basal surface to the upper surface of MTDs (Fig. 9.5). From a seal perspective, such mass-transport deposits, characterized strong stratigraphic continuity form base to top, would constitute relatively poor seals as leakage can occur via permeable beds.

The seal risks associated with the amorphous unit mainly depend on N/G and In cases where the amorphous unit is mud-rich, high capillary entry pressure layers overly the sealing surfaces, thus the fluid transmissibility of the contacts will be very low and stratigraphically assisted trapping of hydrocarbons is possible. Many muddy debrites are described from ODP boreholes penetrating this seismic facies class.
These often have a higher density than the neighbouring units of undeformed clay, implying loss of water during mobilisation and consequent strengthening of the remoulded clay fabrics
However with an increased N/G the amorphous unit will represent high risk since it is more likely that any sandy units will be connected with relatively high permeabilities of the matrix components.
Furthermore, the seal risk associated with the incomplete amorphous unit may be fluid migration pathways provided by connections between sandy units via the thinly bedded sand and silts or faults existing in isolated blocks within the unit.

Figure 9.3. This provides evidence that these seemingly tight faults can be migration paths through an otherwise flat sealing unit. Through going fault in a layered unit filled with mineralised vein.

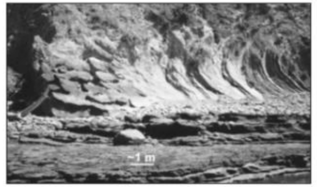


Figure 9.4. Can folds be leaky? Here we see a another 3D exposure of recumbent fold with consistent bed thickness. However, through the hinge of the fold there is no ductile deformation rather we see carbonate concretions aligned parallel to the fold axis on the left side of the fold possibly indicating persistent leakage of formation fluids (from Sporli and Rowland, 2007).

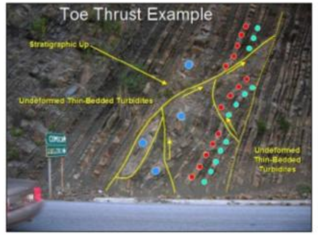


Figure. 9.5. Stratigraphic continuity preserved in a toe thrust comprising of deep-water turbidite deposits. These beds might extend from the base to the top of the MTD and as such constitute poor seal (from Cossey, 2011).

10. Conclusion

1. Three main MTD seismic facies types have been proposed including 1) Layered, Blocky and Amorphous seismic facies. Unequivocal outcrop examples have also been provide. However, there is an inherent difficulty of scaling up from outcrop to seismic scales.

2. Although details of folding and faulting are limited by seismic resolution, our direct observations of slump folds and their associated regional patterns allow greater controls and confidence to be placed on such seismically imaged systems.

3. Features that physically compromise sealing lithologies within MTDs, i.e., faults and sand beds are first order risks and should be incorporated into any risk assessment.

4. Detailed outcrop study of MTDs coupled with accurate subsurface mapping is the approach that will result in the most accurate risk characterization. This requires both detailed mapping and prediction of the stratigraphic and structural geometry of MTDs.

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