Application of Relative Acoustic Impedance Inversion to Constrain Extent of E Sand Reservoir on Kadanwari Field

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ABSTRACT

Both AVO modelling and acoustic impedance inversion studies have been undertaken recently on seismic data over the Kadanwari Gas Field in an attempt to constrain the extent of the E Sand reservoir, particularly in the K-10/K-11 block. The AVO and acoustic impedance inversion studies were performed in-house using Hampson-Russell software. The AVO Modelling work concluded that there is no significant differential moveout between a gas sand and a brine saturated sand, so inversion is the preferred method to delimit the extent of E Sand reservoir. Model based acoustic impedance inversion and relative acoustic impedance inversion methods were tested on seismic line TJ89-503. Model based inversion was shown to be strongly influenced by the background model and this leads to artefacts in the inversion which are not representative of the geology. Relative acoustic impedance (RAI) inversion, which does not rely on an initial model, is therefore the preferred method.

The steps required to produce a RAI seismic section are firstly to convert to zero phase. This was achieved by extracting a wavelet using the K-04 well and applying zero phase (wavelet) deconvolution. After wavelet deconvolution, the RAI section is obtained by trace integration of the deconvolved seismic section.

Forward modelling of the reservoir response concluded that gas saturation has some influence on seismic reflection amplitude of the E sand interval. However, the E sand in the Kadanwari Field is generally below tuning thickness and it is thickness changes which primarily control amplitude changes for the E Sand reservoir. The southerly well K-04 is located on E sand at approximately tuning thickness and thus has strong reflectivity. This reflectivity is found to diminish with thinning E sand reservoir towards the north of the field.

RAI inversion sections of the seismic data together with the forward modelling work have provided additional confidence in delineating E sand reservoir extent over the Kadanwari Field. The RAI sections have improved the understanding of the presence and distribution of the E Sand reservoir, and were used to assist in selecting the location for the K-12 well.

In the K-10/K-11 block, an interpretation of bright RAI downdip from the existing and proposed wells suggests that there may be some thickening of E Sand reservoir to the east, perhaps up to tuning thickness. This observation has implications for reservoir management.

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INTRODUCTION

Kadanwari Gas Field is stratigraphically trapped at Top E Sand of Lower Goru Formation (Lower Cretaceous) in at least one direction particularly in the K-10/K-11 area. Any structure relief associated with the stratigraphic trap is small. LASMO Oil Pakistan Limited and Partners proposed to conduct AVO modelling and acoustic impedance inversion studies to delimit the extent of E sand reservoir over the Kadanwari Field (Fig. 1).

The E sand reservoir is lost in the northern part of the field, due to a loss of thickness (erosion) of the E4 and E5 intervals, along with a reduction in quality. An improved understanding of the presence and distribution of reservoir quality E sand is important in mitigating the risk on the proposed K-12 well, a step out well designed to add additional production to the eastern block produced by the K-10 and K-11 wells.

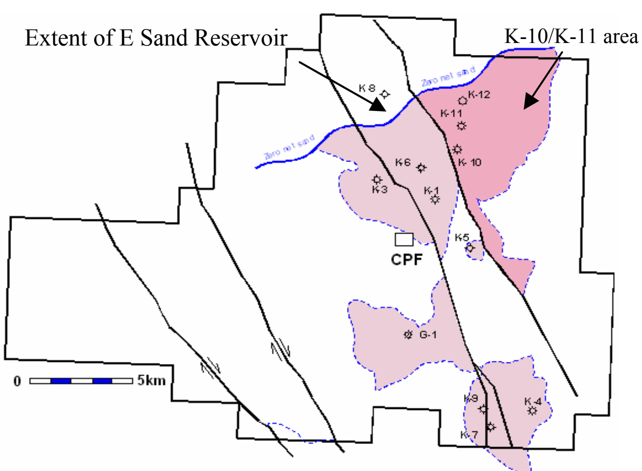

Fig.1: Location Map of Kadanwari Gas Field.

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KADANWARI AVO MODELLING

AVO modelling study was conducted using the Hampson Russell Software. The synthetic offset dependent models were produced in order to test the response similar to the reservoir conditions of the Kadanwari data, particularly in the K-10/K-11. Various simple models on the Kadanwari well data were built to test the validity of AVO effect in the study area.

It is very essential to distinguish the AVO effect of a gas sand from a brine sand before we jump to any spurious interpretation of hydrocarbon presence; particularly it is difficult to detect on the noisy 2-D land seismic data. It is the basis of the Kadanwari AVO modelling work to test the offset response on the two cases, gas-filled sand and the brine-filled sand. The thickness of the "E Sand Porosity" in the K-10/K-11 area is generally less than 10 m, the purpose of the AVO modelling work is also to test the AVO response as a function of sand thickness. The top gas or brine sand was picked on the black peak of the synthetic AVO traces for all the 4 model cases;

1- Thin Sand (10m) Case, 2- K-04 Gas/brine Case (10m of gas sand over 10m brine sand), 3- K-04 Case (20m sand), 4- Single Interface Case (infinite thickness). The cross plots of AVO curves are the amplitude extracted on the black peak of the synthetic modelled traces at the top gas sand (blue curve) and at top brine sand (red curve) versus the offset (Fig. 2).

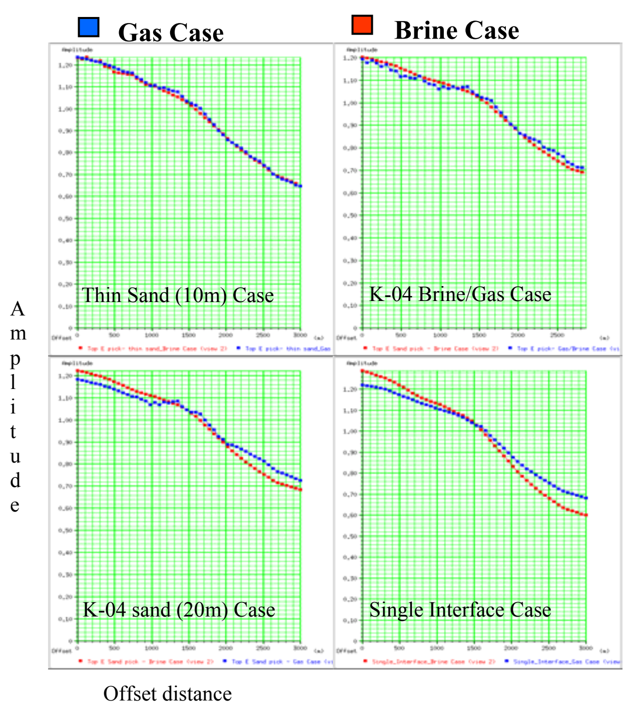


Fig. 2: AVO cross plots of 4 modeled cases.

For the"Thin sand (10m) Case", there is no difference in the AVO curves of gas sand and brine sand. There is very minor separation of AVO curves of top gas sand and top brine picks of the "K-04 Gas/Brine Case" and "20m Sand Case". In the "Single Interface Case", which is not effected by tuning thickness or interference of the top or the base of the sand, the separation of the AVO curves is slightly more. Nevertheless, it is not good enough to distinguish the AVO effect of the gas sand from the brine sand.

The cross plots of $\sin^2\theta$ VS reflection coefficient were generated with association of Rob Simm of Rock Physics Associates (Fig. 3), the AVO response of this additional modelling confirms that there is not any noticeable AVO gradient by replacing the gas sand with brine sand.

The outcome of the AVO Modelling work is summarised in the following bullet points;

- In an infinitely thick sand, there is a small differential AVO observed. This is not considered to be detectable with the currently available Kadanwari data set.
- No AVO differential between the fluid types of gas or brine observed in the thin sand case.
- The additional AVO work in association with Rob Simm (Fig. 3) confirms observation already made concerning little or no differential moveout between gas sand and brine sand cases.
- The AVO modelling results on the Hampson-Russell AVO curves are correct in slope but are not scaled by the zero offset reflection coefficients. This is correctly shown in Rob Simm's work (Fig. 3).

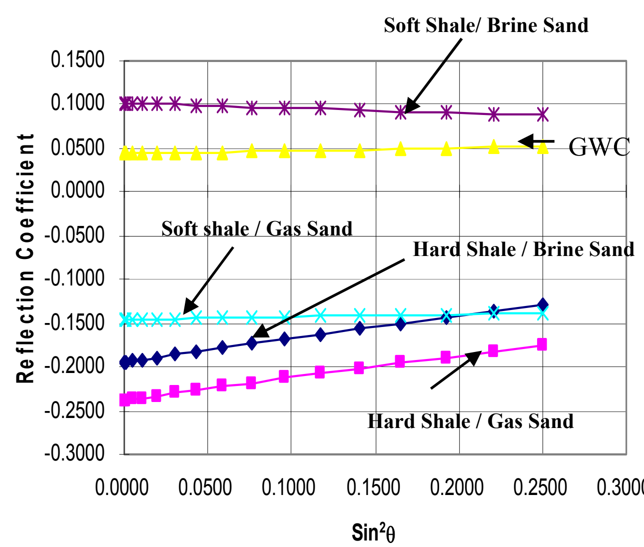


Fig.3: The cross plots of $\sin^2\theta$ VS reflection coefficient, with association of Rock Physics Associates.

KADANWARI ACOUSTIC IMPEDANCE INVERSION

The acoustic impedance inversion studies were conducted (in-house) using Hampson-Russell Software over the Main Kadanwari field. The main steps of Kadanwari inversion studies are Initial well ties, zero phasing and acoustic impedance inversion of the Echo processed Kadanwari seismic data. The results of this work were used to assist in selecting the location for the K-12 well.

Initial Well ties

Initial well ties were considered by comparing seismic line TJJ89-503 and wells K-4, K-1, K-6 and K-8, representing the change in the E sand reservoir across the field from south to north.

After log editing and splicing the well logs for all wells were loaded to Hampson-Russell Geoview and STRATA for analysis. The best quality log suite was that for K4, and this well also had a long section of both density and sonic log data, making it particularly useful in the wavelet estimation procedure.

The general character match between the seismic and synthetic seismogram for the main sedimentary packages is straightforward to establish. An amplitude spectrum was estimated for all traces in the line TJ89-503 over the time window 1.3 – 2.3 s (Fig. 4). Note that the spectrum is rounded in character, not broadband as would be preferred, with a peak amplitude at 35 Hz. The spectrum is very similar to that of a Ricker wavelet. It should be noted that a spectrum extracted in this manner does not represent a supposed wavelet to convolve with the synthetic seismogram, but rather it represents the spectrum of both the seismic signal and the geology.

As a starting point, a 35 Hz Ricker wavelet was used for convolving with the well reflectivity series' and comparing

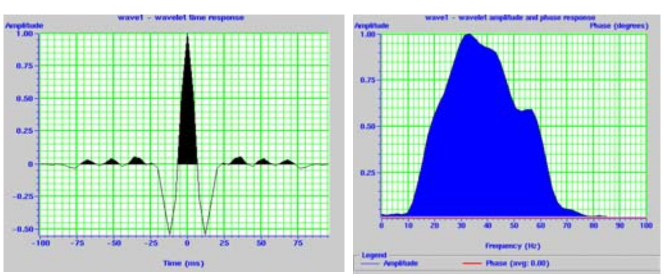


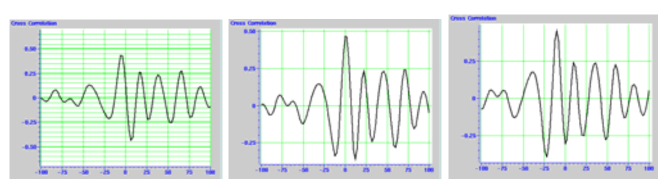
Fig. 4: Time response and amplitude spectrum extracted under a zero phase assumption from 1.3 – 2.3 s window of line TJ89-503.

synthetic seismograms with the seismic data. Use was made of cross-correlation between the synthetic seismogram and the seismic traces. Fig. 5 shows the cross-correlation for well K-4, for three different phase assumptions for a Ricker wavelet (zero phase with no rotation, zero phase with $+90^{o}$ rotation, minimum phase). Considering the first cross-correlation (Fig. 5a), two maxima can be seen, of equal magnitude and opposite polarity. The peak magnitude is about 0.44. After rotating the phase by $+90^{0}$ (Fig. 5b) a single maximum is observed, with a magnitude of approximately +0.47 and the negative maxima are symmetrically distributed either side, with peak values of around –0.35. This is compelling evidence of complexity in the phase spectrum. The minimum phase example (Fig. 5c) shows that, while this results in only a slightly asymmetric cross-correlation, the phase spectrum is probably closer to linear than to minimum phase.

The synthetic seismogram character match for the E sand interval at K-4 for each of the three simple wavelet assumptions is shown in Fig. 6. The traces are not shifted to tie, the lags being those observed on the cross-correlation plots of Fig. 5. Note the top E sand seismic pick has been made in the past on the black peak. Given the simple model (b), this pick corresponds to somewhere within the E sand, with the top of the E sand approximately associated with the zero crossing above this black peak. However, the black peak is a suitable consistent pick to make on the seismic and there is no reason to select an alternative pick criterion.

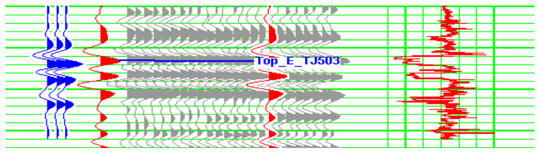
Based on the results of the simple wavelet assumptions, the four wells were tied to line TJ89-503 using a zero phase Ricker wavelet of 35 Hz with a $+90^{o}$ constant phase rotation. Various strategies were then attempted to apply wavelet estimation using full extraction using the wells (Fig. 6). A window of 1.3 – 2.3 s was used and the wavelets obtained from the four wells compared. It was decided that a combination of K-4 and K-8 might be reasonable, although the best extraction was clearly obtained using K-4 only.

Using the extracted wavelet shown in Fig. 6, model based inversion was performed on line TJ89-503.

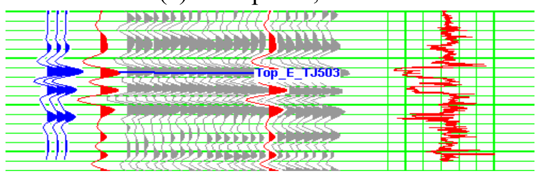


(a) (b) (c)

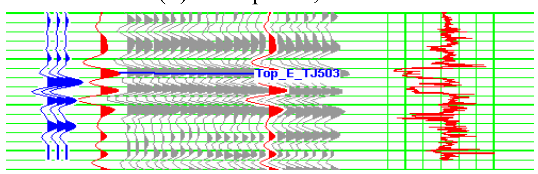
Fig. 5: Cross-correlation between synthetic seismogram at K-4 and seismic line TJ88-503, under three different phase assumptions.



(a) Zero phase, 0^o



(b) Zero phase, $+90^o$



(c) Minimum phase, 0^o

Fig. 6: Well tie for K-4 under three different phase assumptions

The standard blocky inversion available in the Hampson-Russell STRATA package was used. This type of inversion is known as model-based and requires an initial guess starting acoustic impedance profile or background model for each trace. The necessary background model was constructed in STRATA using the four wells K-4, K-1, K-6 and K-8, along seismic line TJ89-503.

The result of model based inversion is shown on line TJ89-503 in Fig. 7. The success of the constrained inversion in resolving the thin E sand interval is clearly evident, just above the original seismic horizon interpretation.

Looking further north on the line section between wells K-1 and K-6 (Fig. 7), the E sand can still be seen clearly close to the interpretation pick. Note however the rapid change of acoustic impedance between the two wells. In particular, it would appear that there is a significant lateral change in impedance midway between K-1 and K-6.

A similar lateral change can also be observed between K-6 and K-8. As before the model based inversion suggests lateral change in impedance between the two wells, with a loss of the bright E sand low impedance seeming to be closer to the northern K-8 than to the K-6 well.
Unfortunately acoustic impedance estimates obtained from model based inversion are strongly influenced by the background model. Whilst using a background model as an initial guess allows the inversion to be constrained to distinguish between impedance extremes and amplitudes related to tuning. This benefit has to be balanced against the fact that the model will exert undue influence on the impedance traces between model control points (the wells). The background model used to constrain the inversion shown in Fig. 8. The model comprises the well acoustic impedance traces which have been interpolated laterally, using the picked seismic horizon as a guide. In particular, the model between wells K-1 and K-6 (Fig. 8) shows a rapid change of impedance midway between the two wells, caused by this interpolation. This change in the model is clearly carried through to the resulting impedance estimate of Fig. 7 as an artefact.

A comparable effect is observed in the northern part of the line, between the wells K-6 and K-8. Referring to the display of the background model for this interval (Fig. 8), an apparent thinning and pinch out can be seen present, its location closer to K-8 than K-6. Comparison with Fig. 7 shows the apparent reservoir change at E sand is most likely associated with this artefact from the background model and is not a geological change.

Relative Acoustic Impedance Inversion – (RAI)

Given the problems of model based inversion described, it was decided to invert the Kadanwari data using an alternative method which does not require a background model and thus avoids the possibility of model artefacts being present in the output. The method chosen is relative acoustic impedance inversion (RAI). It is obtained by firstly ensuring that the seismic section is close to zero phase. This is achieved by using an extracted wavelet and applying zero phase (wavelet) deconvolution.

A RAI section is subsequently derived by integrating the traces on the zero phase seismic section. Integration is mathematically equivalent to acoustic impedance inversion, but the lack of model constraint makes it unable to distinguish bright amplitude as originating from large impedance change or tuning. All bright amplitudes will therefore result in apparently large impedance changes in the result, irrespective of their origin, which could also be tuning related.

For the Kadanwari Field work, a wavelet extracted using just the K-4 well was used for wavelet deconvolution (zero phasing) of the seismic section. Wavelet deconvolution, as applied here, has two actions. Firstly it corrects the phase spectrum to zero phase. In addition, the amplitude spectrum is whitened, which may improve the resolving power of the seismic.

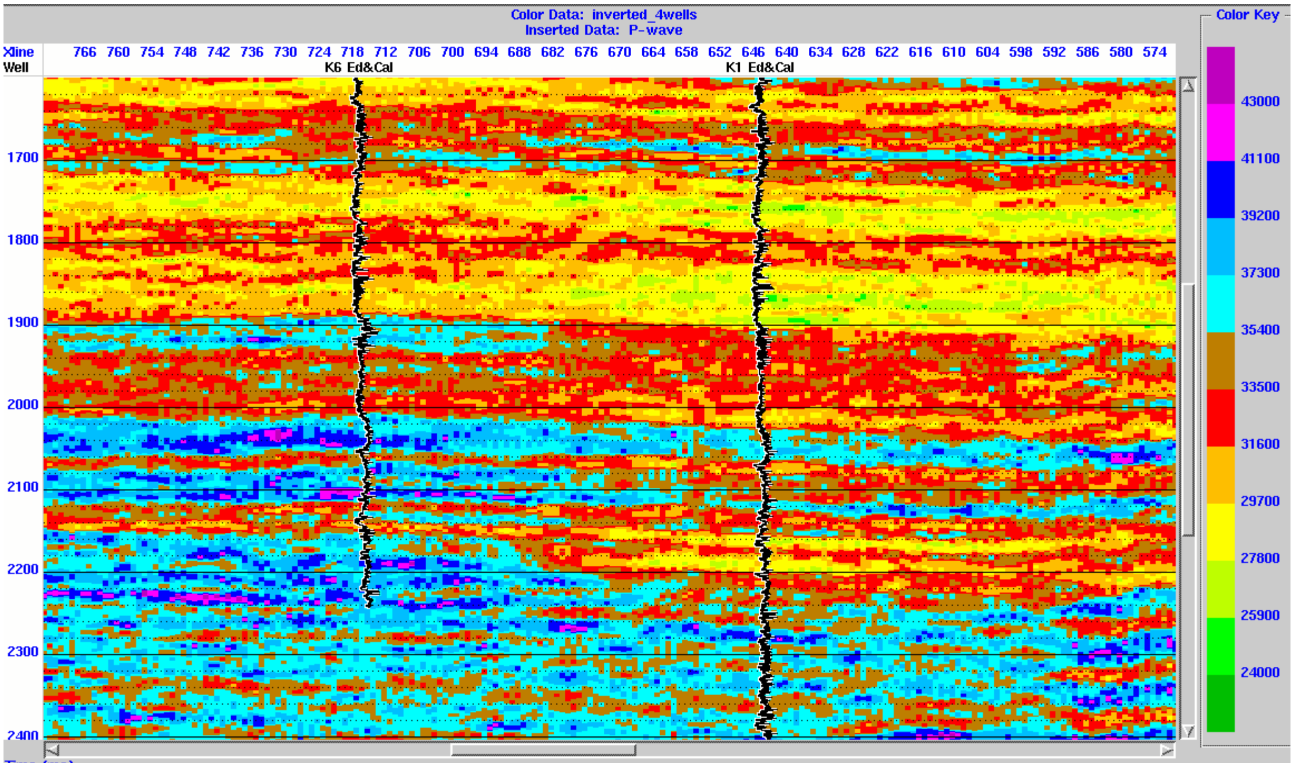


Fig. 7: Model based inversion on line TJ89-503 between k-4 and K-6.

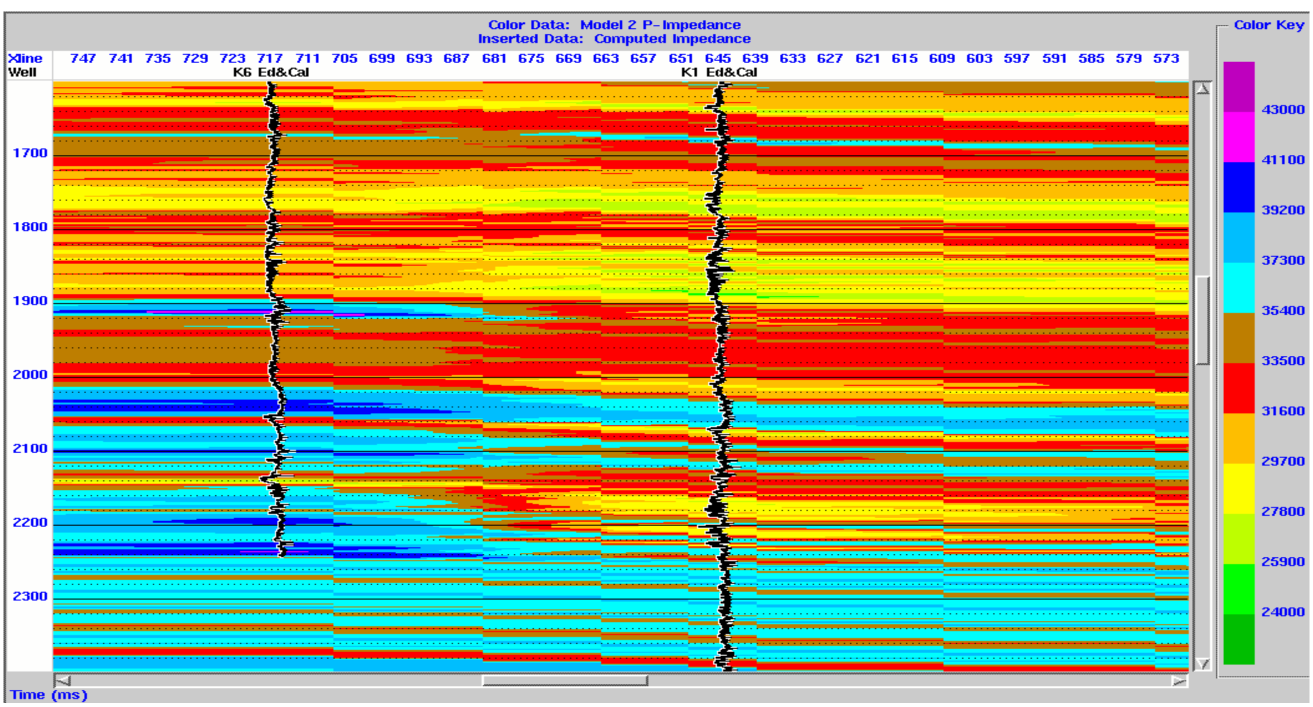


Figure-08: Background model used for inversion of line TJ89-503 between K-4 and K-6

After wavelet deconvolution the seismic traces were integrated to obtain the RAI section, shown in Fig. 9. Around well K-4, the E sand is clearly identifiable as the predominantly green colour just above the picked seismic horizon. In addition the G sand, some 100 ms shallower, is clearly visible as a yellow, occasionally green, interval. The D and C sands are the yellow colours some 20 and 50 ms below the E sand.

Again moving north, the section from K-6 to K-8 is shown in Fig. 10. The E sand, close to the horizon pick can be tracked away north from K-6, and is clearly present between the two wells as far as trace (denoted xline) 850. Beyond this point, it is difficult to confidently pick the E sand as an impedance low (negative). The reservoir quality E Sand interval is absent at well K-8.

This part of line TJ89-503 also shows evidence of trace to trace amplitude problems. The sudden termination of bright reflectors around trace 830 can be seen to extend across a large time interval in the seismic and is almost certainly not reflecting a geological effect at this level. large time interval in the seismic and is almost certainly not reflecting a geological effect at this level.

This emphasises the importance of proper amplitude compensation, including normalisation of horizon amplitudes to shallower events, before attempting to interpret amplitude in terms of subsurface geological or saturation effects. Previous efforts at amplitude extraction on the workstation have been made using seismic data to which a short gate AGC (amplitude gain compensation) has been applied. This is highly undesirable and it is strongly advised that only data without AGC be used for the purpose of studying amplitudes.

On the basis of the results shown for test line TJ89-503, the RAI procedure was extended to other lines throughout the proposed K-12 area. The parallel line TJ89-505 was inverted, as well as strike lines TJ89-508, TJ91-808, TJ89-510, TJ91-810, TJ89-512, TJ91-812 and TJ89-514. These lines encompass an area defined by K-8 to the north and K-1 to the south.

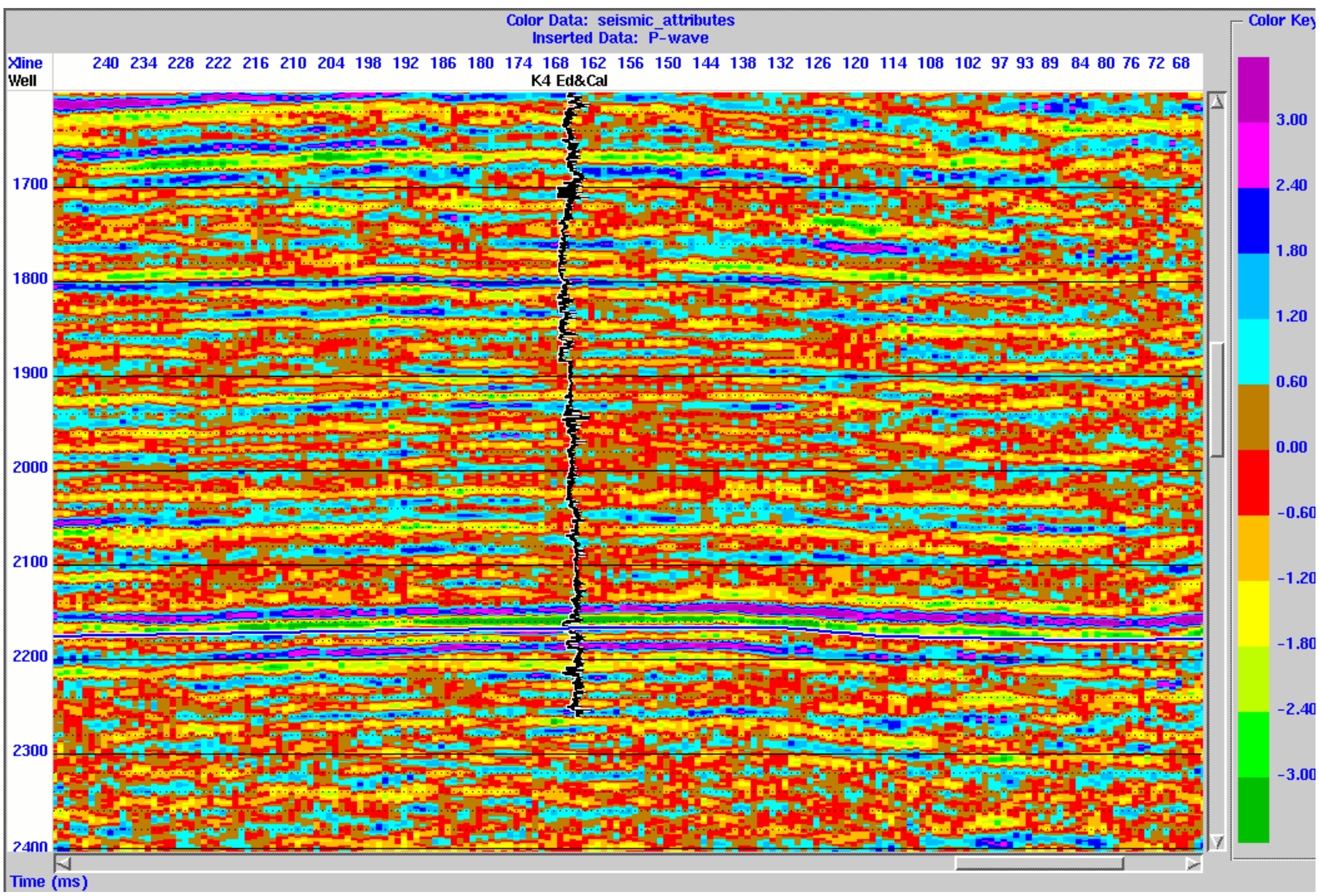


Fig. 9: Relative Acoustic Inversion for line TJ89-503 .

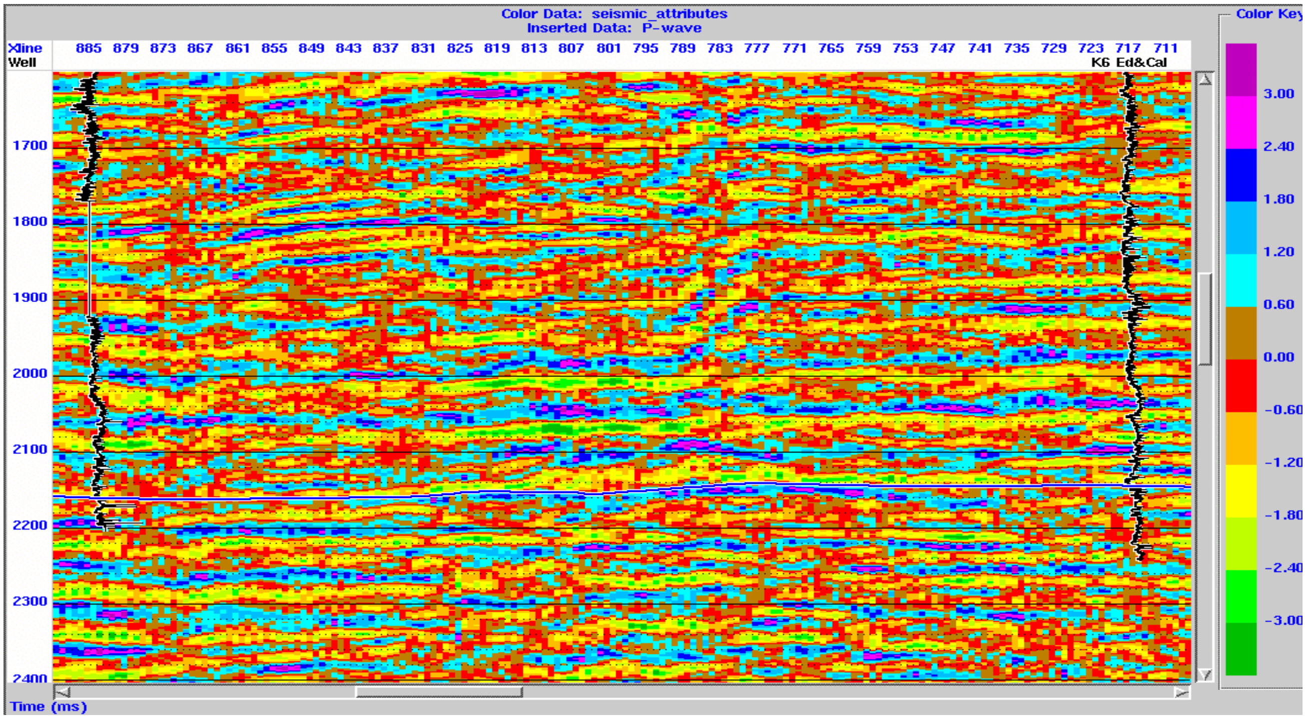


Fig. 10: Relative Acoustic Impedance for line TJ89-503 between K-6 and K-8

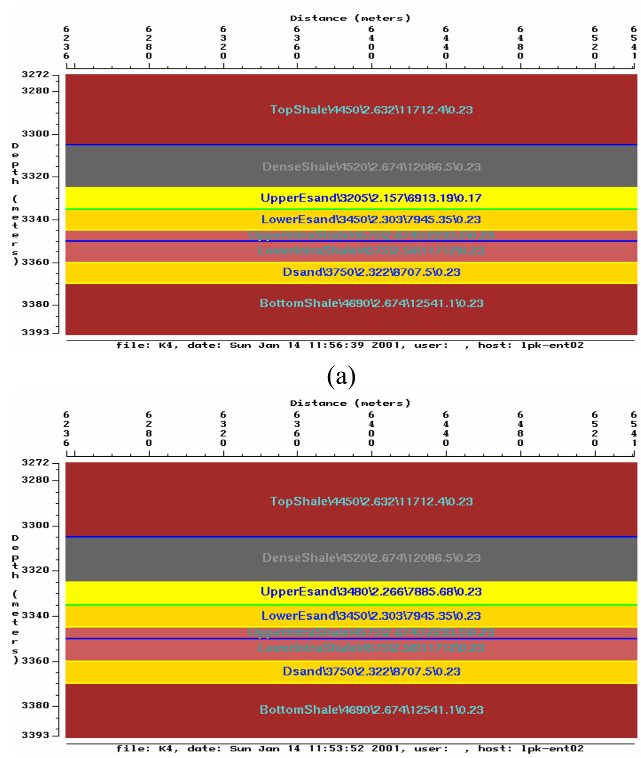
FORWARD SEISMIC MODELLING

In order to better understand the seismic expression of the E sand some simple seismic modelling has been performed using GX2, a ray tracing package from GX Technology. The sensitivity of the seismic response to the presence of gas saturation has been modelled, along with the sensitivity to changes in thickness.

Fluid Saturation Effects

A simple flat, conformable layered earth model has been constructed comprising the E sand and D sand intervals and the surrounding shales based on the K-4 well. Two models are shown in Fig. 11, the first (a) has E sand rock properties based on a gas saturated upper interval overlying a brine saturated lower interval. The second model (b) is fully brine saturated.

The zero offset reflectivity sequence for the two models have been convolved with a 35 Hz Ricker wavelet with a linear phase spectrum and a +90 degree constant phase rotation. As has already been described above, this wavelet is a good working approximation to the wavelet extracted at the K-4 location. The resulting convolutions are shown in Fig. 12, the gas saturated case shown in (a) and the brine saturated case in (b).



(a)

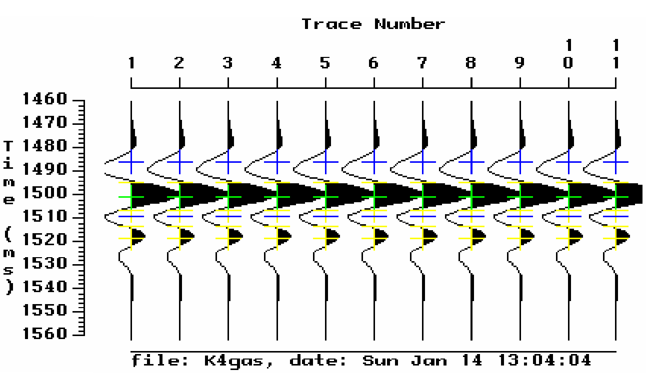
(b)

Fig. 11: Acoustic models of E and D Sand intervals and shales at well K-4.

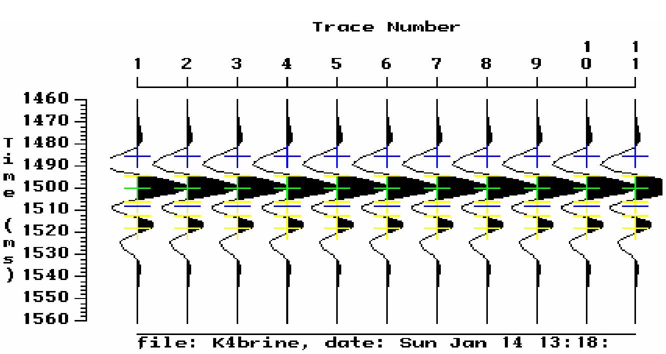
Comparing the two results in Fig. 12, it is clear that the amplitude responses of gas and brine saturated Kadanwari E sand are similar, although the gas response is brighter. The peak amplitude difference is about 25%, which is consistent with the difference in the magnitude of the individual reflection coefficients. The significance of this difference should be considered after consideration of the thickness effects described in the next section.

Thickness Effects

The modelling has been extended to include a lateral thickness variation in the E sand interval, as shown in Fig. 13. The E sand thins from 80 m at left of the model to 0 m at the pinch out, located at an offset of 9000 m in the model. The D sand thins from 20 m to 5 m over the same distance. The models are intended to represent a full thickness range of sands too much greater than tuning thickness. In reality, good quality reservoir sand over the main Kadanwari field area thins from about 20 m at K-4 to about 10 m in the K-10 area over a distance of 14 km. Both sands are modelled as brine saturated and the rock properties chosen accordingly.



(a) Gas saturated



(b) Brine saturated

Fig. 12: Synthetic seismic response of E and D sand intervals and shales at well K-4.

The zero offset reflectivity sequence calculated for the model has been convolved with a 35 Hz Ricker wavelet with a linear phase spectrum which has been rotated by +90 degree. The resulting synthetic seismogram is shown is Fig. 13 (b). The effect of tuning can be clearly seen, its onset occurring at a thickness of around 40 m with peak tuning at around 20 m.

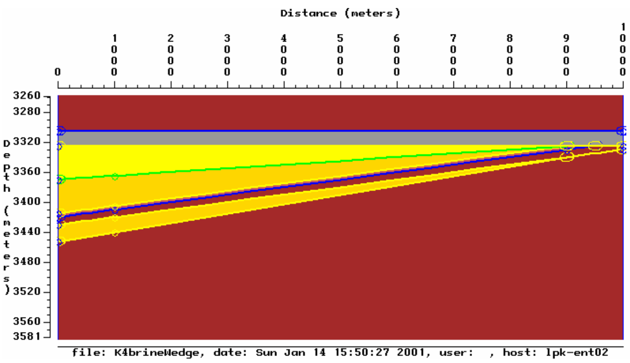
The synthetic seismogram of Fig. 13 (b) has been subjected to the same processing sequence as that used to obtain the RAI sections, described above in the section on acoustic impedance inversion. The synthetic has been rotated –90 degrees and then the traces integrated. The result, windowed around the modelled E sand pinch out, is displayed in Fig. 14 with the same colour table as that of the RAI sections.

The synthetic RAI response of Fig. 14 shows clearly the brightening of amplitude (converted here to relative acoustic impedance). A comparison of Fig. 14 to Fig. 9 shows that the modelled tuning effect is consistent with the actual seismic response at K-4. The thickness is also consistent, the E sand being 20 m thick at K-4, coincident with maximum tuning in the model.

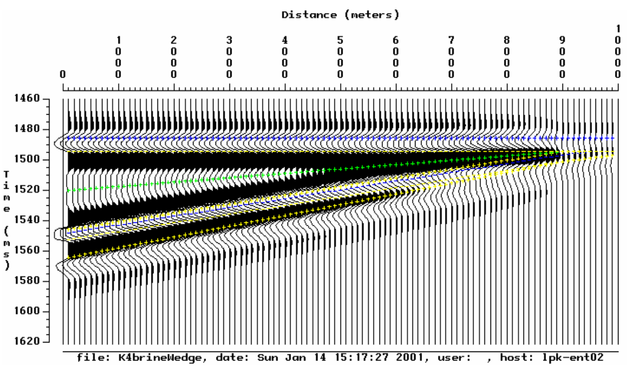
Fig. 15 shows a graph of two way time and amplitude for the E sand, based on picking the black peak (as in the regional seismic interpretation) from the synthetic seismogram of Fig. 13(b) and also picking directly the bright negative impedance values from the RAI result of Fig. 14. Two (well known) effects are clearly observed in the seismic response.

Firstly, the two way time which is nominally at 1500 ms (arbitrary, not related to the actual E sand two way time) initially increases (apparently deepens) with the onset of tuning before then rising to earlier times at and below tuning. There is a systematic, almost linear, shift in the time pick from +2 to –4 ms associated with the thickness change from 30 m to 5 m.

Secondly, there is the expected strong amplitude variation with tuning thickness, which is non-linear. The peak amplitude occurs at maximum tuning, which in the case of Kadanwari E sands is at a thickness of around 20 m. Both an increase and decrease of thickness would result in a reduction in amplitude. It would appear that the K-4 well is situated at maximum tuning and, as this well is also maximum thickness for the field, it should therefore be possible to interpret thickness changes with amplitude changes with little ambiguity over the Kadanwari field. The magnitude of amplitude change caused by tuning is around 80% at peak tuning as compared to the amplitude without tuning. This amplitude change corresponds to a thickness change of around 20 m about the tuning thickness.



(a)



(b)

Fig. 13: (a) Acoustic model of thinning wedges of E & D sand intervals and shales, (b) Synthetic seismic response of wedge model

The effect of gas is to modify the amplitudes by up to 25%. Therefore it is concluded that tuning effects and not gas saturation effects are the first order effect in determining seismic amplitude over the main Kadanwari field area.

RAI ANALYSIS

Based on an analysis of the RAI seismic lines and the observations from forward modelling, it was concluded that strong (negative) RAI values with good continuity could be taken as evidence for the presence of E sand. Well K-12 was proposed on a continuous RAI response on line TJ89-510 nominally at SP282. Due account of other factors such as structural elevation (prognosed to be 3275 m) and reservoir engineering considerations was also made in reaching this recommendation. One of the concerns in locating the K-12 well was the possible loss of good quality E sand moving north due to erosion, such as occurs between K-6 and K-8.

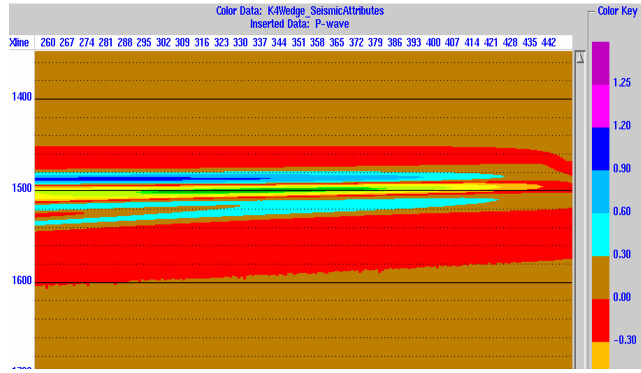


Fig. 14: RAI of synthetic seismic response of wedge model of E and D sand intervals and shales

Based on the RAI results, the previously defined erosion limit was moved closer to K-8. This change is also supported by simple volume calculations based on production from K-6. In addition, based on inspection of RAI results on seismic data to the north and east of K-11, the extent of E Sand reservoir limit (Fig. 1) was rotated slightly northwards than previously thought, with the expectation that the proposed K-12 well should encounter similar sands to K-11.

Down dip of K-11 and the proposed K-12 location the RAI shows a strong, continuous E sand reflector. This may be evidence of thicker, good quality E sand to the east of these wells, probably in the water leg. This may be of significance to reservoir engineering as it may have implications for aquifer behaviour.

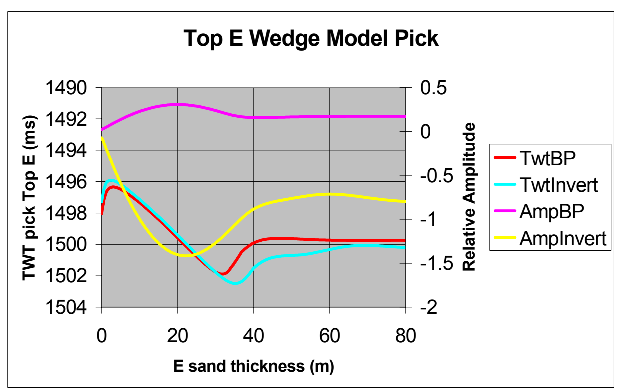


Fig. 15: Travel time and amplitude of synthetic seismic response and relative acoustic impedance of synthetic seismic response as a function of thickness .

CONCLUSIONS

Zero phase conversion of the Echo processed data over the main Kadanwari field has been successful via a good quality well tie at K-4.

Model based acoustic impedance inversion on Kadanwari data carries the risk of introducing artefacts which are not representative of the geology.

Relative acoustic impedance (RAI) inversion usefully converts seismic amplitudes to acoustic impedance and has been applied to Kadanwari data set.

Over the main Kadanwari field, forward modelling indicates that the seismic response (amplitude or RAI) is most sensitive to thickness and that fluid type (presence of gas) is a low order effect on amplitude.