Orthogonal wide azimuth surveys: acquisition and imaging

Simon Baldock,[1*] Cristina Reta-Tang,[1] Brad Beck,[1] Wei Gao,[1] Jun Cai[1,2] and Steve Hightower[1]

Abstract

Wide azimuth seismic surveying is firmly established as a key element in subsalt exploration and production in the Gulf of Mexico. The challenge now facing the industry is to further improve subsalt images in areas with existing wide azimuth coverage. Orthogonal wide azimuth acquisition, acquiring a second wide azimuth dataset over existing wide azimuth data, is a technique that provides close to full azimuth coverage while utilizing existing wide azimuth data. A case study performed in the Gulf of Mexico demonstrates that the increased source and receiver illumination created by orthogonal wide azimuth surveys significantly improves imaging results and increases the effectiveness of the tomography and salt interpretation steps.

Introduction

When the first results from marine wide azimuth (WAZ) acquisition and processing became available in 2006, it was immediately apparent that WAZ data could provide significantly improved images of complex salt and subsalt structures compared to those derived from narrow azimuth 3D acquisition. Since that time, WAZ streamer acquisition has become firmly established as an indispensable technique for exploration and development objectives in places where conventional narrow azimuth acquisition fails to provide sufficient subsurface illumination. In fact, WAZ surveying has been so successful that in the space of only a few years there is now almost blanket coverage of WAZ data in the Gulf of Mexico.

This success story, however, has created challenges of its own. Although the uplift in image quality provided by WAZ data can often be dramatic, there still remain areas where WAZ does not provide as clear an image of the sub-surface as might be desired, especially in the case of steep dips below a complex salt body (Ting and Zhou, 2010) or underneath salt overhangs. Therefore, one of the challenges facing the industry is that of finding ways to improve subsalt images in regions that already have WAZ coverage. One way to do this is to apply new technology to existing datasets. An impressive range of techniques has been successfully developed and applied to WAZ data. True-azimuth, surface-related multiple elimination has been successful in removing complex subsalt multiples, particularly those from the base of salt. New imaging algorithms and workflows, including tilted transverse isotropy, multi-azimuth tomography, subsalt velocity scanning, and reverse time migration (RTM) have all helped the industry to both image data better and build more accurate velocity models.

As impressive as these results often are, the techniques themselves do nothing to address the limitations that exist in the data due to the constraints imposed by the acquisition geometry. In a WAZ survey the crossline direction is typically sampled much less well than the inline direction. Crossline source sampling is often reduced by a factor of four compared to the inline; and crossline receiver sampling by up to an order of magnitude. Furthermore, for operational and logistical reasons, the maximum crossline offset of a WAZ towed-streamer survey is typically between 4 km and 4.5 km. This limitation in azimuth coverage at offsets beyond 4 km falls far short of so-called full azimuth coverage: a full 360° of azimuth coverage at all offsets up to the maximum offset (usually ~8–9 km) and consequently can lead to insufficient illumination of complex subsurface structures, especially in the crossline direction.

In order to overcome this offset and azimuth limitation, a range of methodologies for full azimuth acquisition have been developed. These include ocean bottom node acquisition (Ross and Beaudoin, 2006) and coil shooting (Moldoveanu and Kapoor, 2009). Howard (2007) proposed 'rich azimuth' acquisition in which three WAZ surveys with 60° separation are combined together. Each of these approaches possesses strengths and weaknesses. For example, ocean bottom node acquisition offers a regular sampling of sources and receivers, but the practical considerations of node deployment mean that it is cost-effective only for appraisal or development scale surveys (Beaudoin, 2010).

An attractive solution to the challenge of full azimuth acquisition is orthogonal WAZ acquisition. With this technique, two WAZ surveys, co-located in space, are acquired with identical (or nearly identical) acquisition geometries.

[1] *TGS, 2500 Citywest Boulevard, Suite 2000, Houston, Texas 77042, USA.*
[2] *Present address: BHP Billiton, 1360 Post Oak Boulevard, Suite 150, Houston, Texas 77056, USA.*
[*] *Corresponding author, E-Mail: simon.baldock@tgs.com*

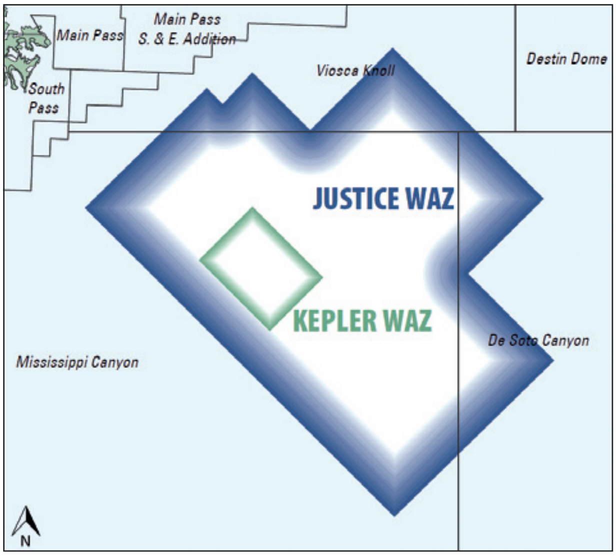

Figure 1 The Kepler and Justice wide azimuth surveys, located in the Mississippi Canyon area of the Gulf of Mexico.

One of the two surveys is acquired with an orientation at 90° with respect to the other. It is an approach that comes close to achieving the goal of full azimuth acquisition. It also allows large volumes of data to be acquired relatively quickly. Furthermore, by acquiring a second survey over the top of an existing survey, orthogonal WAZ acquisition has the advantage of being able to utilize existing WAZ data by combining it with new data into one unified processing sequence.

In this article we present the results of the acquisition and processing of an orthogonal WAZ survey in the Gulf of Mexico. Beginning with a review of the orthogonal acquisition and the initial fast track results, we then go on to discuss in more detail the processing flow that was used for the combined processing of the two surveys.

Background

In 2010 TGS acquired the Kepler and Justice orthogonal WAZ surveys offshore Louisiana, in the Mississippi Canyon protraction area of the Gulf of Mexico (Figure 1). One large overhanging salt body dominates the survey area. Two other salt bodies to the south and northeast are separated from this main salt body by sedimentary basins. The salt body to the northwest creates illumination issues for sediments in the mini-basin. The overhang on the main salt body does the same for the sediments truncating against its southwestern flank. Figure 2 summarizes the main imaging challenges of this project.

The Kepler WAZ survey covers an area of approximately 420 km^2. Acquisition began in January 2010 and was completed in around three weeks. Acquisition was undertaken in the NE–SW orientation. As soon as the Kepler acquisition was completed, acquisition began on the much larger Justice WAZ survey, acquired in the NW–SE orientation. The end result of the two acquisition phases was approximately 420 km^2 covered by two WAZ surveys acquired in orthogonal directions. Apart from the survey orientation, the acquisition geometry for Kepler and Justice was identical. Each survey was acquired using four source vessels with 1200 m separation. The outer two vessels each towed 10 cables (Figure 3). The inline shot spacing was 150 m and the roll between swaths was 1200 m. Interleaved anti-parallel acquisition swaths gave a final shot spacing of 150 m in the inline direction and 600 m in the crossline direction. In 1999, a narrow azimuth survey had been acquired over the area covered by the two WAZ surveys, in the N–S orientation. It was used to provide an initial depth model, but was not otherwise incorporated into the processing sequence.

The resulting shot distribution of the two WAZ surveys consists of two superimposed shot grids of 150 m × 600 m (Figure 4). The Justice shot grid is indicated by the small red dots and the Kepler shot grid by the small blue dots. Each dot represents a one-way supershot consisting of eight superimposed shot locations. At the intersection of the two grids a 600 m × 600 m grid of two-way supershots is formed. The larger blue and red circles in Figure 4 represent these two-way supershot locations.

The effect of combining the two surveys can also be examined in the common midpoint (CMP) domain. Figure 5a

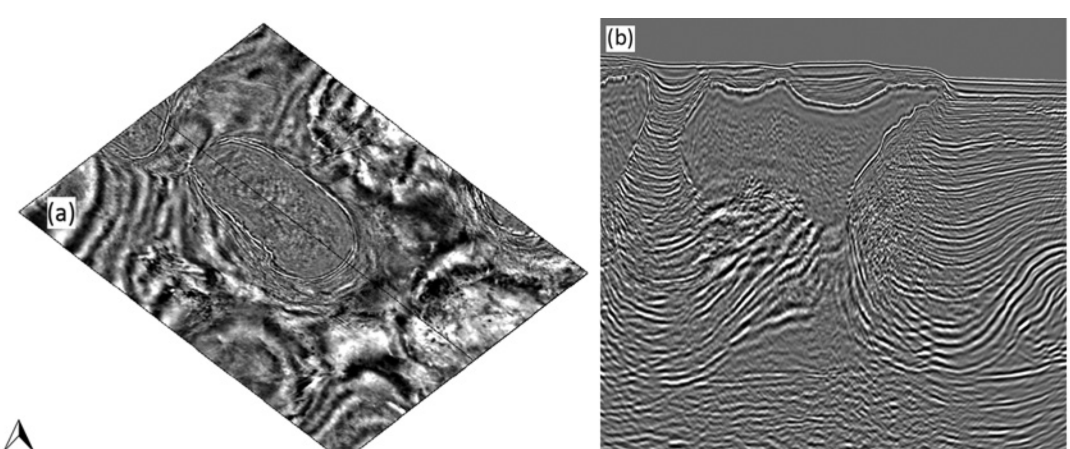

Figure 2 (a) Shallow depth slice and (b) inline section through the survey area illustrating the imaging challenges of the project.

shows the offset and azimuth distribution at a CMP for the Justice survey in the form of a rose diagram. The limitation in azimuth coverage with offset for crossline offsets greater than 4.5 km can be seen clearly. The offset and azimuth distribution for the Kepler survey (Figure 5b) is the same as for the Justice survey except that it is rotated through 90°. The combined offset and azimuth distribution for the two surveys (Figure 5c) demonstrates that close to full azimuth acquisition is achieved with this method.

The combination of two WAZ surveys results in improved penetration of energy into the subsurface, especially in the regions underneath and between the complex salt bodies. This improvement comes about in two ways. Firstly, there is increased illumination due to the additional acquisition along the orthogonal direction. Secondly, the fold is doubled, which increases the signal-to-noise ratio. The uplift from this enhanced illumination is nicely illustrated by the output of the initial fast track migration.

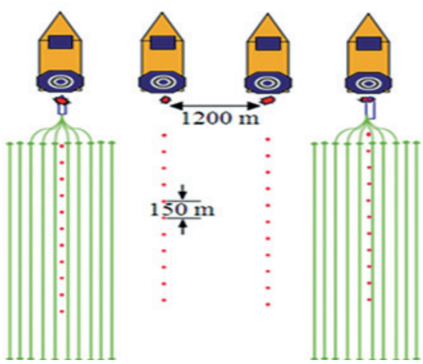

Figure 3 *Acquisition set up for the Kepler and Justice surveys.*

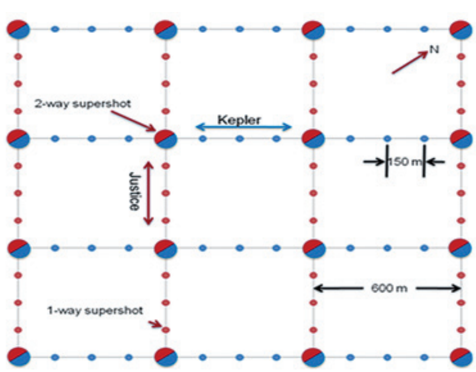

Figure 4 *Supershot distribution for the Justice and Kepler surveys.*

Fast track migration

After acquisition was completed, the first seismic images to be available came from a fast track migration performed with minimal pre-processing, using a depth model built from the 1999 narrow azimuth data. Figure 6 shows an inline from this fast track migration volume. The model included anisotropy in the form of vertical transverse isotropy (VTI) and the images were produced using RTM. In this example, the data are oriented along the inline direction of the Justice survey (NW–SE). Figure 6a shows the results from the Justice survey and Figure 6b shows the results from the Kepler survey.

Close inspection of these images reveals some areas of good imaging and others of poor imaging. The Justice survey successfully images sediments dipping up against the salt flank where indicated by the green arrows (Figure 6a). Deeper events and the area between the two salt bodies are poorly imaged; the red markers highlight these events. The areas that are poorly represented in the Justice image are much better imaged by the Kepler dataset, and are indicated by the green highlights in Figure 6b, which is a crossline from the Kepler volume. Because the same velocity model was used to migrate each volume, it is reasonable to conclude that the imaging differences seen on the two volumes primarily come from differences in illumination between the two orthogonal acquisition directions.

Figure 7 shows a comparison between the crossline direction of the Justice survey and the inline direction of the Kepler survey. A strong amplitude anomaly against the flank of the salt in the Kepler survey (green arrows in Figure 7b) is absent from the Justice image (red arrows in Figure 7b). This comparison again shows how additional data can better illuminate the areas beneath and against salt.

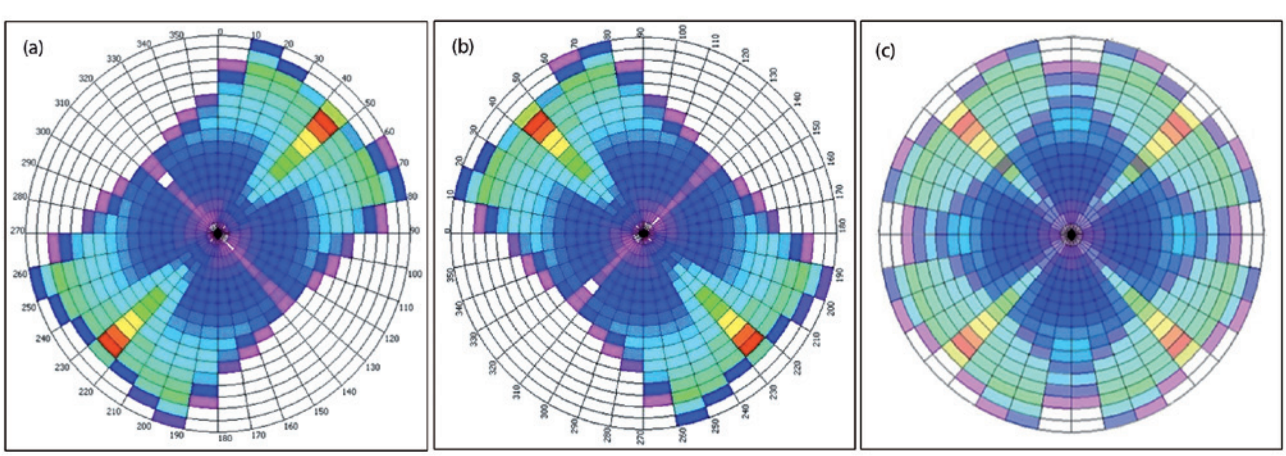

Figure 5 *A series of rose diagrams showing the azimuth and offset distribution for (a) the Kepler survey, (b) the Justice survey, and (c) the Justice and Kepler surveys combined.*

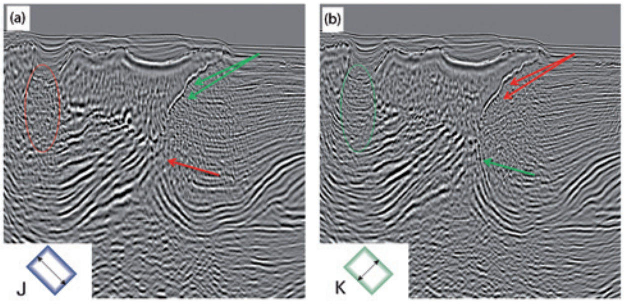

Figure 6 *Inline direction: VTI RTM of (a) Justice survey and (b) Kepler survey. Green and red markers indicate areas of good and poor imaging, respectively. The acquisition direction is shown in the inset box in the bottom left corner of each image.*

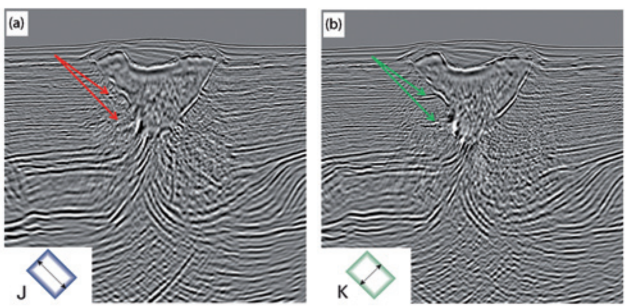

Figure 7 *Crossline direction: VTI RTM of (a) Justice survey and (b) Kepler survey. Green and red markers indicate areas of good and poor imaging, respectively.*

Workflow

The initial fast track results showed the advantages to be gained from acquiring orthogonal WAZ data. However, in order to understand the full value of orthogonal WAZ data, we needed to know whether the additional azimuth and offset information helps us to build a more accurate velocity model. To investigate this question, we processed the data through three distinct workflows (Figure 8). In flow A the Kepler survey was run through tomography, salt model building, and final migration on its own with no input from the Justice data. Likewise, in flow C the Justice dataset was processed on its own with no input from the Kepler survey. In flow B data from the Kepler and Justice surveys were combined together for the tomography, model building, and final migration. Here we focus on the results from flows A and B.

Before moving on to a consideration of the methodology and results from the tomography, we summarize the pre-processing that was applied to both datasets. Each dataset was processed through a flow consisting of deterministic zero-phasing and debubble, noise attenuation, water column static corrections, and true-azimuth 3D surface-related multiple elimination using a TGS proprietary technique known as TAME. Although the processing sequences were similar for both datasets, no attempt was made to combine them for any of these steps.

Tomography

A benefit of WAZ acquisition is the opportunity to use the additional azimuth coverage to better resolve vertical

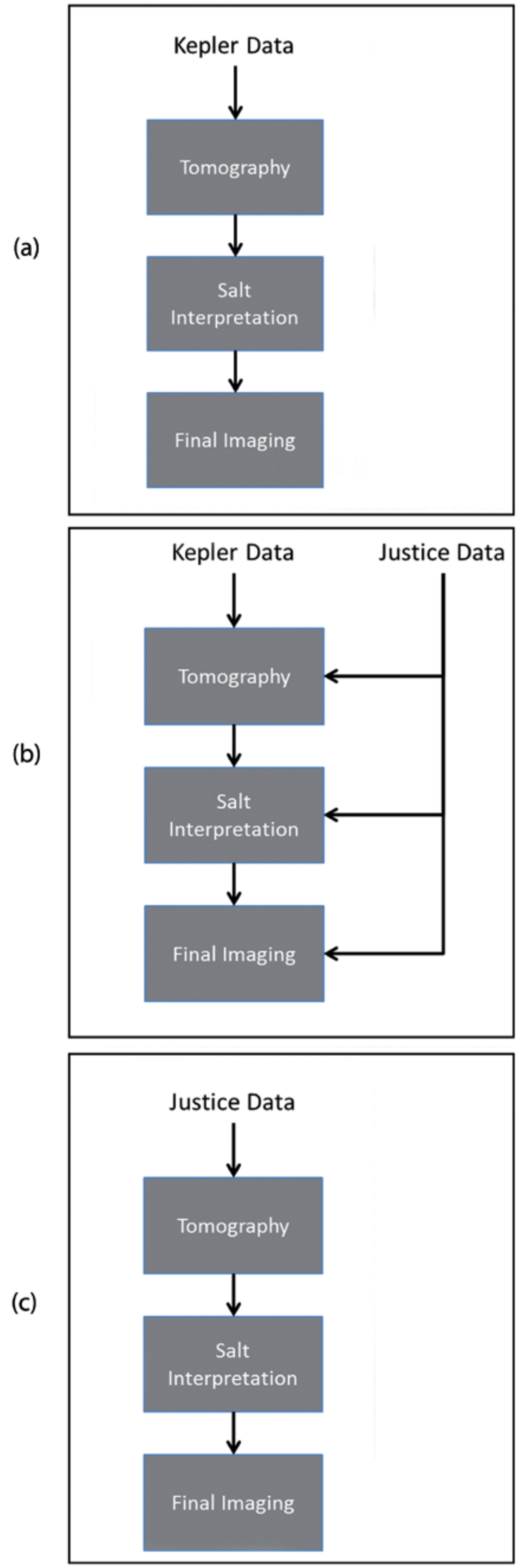

Figure 8 *Flow diagrams illustrating the three flows through which the data were processed.*

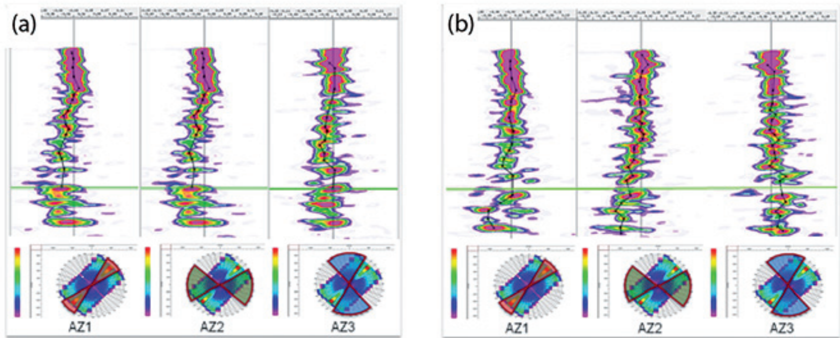

Figure 9 *Semblance displays from Kepler three azimuth-sector tomography (a) prior to tomography, and (b) after one pass of azimuth-sector tomography.*

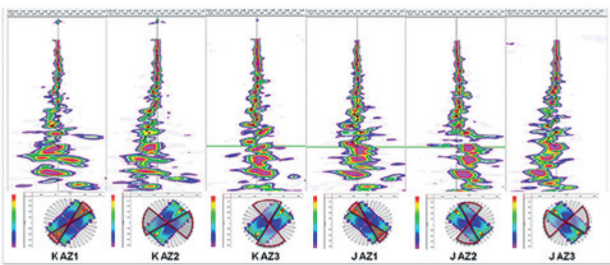

Figure 10 *Kepler plus Justice six-azimuth tomography: semblance display after tomography from the same location as Figure 9.*

and, more importantly, lateral heterogeneity in the velocity structure. For the Kepler and Justice surveys this was done by partitioning the CMP binned data into azimuth sectors and incorporating the unique information (residual moveout from image gathers) from each sector into a single joint tomographic update. For standard WAZ acquisition, the CMP gathers are typically partitioned into three azimuth sectors. The azimuth sectors were selected so that each sector provided good fold coverage, but over a narrow azimuth range to ensure accuracy in the ray tracing step. In order to maintain consistent fold between sectors, these sectors were of unequal size. Residual curvature picking on image gathers and ray tracing using dip information from a combined stack image were performed for each azimuth sector separately. The individual raypath volumes were then combined to create a single raypath volume that was input to a joint inversion. With the introduction of an orthogonal WAZ dataset, the number of azimuth sectors is increased from three to six, enabling valuable far-offset data in the crossline direction of the inline data set to be utilized and allowing a smaller range for each azimuth sector.

Residual moveout semblances computed prior to tomography from image gathers for each of the three azimuth sectors of the Kepler survey are shown in Figure 9a. After one iteration of three-azimuth-sector tomography, semblances at the same location show convergence to smaller moveout (zero moveout is at centre of each panel) for all three azimuths (Figure 9b). Figure 10 shows semblance panels for the six azimuth sectors from the Kepler and Justice surveys.

Figure 11a shows a depth slice through the velocity model after one pass of three-azimuth tomography using the Kepler data only, and Figure 11b shows the same depth slice after one pass of six-azimuth tomography incorporating both Kepler and Justice data in a single inversion. A careful comparison of the two velocity slices reveals lineations (or roughness) in the result from Kepler data only (Figure 11a, white circles), which are most likely related to reduced data coverage and poorer illumination compared to the result from the Kepler and Justice data combined (Figure 11b). This leads us to conclude that a smoother velocity model can be generated by the incorporation additional offset and azimuth information.

Salt interpretation and comparison of results

Salt geometry definition was the second major step where data from both surveys were combined together. The Kepler and Justice surveys were migrated separately and salt interpretation performed simultaneously on the Kepler and Justice data. The introduction of the Justice data meant that areas of ambiguity in the Kepler image could be resolved; in this way a single unified salt model incorporating information from both surveys was built. At this point it is possible to compare the results from the flows described earlier. Figure 12a shows the final RTM model built using the Kepler data only, corresponding to flow A. Figure 12b shows the final RTM model built using both the Kepler and Justice datasets, and corresponds to flow B. The base salt and the connection with the deeper salt have been dramatically revised through the use of both datasets. The results of RTM on the Kepler data using these models are shown in Figure 12c and d, respectively, with the areas of improvement indicated by white arrows. Figure 12e shows the result of migrating the Justice data with the combined Kepler and Justice velocity model.

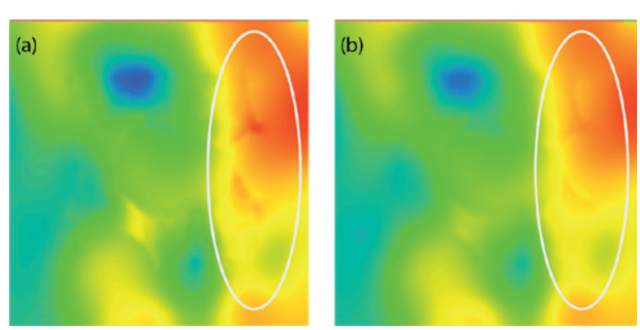

Figure 11 *Depth slice at 3600 m after tomography using (a) Kepler survey only, and (b) Kepler plus Justice. The white oval indicates the location of lineations in the Kepler survey attenuated after the six-azimuth tomography.*

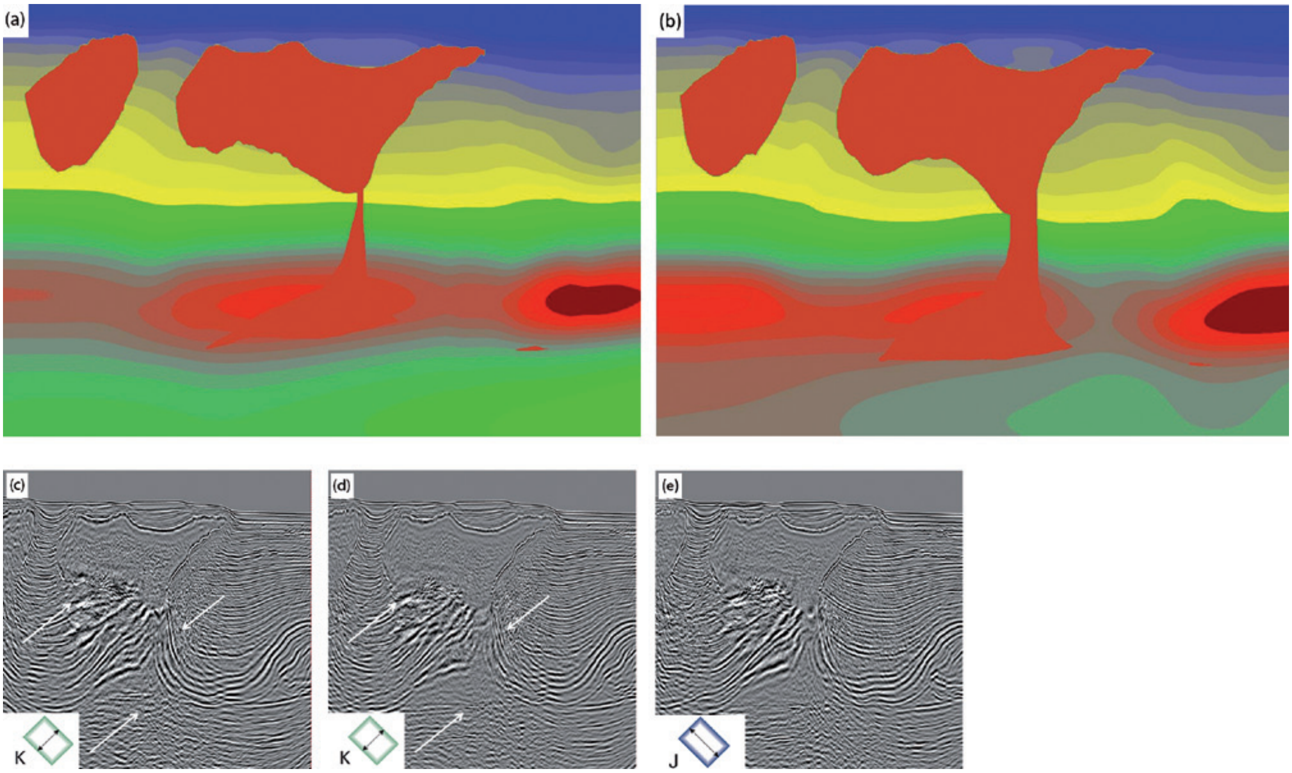

Figure 12 Results of the test workflows. Final velocity models built on (a) Kepler data only (flow A), and (b) Kepler and Justice data (flow C). RTM migration of (c) Kepler data using the Kepler model only (flow A), (d) Kepler data using the combined Kepler and Justice model (flow C), and (e) Justice data using the combined Kepler and Justice model.

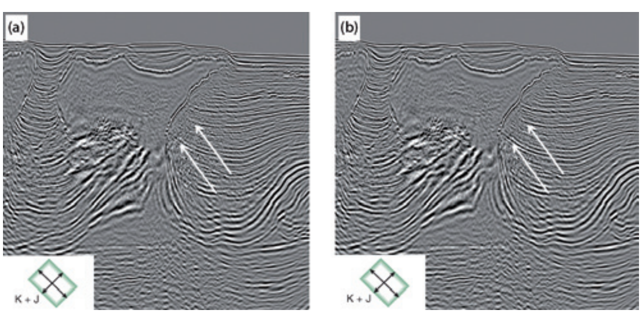

Figure 13 Final VTI RTM migrations showing (a) straight summation of Kepler and Justice, and (b) summation using semblance-weighted sum. The white arrows indicate a location where the weighted summation has preserved the optimal image from both volumes.

Combination of volumes

The final major step in the sequence is to combine the processed datasets together into a single image. We have already seen that orthogonal shooting directions illuminate different portions of the subsurface. When we come to the combination of the individual volumes these illumination differences present a problem. A straightforward sum of the two volumes leads to an averaging of the image, downgrading the result in the region of the stronger image. To overcome this problem the combination was performed using a semblance-weighted sum. The Kepler and Justice volumes were migrated separately. After migration a 3D coherency value was calculated for each volume separately; each volume was then weighted according to its coherency and then summed together. The results of this process are shown in Figure 13. In areas where there are large illumination differences between the Kepler and Justice volumes, the semblance-weighted sum (Figure 13b) allows the illumination benefits of both surveys to be successfully combined into a single volume. These areas are indicated by white arrows. The migrations before summation are shown in Figure 12d and e. Finally, Figure 14 shows the full sequence of crossline images before and after summation.

Conclusions

The Kepler and Justice orthogonal WAZ surveys demonstrate that considerable uplift in the imaging of complex salt structures and the surrounding sediments can be achieved through the utilization of orthogonal WAZ datasets. In particular we have shown that by introducing an independent orthogonal shooting direction to an existing WAZ dataset, the imaging of steeply dipping salt flanks, salt overhangs and subsalt sediments is improved. Furthermore, the orthogonal survey provided significant additional information which allowed the salt model to be refined compared to that derived using a single WAZ survey.

The initial fast track results indicated that, even for WAZ data, survey orientation is a key factor in the quality of the final migrated image. These indications have been confirmed in the full depth imaging flow. A comprehensive test of three distinct processing flows confirms that the tomography and

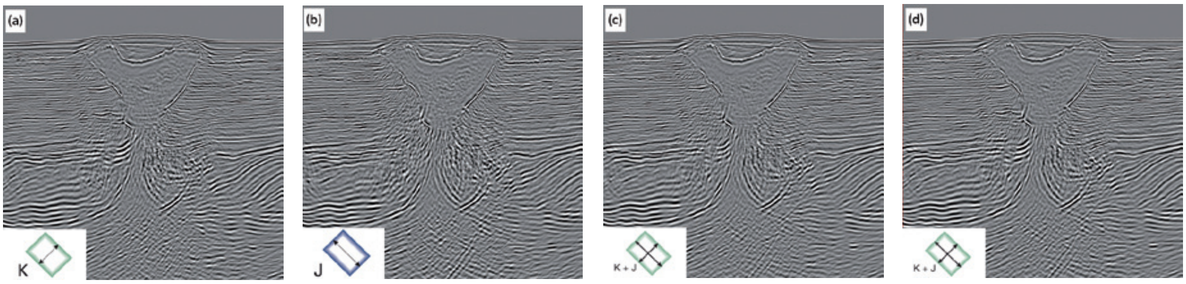

Figure 14 *Final sequence of results for a crossline. (a) Final RTM o Kepler data, (b) Final RTM on Justice data, (c) straight summation of Kepler and Justice, (d) semblance-weighted sum of Kepler and Justice. All migrations used the model from Kepler and Justice data combined.*

salt body interpretation steps both benefited from the introduction of additional azimuth and offset information. After migration, the data from each acquisition direction were successfully combined into a single volume using semblance-weighted summation.

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