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Visualisation of geomorphological features and interpretation of the depositional system of the Brewster Member, Ichthys Field

Syed Iftikhar Arsalan[A], *Keiji Ichizawa*[A] *and Keiichi Furuya*[A,B]

[A]INPEX, 100 St Georges Terrace, Perth WA 6000, Australia.
[B]Corresponding author. Email: keiichi.furuya@inpex.com.au

Abstract. The Brewster Member of the Early Cretaceous Upper Vulcan Formation is one of the main reservoirs of the Ichthys Field. The Brewster reservoir is characterised as massive sandstone, 150–200 m thick, deposited in a deep marine environment. It has a high net sand-to-gross ratio (over 90%) throughout the field, but heterogeneous reservoir quality between the wells. Visualisation of various geo-morphological features from seismic data is critical for the better understanding of the reservoir. Due to thick overburden, frequency content of the seismic volume is limited at reservoir level. Since the reservoir primarily consists of high net sand-to-gross sandstone, and seismic data has limited resolution, it is difficult to identify the various depositional elements using conventional seismic amplitude interpretation. Seismic attribute visualisation techniques were applied to Ichthys 3D seismic and inverted P-impedance data, enabling identification of several geo-morphological features in this otherwise massive sandstone interval (e.g. feeder channel belt, channel-lobe complex, channel-lobe fringe). Core and log scale sedimentological interpretation were tied to the identified feature to understand the depositional architecture of the Brewster Member, which could lead to a better understanding of the distribution of reservoir properties.

Keywords: Browse Basin, depositional facies distribution, Ichthys gas-condensate field, seismic visualisation.

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Introduction

The Ichthys gas-condensate field is located in the Browse basin, North West Shelf, Australia with water depth ranging from ~200 m to 400 m. This field consists of a ~600 km^2 anticline structure. Produced gas and condensate will be brought to an onshore liquefied natural gas (LNG) plant in Darwin through a ~890 km long subsea pipeline (Fig. 1).

The Brewster Member of the Early Cretaceous Upper Vulcan Formation is one of the main reservoirs in this field (Fig. 2). The Brewster Member consists mainly of thick bedded, massive sandstone (quartz arenite) with a very high net-to-gross (NTG >90%) sand ratio (Ban and Pitt 2006; Nakanishi *et al.* 2014).

Although the Brewster Member is very homogeneous in terms of lithofacies, the reservoir quality distribution is not homogeneous within the sandstone. Petrographic analyses indicate that quartz overgrowth is seemingly the one main permeability controlling factor in the Brewster Member (Nakanishi *et al.* 2014). Since grain size is the one of main contributors to quartz overgrowth, and it could be subjected by the depositional process of the sandstone, the depositional facies distribution should be established in order to predict reservoir quality distribution. However, since the Brewster Member has a very high NTG ratio and massive sandstone is the dominant lithofacies, the confidence of conventional well based correlation is limited.

Seismic attribute visualisation techniques were applied to the Ichthys 3D seismic (I3D) and inverted P-impedance (Ip) volume data that covers the whole of the Ichthys Field (Fig. 3), enabling seismic facies variation to be distinguished in this otherwise massive sandstone interval. By integrating core and log-based sedimentological interpretation with seismic attribute visualisation techniques, the spatial distribution of the depositional facies can be interpreted.

This paper describes the use of seismic attributes and geobody visualisation of 3D seismic data for investigating the spatial distribution of depositional architecture in very high NTG monotonous sandstone.

Body

General geological description of the Brewster Member

The Brewster Member consists of very high NTG ratio sandstone ~150–200 m thick. It is separated into two by a field-wide

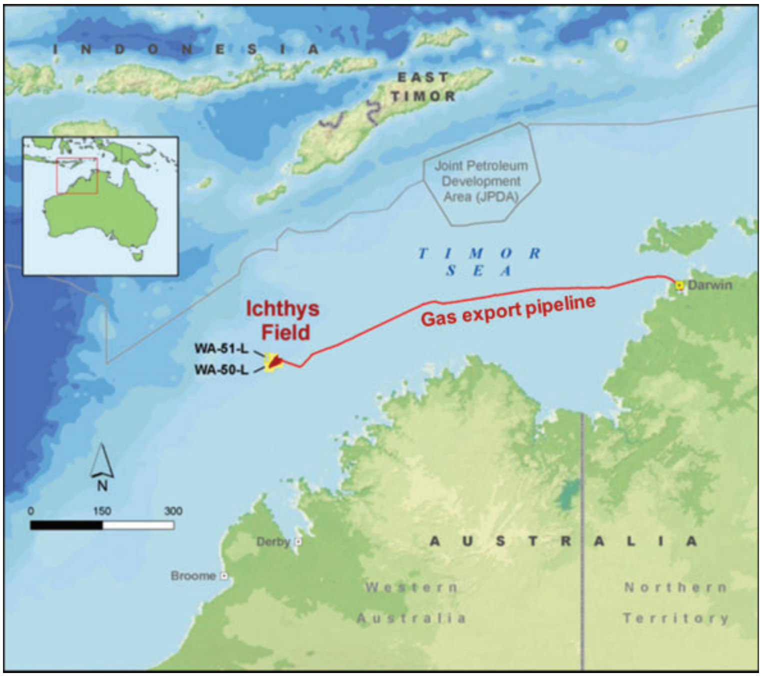

Fig. 1. Location of the Ichthys Field and gas export pipeline route to Darwin.

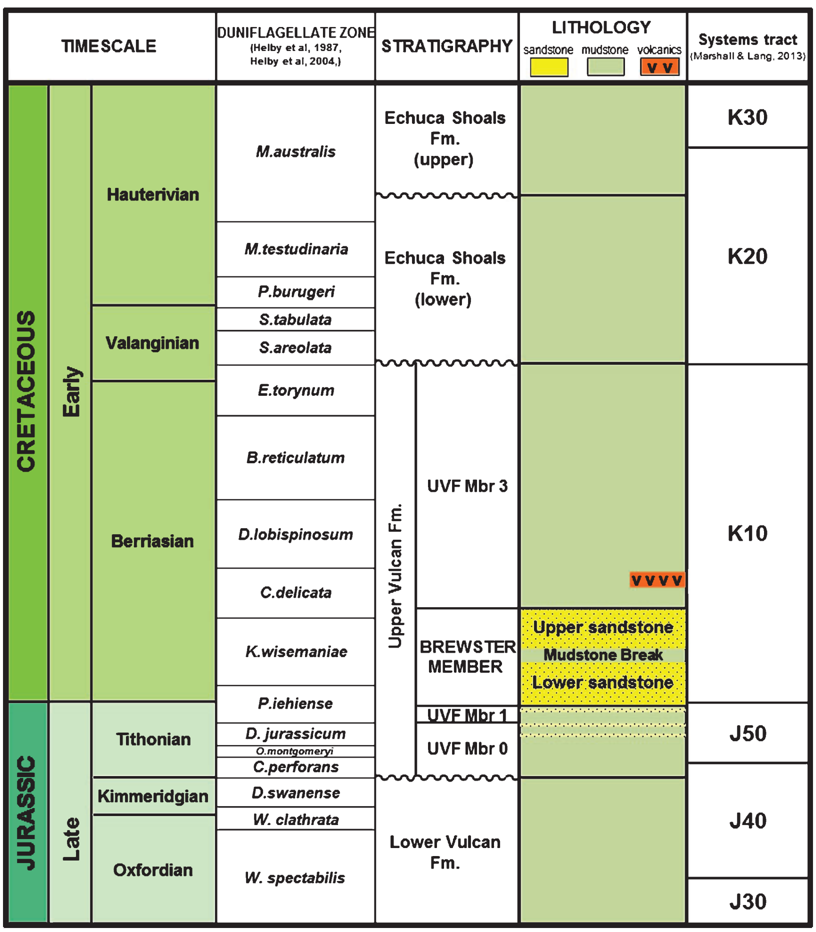

Fig. 2. General stratigraphy of the Ichthys Field (after Nakanishi *et al.* 2014).

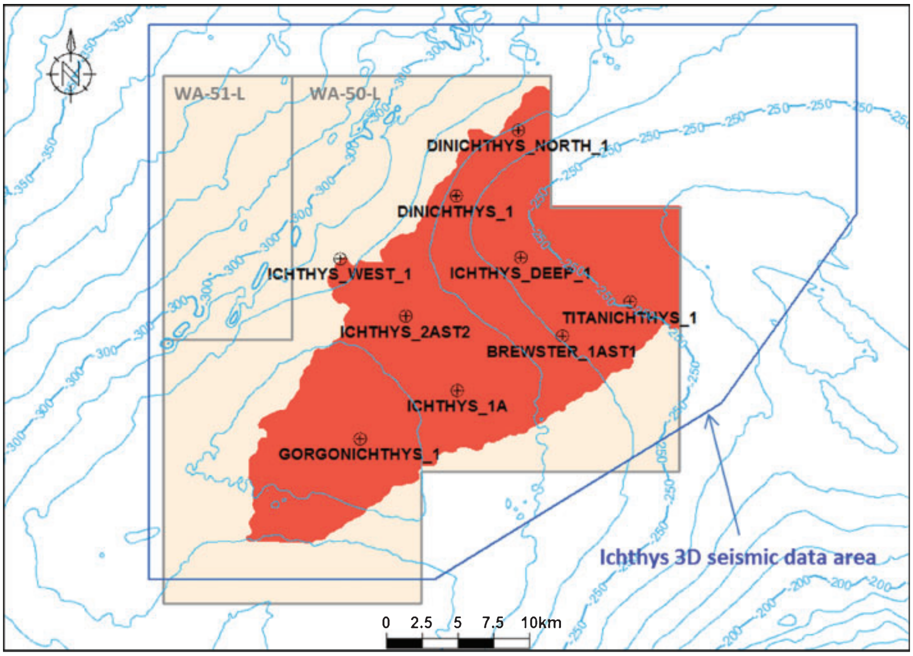

Fig. 3. Ichthys Field, Brewster Member reservoir outline and the Ichthys 3D seismic data area. Contours show water depth (m).

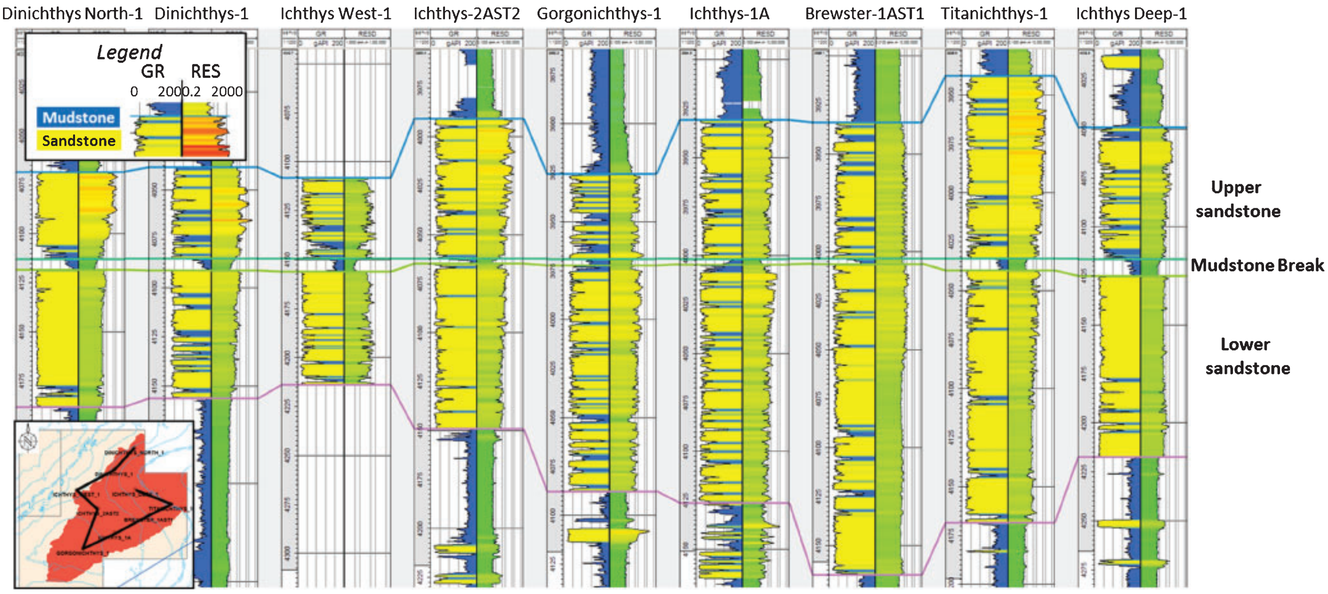

Fig. 4. Stratigraphic well correlation of the Brewster Member. GR, gamma ray; RES, deep resistivity.

correlatable mudstone interval called the Mudstone Break. The sandstones above and below the Mudstone Break are called the Upper Sandstone and Lower Sandstone (Fig. 4). Both Upper and Lower Sandstones consist of fine- to medium-grained sandstone with a quartz arenite composition and have a low clay volume (less than 10%).

Since the Brewster Member has very high NTG ratio and most of the intervals are covered by a single biozone (*K.wisemaniae* zone), it is difficult to identify time lines in the sandstone; hence, correlation of individual sandstone packages encountered by various wells is very difficult.

Depositional setting of the Brewster Member

Based on the core and regional seismic interpretation, the Brewster Member has been interpreted as an extensive submarine channel-lobe complex which prograded into the field area from the east and south-east. It thins and pinches out to the west and north-west. The sediment is interpreted to be supplied by slumping and reworking from the more proximal shallow marine Yampi Shelf (Fig. 5; Ban and Pitt 2006). Typical core facies examples of upper sandstone are shown in Fig. 6. Massive sandstone is the dominant lithofacies in the field. Laminated, cross-stratified and de-watered sandstones are also observed in cores. A total of nine exploration and appraisal wells were drilled within the field area and they confirmed that the Brewster Member sandstone was deposited throughout, with only minor changes in the lithofacies and NTG ratio (Fig. 4). Based on core facies, high-density turbidity currents are interpreted to be the main flow mechanism by which sediments were supplied to the Ichthys Field.

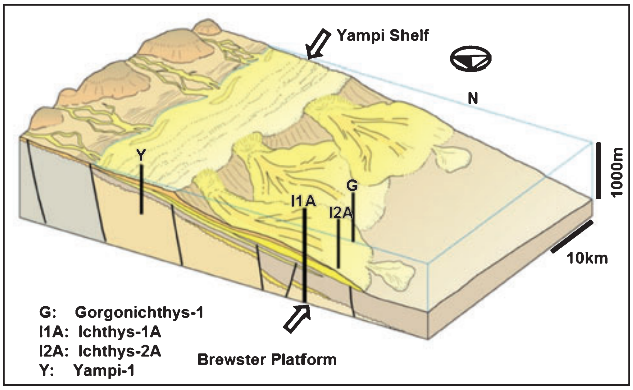

Fig. 5. Schematic diagram of the Brewster Member depositional setting (after Ban and Pitt 2006).

An example of a sedimentological interpretation of the Upper Sandstone interval is shown in Fig. 7. Based on detailed core observation and log motif analysis, we identified the three main depositional elements – the channel complex, the sheet lobe complex and the off-axis of channel lobe complex.

Channel complex

The channel complex consists of thickly-amalgamated (typically 2–5 m), massive fine- to medium-grained sandstone with some very coarse, poorly sorted sandstone intervals. The base of the sandstones is sharp and sometimes appears erosional. High-angle cross-stratification is observed but rare. Thin-bedded planner-laminated and ripple cross-laminated sandstone and mudstone intervals are also recognised but much less abundant. The gamma ray log (GR log) motif shows a box-shape profile but high frequency fluctuations are also recognised.

Sheet lobe complex

The sheet lobe complex mainly consists of thickly-amalgamated (typically 2–5), massive fine- to medium-grained sandstone. Coarser sandstone intervals are minor. Most of the sandstone bases are sharp but erosional features are not common. The sandstone units which contain mud-clasts are not common compared with the channel complex. De-watering structures are commonly recognised in this element. Thin-bedded planner-laminated and ripple cross-laminated sandstone and mudstone intervals are also recognised but much less abundant. The GR log motif shows a box-shape profile and seems more stable compared with the channel complex and off-axis of channel-lobe complex.

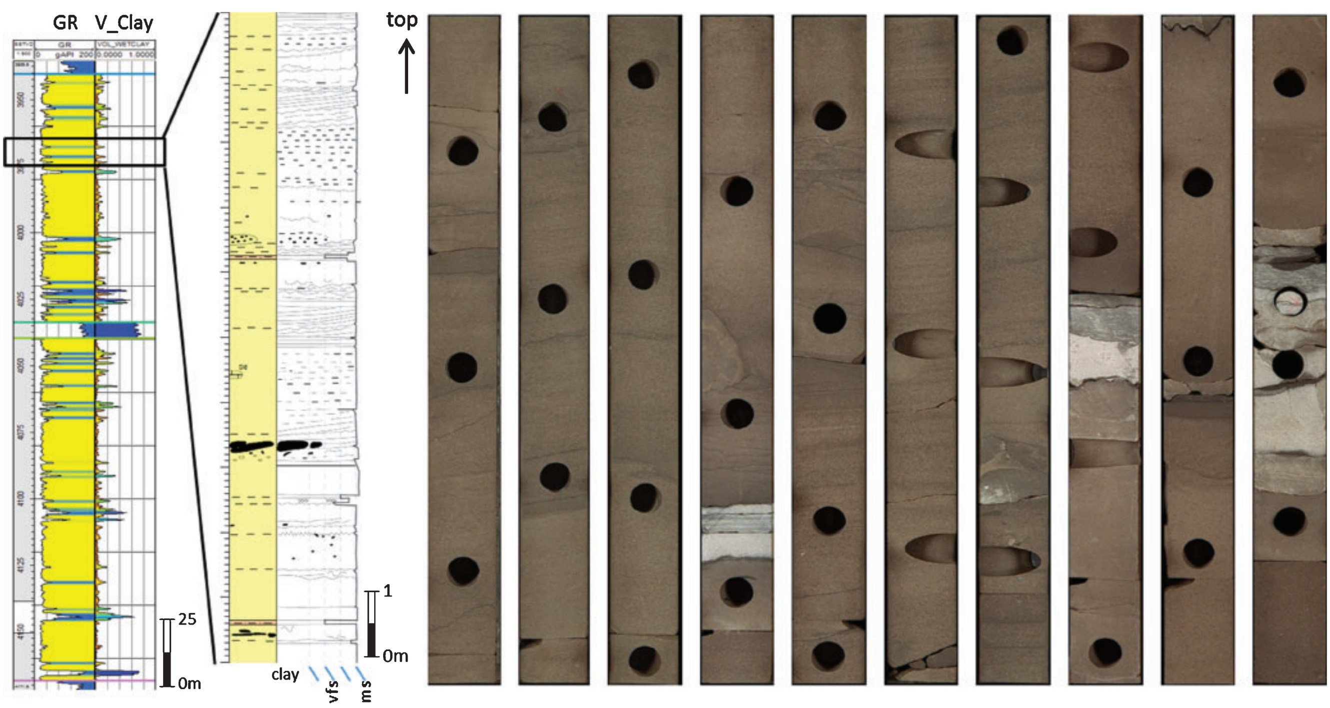

Fig. 6. Typical core facies examples of the Brewster Member (Upper sandstone of Titanichthys-1).

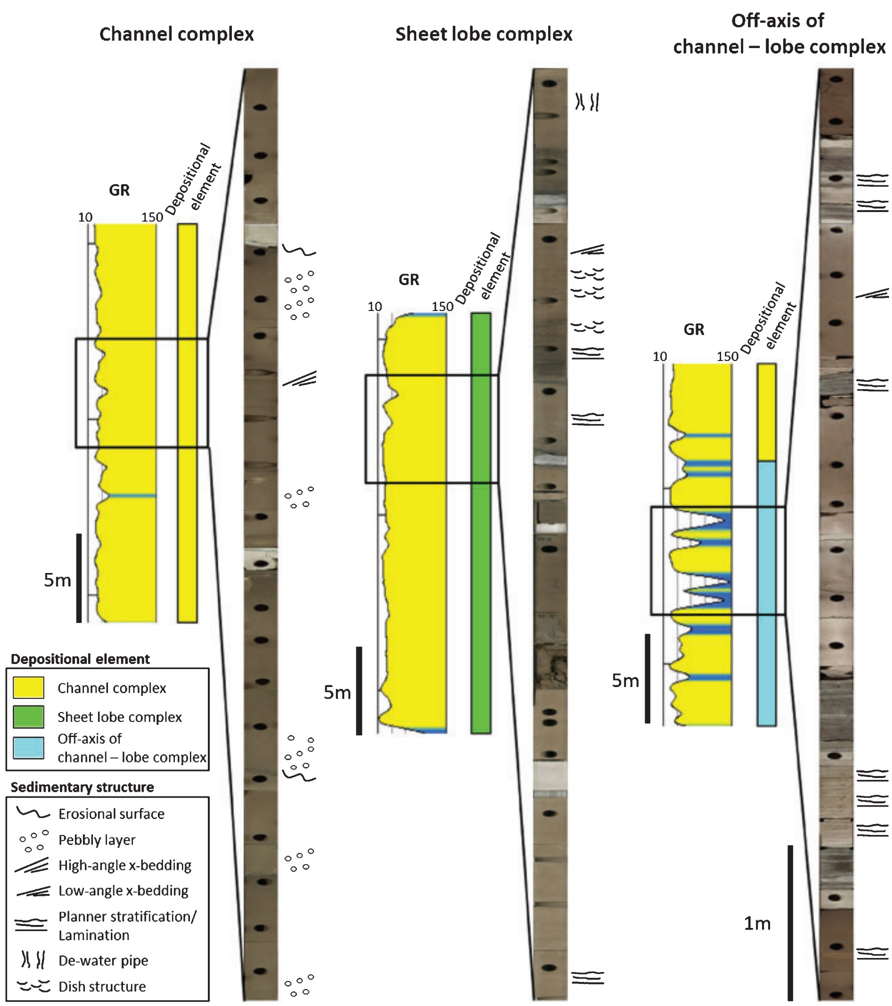

Fig. 7. Core and log examples of the three main depositional elements in Upper Brewster Sandstone.

Off-axis of channel-lobe complex

The off-axis of channel-lobe complex consists of thin- to medium-bedded, massive fine-grained sandstone with some stratified sandstone intervals. Most of the sandstone bases are sharp and sometimes appear erosional. Planar- and low-angle cross-stratification is more common when compared with the other two environments. The thickness of single sandstone intervals is thinner and the NTG ratio is lower than the other two elements (typically 2 m). The GR log motif appears spiky, reflecting sandstone-mudstone intercalation.

Reservoir quality distribution of the Brewster Member

Although massive sandstone is the dominant lithofacies in all wells in the field, reservoir quality distribution is quite complex. Lateral porosity change is shown in Fig. 8. As the figure shows, reservoir quality is variable between the wells. As the porosity variation is likely to be controlled by primary sedimentary characteristics (e.g. grain size, sorting, mineral composition), the spatial distribution of depositional facies should be first established in order to predict the distribution of reservoir quality.

However, because of a lack of time markers which can be correlated field-wide (except the Mudstone Break), there is significant uncertainty associated with well correlation and prediction of the spatial distribution of depositional facies.

Seismic visualisation

Identifying and understanding the distribution of the different geomorphological features in the Brewster Member is an important step to successfully developing the reservoir. Traditional 3D seismic data interpretation involves interpreting 2D sections along inline and cross line directions. Interpretation carried out using this 2D display technique suffers from a loss of information that exists in the third dimension (Chopra and Marfurt 2011). Therefore, seismic visualisation and qualitative geobody interpretation to identify possible geo-morphological features using seismic attributes was conducted on the Brewster Member so as to make maximum use of the 3D seismic data. Three visualisation techniques were adopted: the first using inverted elastic attribute, whereas the second and third techniques involve RGB blending of spectral decomposition volumes and displaying these with varying opacity. The first was considered to be the primary interpretation method and

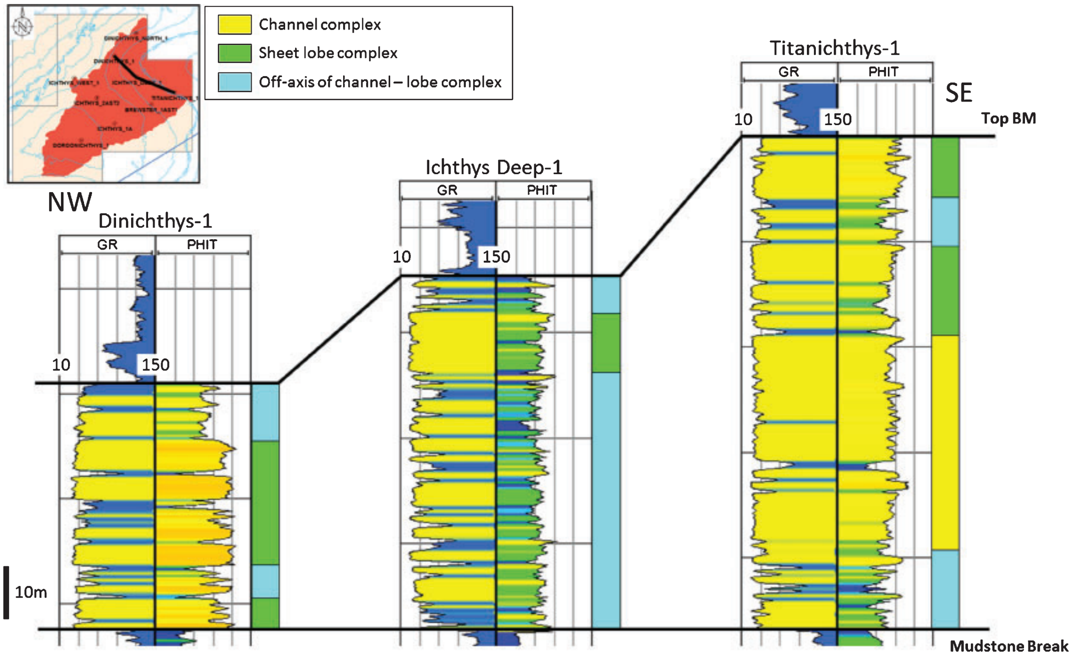

Fig. 8. North-west to south-west well correlation section (general depositional trend). Well spacing is 6–8 km.

the other two were used as cross-validation of the results obtained using the first technique.

Methods and discussion

Determine suitable seismic attributes

This step was focused on the reservoir zone; hence, the interpretation was limited by reservoir top and base surfaces. For the purpose of determining the most suitable seismic attribute, the assumption was made that the reservoir quality is related to total porosity (PHIT). Four possible reservoir quality (RQ) classes were defined at the well log scale by applying a cut-off based on the PHIT log. These are known as RQ0 to RQ3 where 0–3 refers to increasing PHIT and hence reservoir quality.

Histograms and cross-plots of various elastic attributes such as Ip and Vp/Vs (ratio of primary (P) and shear (S) wave velocity), colour-coded by RQ class, were analysed. A suitable primary seismic attribute was then identified. This attribute was used to identify geomorphological features, whereas the other attributes were used to substantiate the results.

Establish the workflow

After finalising the base attribute, a similar analysis was then performed using inverted data and possibility of identifying geomorphological features was re-investigated. Appropriate cut off values for single attributes and cut-off polygons for a combination of attributes were then investigated to identify potential geomorphological features. The sensitivity of these cut off values and polygons were analysed to understand the impact on interpretation of the geomorphological features.

Identify and characterise potential morphological features

The top and base of the geo-morphological features were mapped, and the geobody distributions were validated given present geological understanding. The mapping was performed qualitatively. Different visualisation techniques including spectral decomposition and RGB colour blending were incorporated to confirm the existence of these features. Characterisation of the geomorphological features was conducted in the context of the current understanding of the deposition of the Brewster Member. Seismic attributes were used in the identification and delineation of geomorphological features.

The study area and seismic data coverage is shown in Fig. 3. Nine near vertical exploration and appraisal wells have already been drilled in the available 3D seismic area. Good quality sonic and density logs are available over most of the drilled interval. Several highly deviated development wells are also available and have been used in this study.

Figure 9(*a*) shows the 1D analysis of Ip coloured by RQ classes for all drilled wells. A significant amount of overlap of RQ0, 1 and 2 seen on the figure could possibly negate the study. However, since the 3D seismic area is spread over a relatively large area and heterogeneity of reservoir quality is expected, it is possible that the overlap is due to a mixture of different depositional elements having different Ip values. Analysis involving individual wells indicates that there are four possible types of distributions persisting across the reservoir shown in Fig. 10. Several wells can be grouped into Type 1 where RQ3 is separate but RQ0, 1 and 2 overlap. Three wells fall into Type 1A, where the separation of RQ3 is weaker in comparison to Type 1. Wells in the Type 3 category are defined as having RQ classes moderately well separated. Type 4 wells show poor separation of RQ classes.

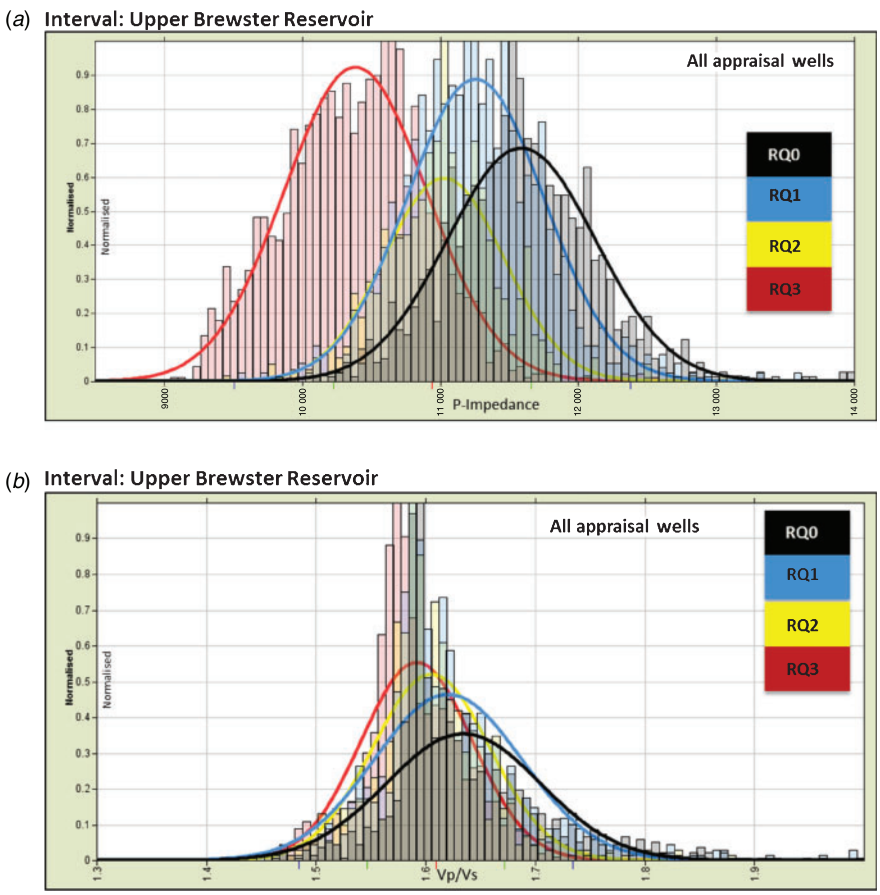

Fig. 9. (*a*) Histogram distribution of Ip for upper sandstone reservoir coloured by RQ classes. (*b*) Histogram distribution of Vp/Vs for upper sandstone reservoir coloured by RQ classes.

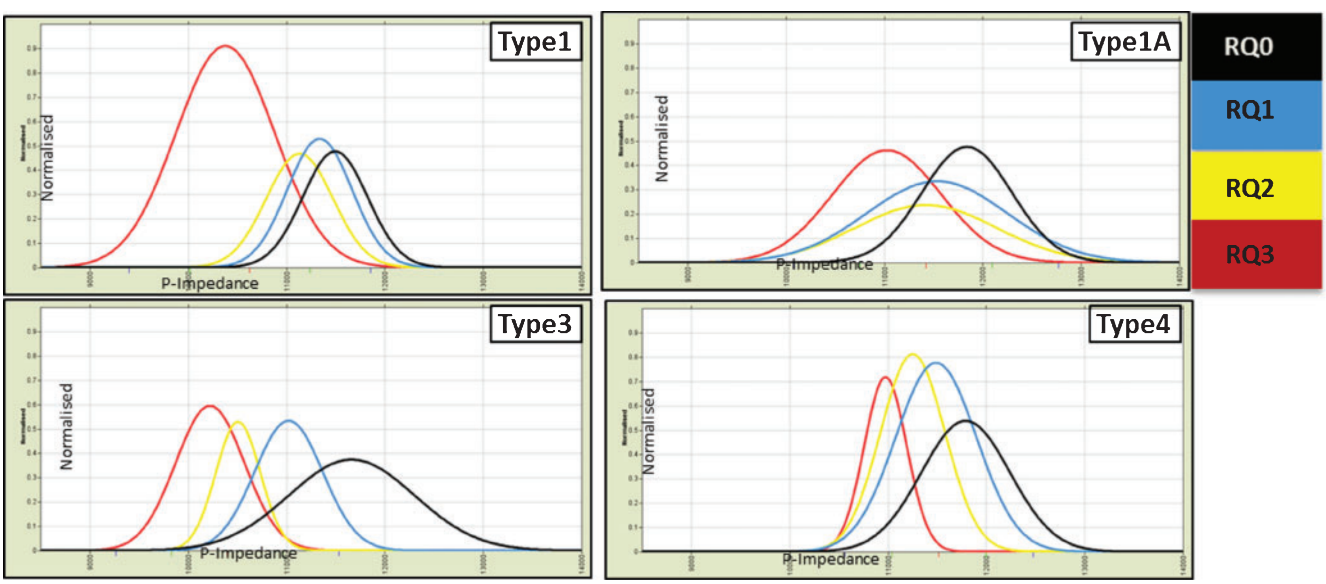

Fig. 10. Different types of Ip distributions of upper sandstone (colour coded with RQ classes) persisting across field.

A similar 1D analysis of the Vp/Vs attribute shows a complete overlap of all RQ classes as it is most likely responding to lithology and not reservoir quality (Fig. 9(*b*)). The following conclusions were made on the basis of the results of these analyses:

- Ip logs appear to be able to distinguish the different RQ classes within reservoir interval.
- Identified bodies may be a mixture of several RQ classes depending on the degree of overlap
- Histogram analysis of Ip logs at drilled well locations indicates that there are four different types of separations in the Upper Sandstone in the 3D seismic area. This implies four different criteria or cut-offs may be applied to captured geo-bodies.
- Good reservoir quality class (RQ3) is well separated in Type 1 whereas separation is moderate for Type 1A and Type 3. Complete overlap seen on Type 4.
- Vp/Vs as a single attribute volume does not help to separate different RQ classes; however, it can be used in combination with Ip.

Since Ip appears to permit us to distinguish good RQ classes, the Ip volume was considered to be the base attribute volume to identify possible geomorphological features across the 3D seismic area, with spatially variable cut-offs.

The above inference was drawn based on the well log data which indicates the Ip of the rock has the potential to be used as a base volume for identification of geomorphological features. Since inversion quality can impact the degree of separation, a similar analysis was performed using inverted Ip logs to determine the feasibility of the study. Fig. 11 shows the Type 1 example where applying a suitable cut-off enabled us to identify the RQ3 class. Histogram was color coded by upscaled RQ log. Upscaled RQ log was generated by applying PHIT cut-off on the high cut filtered PHIT log.

Due to high lateral heterogeneity these cut-off values are varying spatially. Rational cut-off values were determined area-by-area referring nearest well observation and applied, allowing us to identify several geomorphological features within the Upper Sandstone. Due to a lack of resolution (~30 m) and moderate data continuity, the identified features appear to be somewhat scattered. Manual interpretation was finally performed to obtain a rational distribution. As the results of 1D analysis show that in most cases there is an overlap of RQ classes, it is difficult to directly infer the reservoir quality of interpreted geobodies.

Visualisation of geomorphological features

A well based cut-off and voxel-based geobody detection technique was applied to identify geomorphological features. The Brewster reservoir primarily consists of a channel lobe complex which was deposited over a considerable time scale. Seismic data does not have enough vertical resolution to identify the distribution of individual depositional elements for a given time period. The voxel-based detection technique primarily captures an amalgamation of multiple stratigraphic successions over a period of time and provides a good idea of their distribution. Fig. 12 shows geomorphological features identified in the eastern part of the field. Channel like features (CLF) and Lobe like features (LLF) were captured. These seismically captured geo-morphological features may be related to feeder channel belts, channel-lobe complexes and channel-lobe fringes. These features can also be seen in a horizon slice near the upper part of the reservoir shown in Fig. 13.

A detailed interpretation of the south-east region is presented in Fig. 14. A feeder channel is possibly seen on the south-east side of the field. Multiple channel-like features were detected, extending further towards the north. An Ip section across the channel-like feature shows it is characterised by low Ip values. The section along the channel shows good continuity of low Ip values. It is important to note that due to low seismic resolution, even if the geobody appears to be a single thick low Ip body (Fig. 14*c*), it could represent the amalgamation of many

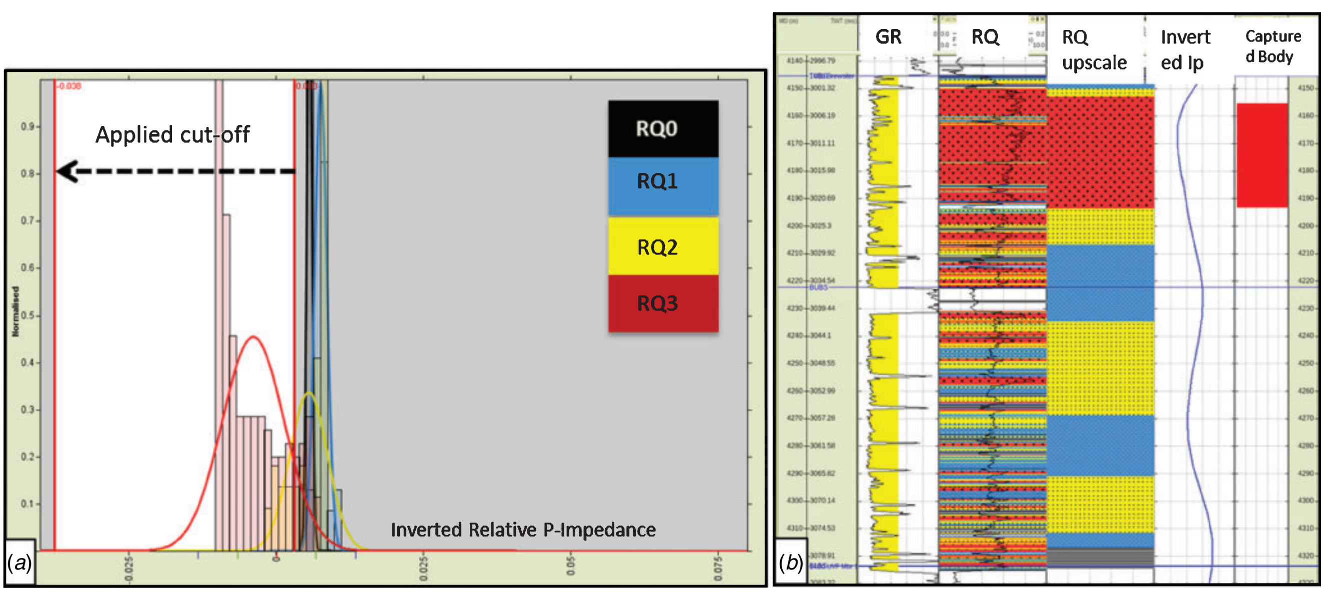

Fig. 11. (*a*) Histogram distribution of Ip for upper sandstone colour coded with RQ classes. Black dotted arrow indicates the cut-off limit. (*b*) Well log panel displaying the different logs. Depth range highlighted in red, coloured in fifth track is the captured body after applying the cut-off shown in (*a*).

geological episodes of deposition. The results, obtained using the above technique, were subsequently checked using the following two methods.

Spectral Decomposition and RGB blending is one of the standard seismic interpretation methods which industry has been using over last few years. By colouring different spectral components separately and then merging them together, one may be able to see additional geomorphological features or further delineate ones previously identified using other techniques. Continuous wavelet transform (CWT) was applied to generate multiple spectral decomposition volumes. Three volumes of frequency range 12, 24 and 32 Hz were blended and the results are presented in Fig. 15. Clear evidence of a channel-like feature oriented in a south-east to north-west direction can be identified. The presence of feeder channels and their orientation is in concordance with the interpreted geomorphology. Apart from these geomorphological features, major structural faults and lava flow features in the overburden can also be clearly delineated on the RGB image.

Applying opacity techniques to different seismic attribute volumes is one of the standard approaches to identify and delineate geomorphological features. The Ip volume was used as an input for this analysis, with a rational opacity curve applied to illuminate depositional elements. Geomorphological features identified by applying opacity are shown in Fig. 16. Geomorphological features related to CLF and LLF features are clearly identified using this technique. The method is similar to the first technique but it is more qualitative, for

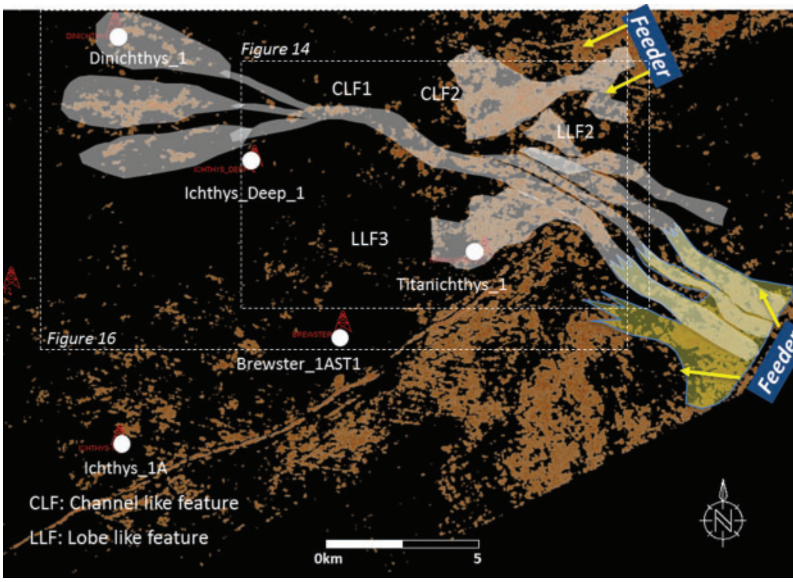

Fig. 12. Identified geomorphological features in the eastern part of the field. Interpretation of possible feeder channel belts, isolated channels, lobes and channel-lobe complexes is overlaid onto the captured geobody.

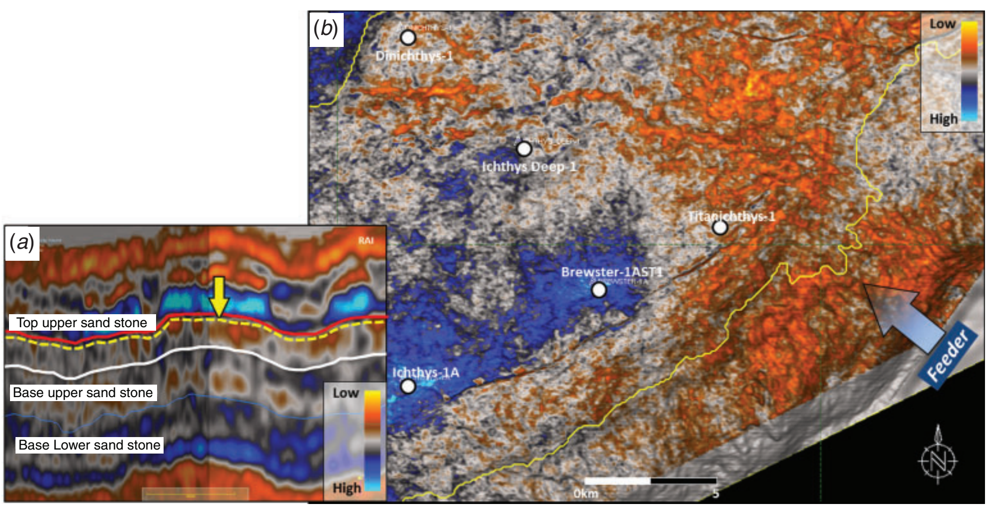

Fig. 13. (*a*) Relative Ip section showing Top and Base of different sand stone unite. Yellow dotted horizon indicates the position of horizon slice shown in (*b*). (*b*) showing horizon slice using relative Ip. Existence of feeder channel belts, isolated channels, lobes and channel-lobe complexes are visible in the slice.

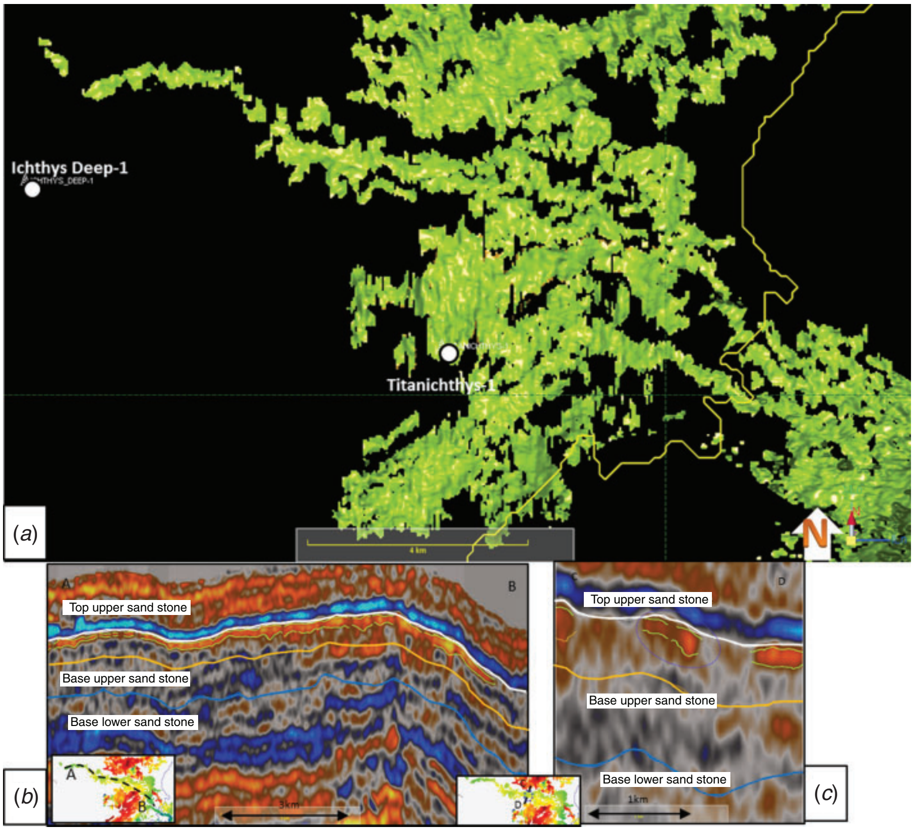

Fig. 14. (*a*) Interpreted Top of identified geobody. (*b*) Section of relative Ip along the channel like feature. Top and base of the feature overlayed on the section. (*c*) Section of relative Ip across the channel like feature. Top and base of the feature overlayed on the section.

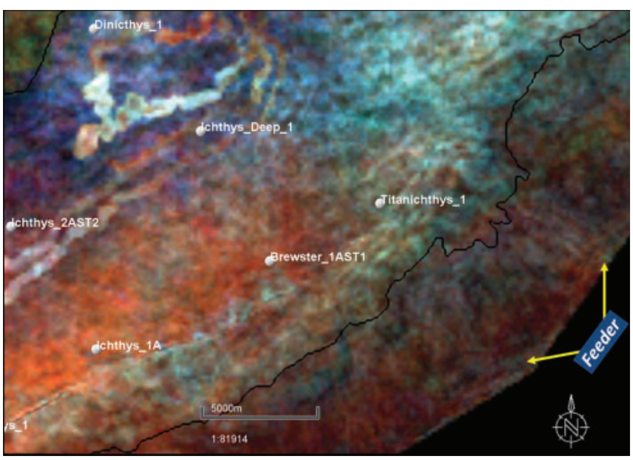

Fig. 15. RGB blending of three different frequency volumes (12, 24 and 32 Hz).

example, selecting the opacity curve is subjective and can impact the spatial limits of the geomorphological features.

Geological interpretation of extracted geomorphological features

Seismic visualisation techniques reveal multiple depositional elements of the Brewster Member. It suggests that the formation consists of multiple channel-lobe complexes consistent with the well based sedimentological interpretation.

Figure 16 shows the opacity display of the 3D seismic volume around the eastern area of the field, overlaid with the top Brewster Member depth structure map. The voxel based geo body detection and opacity display allows us to delineate an amalgamated channel-lobe system. Multiple source points could be interpreted to lie on the east and south-east of the Ichthys Field. The general depositional trend is east to west or south-east to north-west. Large lobate, sheet lobe systems can be interpreted around Titanichthys-1 and Dinichthys-1. A prominent channel system can be interpreted north of Titanichthys-1 and Ichthys Deep-1. This channel system turns into a sheet lobe system to the east of Dinichthys-1. Some distributary channels can be interpreted within this sheet lobe system. Other elongated lobe systems can also be interpreted to the north of the prominent channel system.

No apparent morphological features are identified around the Ichthys Deep-1 with current cut-off values. This suggests a lower Ip contrast between the overburden and the reservoir section compared with elsewhere. Well based sedimentological interpretation suggests that thick off-axis packages are stacked at the Ichthys Deep-1 location. Off-axis deposits mainly consist of slightly finer-grained sandstone compared with the channel complex or sheet lobe complex. This might have led to more severe diagenesis in this area. As a result, off-axis deposits tend to have lower porosity compared with the other two depositional environments. Despite the fact that a thin sheet lobe complex package (~10 m) has been interpreted at Ichthys Deep-1, it is not possible to define the top and base of the package using 3D seismic data due to lack of sufficient vertical resolution.

Figure 16 shows an example of a possible depositional history for the eastern area (focused on the Upper Sandstone interval). In this scenario, the sheet lobe complex package observed at Dinichthys-1 is interpreted to comprise the distal facies of the channel complex package observed at Titanichthys-1. Furthermore, the sheet lobe complex package overlying the channel complex package at Titanichthys-1 is interpreted to be a result of back stepping of the depositional system. Ichthys Deep-1 is basically located in the off-axis area of the channel system.

In the eastern area, the distribution of prominent channel systems has a similar trend to the structural trend of the Brewster Member (east-south-east to west-north-west; Fig. 16). It might be a possible interpretation that the Brewster Member deposition was guided by a paleo-structure in this area. This interpretation does not contradict with the thick off-axis package amalgamated at Ichthys Deep-1.

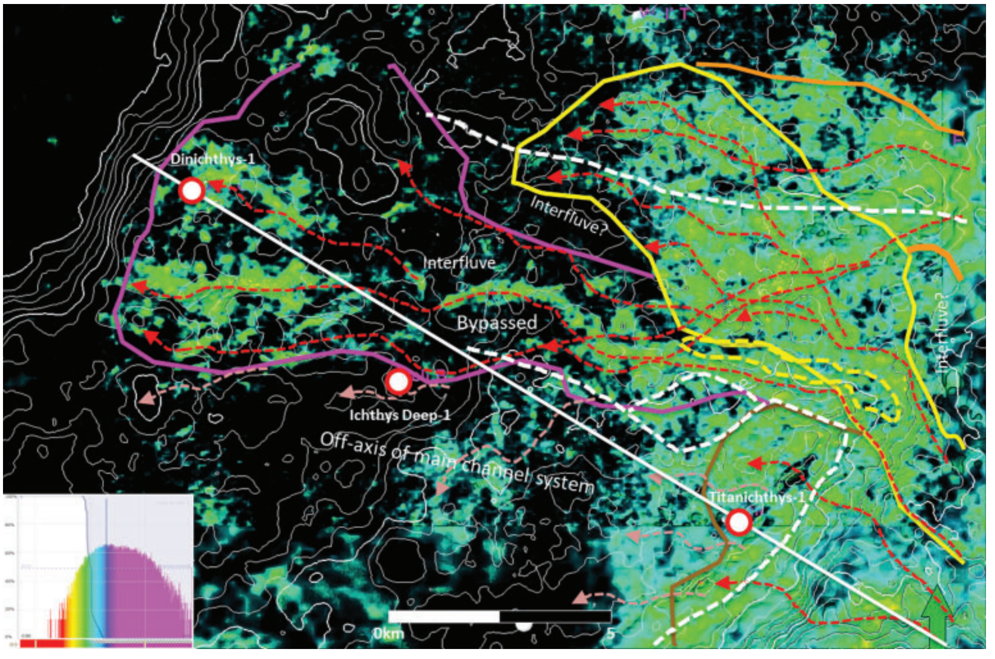

Fig. 16. Geomorphological features identified by applying opacity on relative volume. White straight line is the section line of Fig. 17.

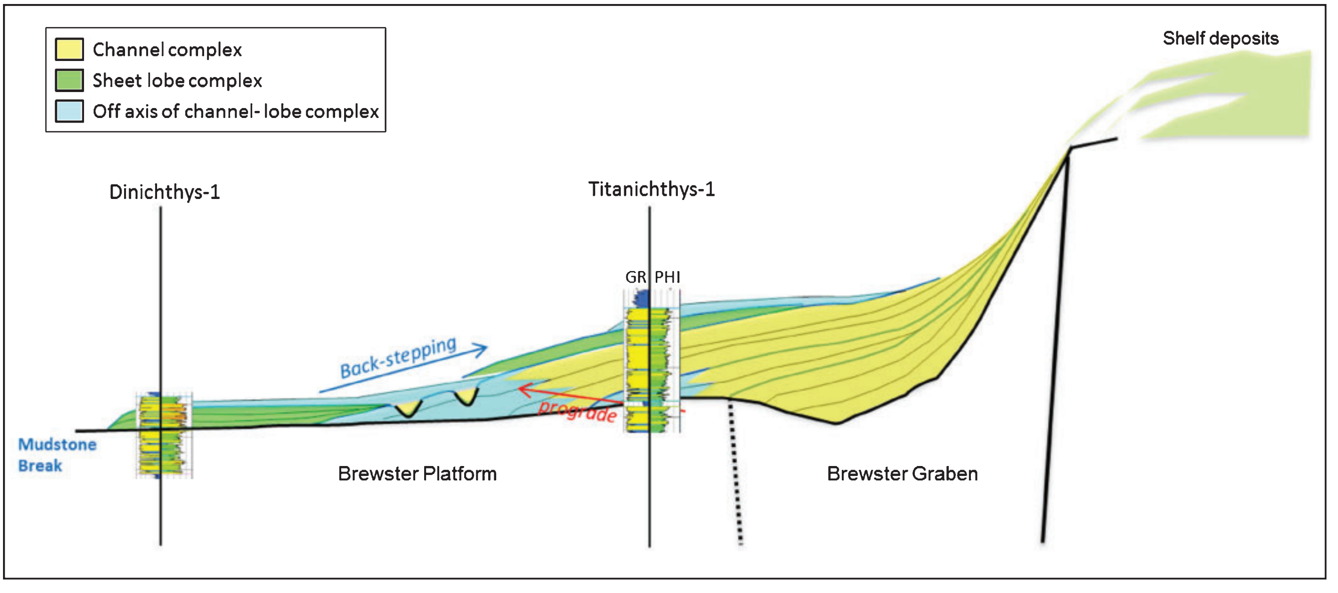

Fig. 17. Example of possible sandstone correlation scenario.

Conclusions

(1) Various seismic visualisation techniques were applied to delineate the spatial distribution of sandstone architecture of the Brewster Member.
(2) The Brewster Member consists of multiple channel-lobe complexes. Feeder channels could be interpreted in the east to south-east of the Ichthys Field and the general depositional trend is east to west or south-east to north-west. Since the geomorphological features identified through this work and the Brewster structure map shows a similar spatial trend, it might be a possible interpretation that the deposition of the Brewster Member is guided by the paleo-structure of the area. This interpretation does not contradict with the thick off-axis package amalgamated at Ichthys Deep-1.

Conflict of interest

None.

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References

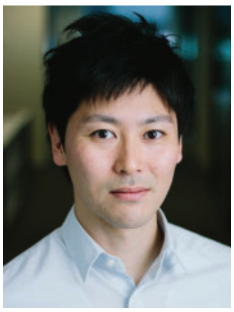
Ban, S., and Pitt, G. (2006). The Ichthys giant gas condensate field. In 'American Association of Petroleum Geologists 2006 International Conference and Exhibition, Perth, Australia, 5–8 November 2006' Available at: http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2006/intl_perth/abstracts/ndx_ban.pdf.html [Verified 20 March 2017].

Chopra, S., and Marfurt, K. J. (2011). Volume co-rendering of seismic attributes – a great aid to seismic interpretation. SEG San Antonio Annual Meeting 2011, 1150–1154. Available at: https://www.onepetro.org/conference-paper/SEG-2011-1150 [Verified 20 march 2017].

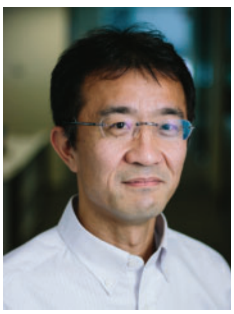
Nakanishi, T., Ando, T., Beales, V., Seth, K., Otten, F., and Matsui, H. (2014). The Ichthys Field: challenges of geological modelling for the field development. *The APPEA Journal* **54**, 31–44.

The authors

Syed Iftikhar Arsalan received his MSc Tech degree in Applied Geophysics in 2004 from the Indian School of Mines (Dhanbad), India. He has 12 years' experience as a development geophysicist in different oil companies in India and Australia. He has worked expensively in the multi-Tcf plio-pleistocene deep water offshore gas development project on the east coast of India. In addition, his experience also includes explorations of onshore rift in Cambay basin, India and offshore basins like the Browse Basin on the North West Shelf, Australia. He has been working as a senior development geophysicist for INPEX, Perth since 2012. He is currently involved in the Ichthys field development project in INPEX. His core area of work and research interest is inversion study to facilitate reservoir characterisation and predict reservoir behaviour. He is an active member of SEG, ASEG and EAGE.



Keiji Ichizawa received his BSc in 2008 from Niigata University, Japan and MSc in 2010 from Kyoto University, Japan. He joined INPEX in 2010 and worked on projects including the Bight Basin, Papuan Basin and Onshore Japan. In 2013, he joined INPEX Perth as a development geologist for the Ichthys Project to conduct geoscience studies including reservoir rock characterisation. He is a member of EAGE and the Japanese Association for Petroleum Technology.



Keiichi Furuya received his BSc in 1993 and MSc in 1995 from Chiba University, Japan. He joined Japan Oil Development Co. Ltd in 1995 and thereafter worked on various 3D OBC seismic data acquisition, processing and interpretation projects for oil fields in offshore Abu Dhabi. Since 2012 he has been assigned as the manager of development geophysics at INPEX Perth for the Ichthys project. He is a member of SEG, EAGE, SEG Japan and Japan Association for Petroleum Technology.