3D demultiple techniques dramatically improve the imaging of a giant Kashagan reservoir in the ultra-shallow North Caspian Sea

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Introduction

The Kashagan oil field is located in the Southern Pre-Caspian Basin (4-4.5 km depth), comprising a Paleozoic carbonate platform. The reservoir is overlain by mobilized, diapiric Triassic evaporites and a mixture of clastic and carbonate layers (Jurassic to Cretaceous). Large faults have significant displacement from the evaporites to the near surface. The basin is draped by recent thin sedimentation and is capped by approximately 3-10 m of water. The geophysical challenges include significant shallow-water multiples, inter-bed multiples and strong lateral and vertical velocity contrasts. In addition, the available field-wide 3D survey (OBC data acquired in 2001-2002) is quite sparse by modern seismic standards and lacks long offsets and true full azimuthal coverage. This article will focus on the technology and workflows implemented to overcome the challenges associated with the sparse seismic geometries, specifically the lack of near-offset coverage needed for near-surface imaging and multiple prediction with traditional methods.

Geological setting

This giant carbonate field is an isolated Devonian-Carboniferous carbonate build-up in the southern part of the Pre-Caspian Basin at a depth of 4-4.5 km and is one of several similar-aged build-ups in the Primorsk Archipelago (Figure 1). The build-up is divided into geographic regions based on the present-day structural elevation (Figure 1), a structurally depressed interior region (platform area), mostly surrounded by a narrow elevated margin (rim area). Both aggradational and progradational geometries are present. The boundary between the platform and rim areas (platform-rim boundary) divides well penetrations into two classes, platform wells and rim wells. The upper part of the build-up contains four major platform sequences (3rd order sequences) related to changes in the location and geometry of the build-up margin: Sequence 1 (Tournaisian-early Visean) and Sequence 2 (late Visean) form successive backstepping margins above a Famennian foundation. Sequence 3 (late Visean-Serpukhovian) contains a progradational margin that filled in accommodation space above the Famennian created by the retreat of Sequences 1 and 2. Sequence 4 is a Bashkirian terminal aggradational platform containing shallow marine carbonates (Figure 1). In the platform facies, multiples obscure many of the subtle geometries associated with the deposition of these units, while in the rim, sub-seismic fracture systems and karst features dominate.

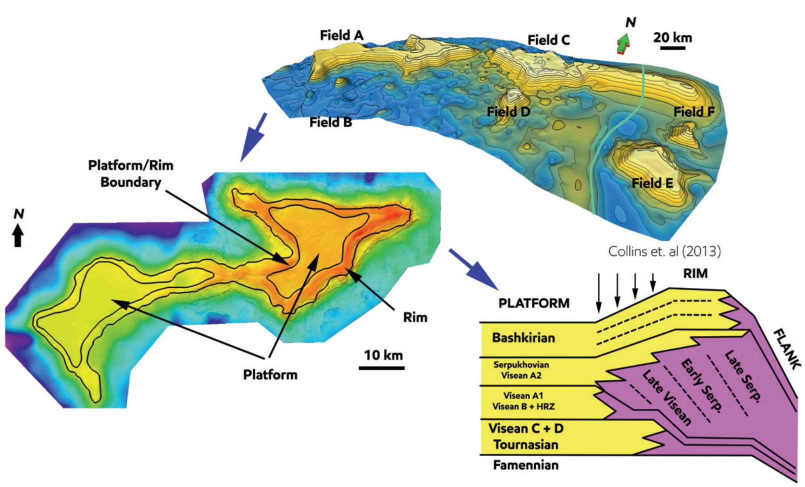

Figure 1 Starting from the upper right, counter-clockwise: (1) Location of the study field (Field A) within the Primorsk Archipelago; (2) Map view of the study field and main physiographic elements; (3) Reservoir architecture with main stratigraphic sequences.

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Well placement and field development efforts at Kashagan have faced significant challenges, including the ability to accurately interpret carbonate stratigraphy in the presence of complex multiples, the targeting of high permeability features (e.g. karsts, fracture systems), as well as the avoidance of drilling hazards. Achieving improvement over the legacy seismic volumes (in terms of both S/N and imaging fidelity) was critical to enhancing the understanding of the geologic evolution of the field, the optimization of the geologic and production models, and the success of future drilling campaigns. The reprocessing effort focused on careful, cascaded passes of noise and multiple attenuation, using state-of-the-art algorithms and innovative workflows, to produce significantly improved results. In the sections below, emphasis will be placed on implementing cascaded multiple attenuation techniques, specifically 3D Wavefield Extrapolation (Brittan *et. al.*, 2011) and 3D SRME, to address the wide range of multiples present in the data.

Seismic programme

The 3D seismic survey over the Kashagan field was acquired by WesternGeco over two seasons in 2001 and 2002. Due to the ultra-shallow water environment with water depths varying from 3 m in the east to 10 m in the west, an OBC (ocean bottom cable) technology with an orthogonal (cross-spread) layout of shot/receiver lines and dual sensors (one geophone/one hydrophone at each position) was chosen. The main survey parameters are summarized in table 1.

A basic acquisition patch (Figure 2) consists of four receiver lines oriented south-north and one source line in the orthogonal west-east direction. The length of the active spread is 9000 m (+/-4500 m), and the total length of the source line is 9000 m. The roll in the inline direction is 450 m (equal to the source line spacing), and the roll in the crossline direction is 2400 m (equal to the width of four receiver lines swath). Thus, the maximum signed offset in the inline direction is 4500 m, and the maximum signed offset in the crossline direction varies from 3600 m to 5400 m.

In 2002-2003 the newly acquired 3D OBC data were processed by two contractors with the work scope split as follows: the pre-processing and post-migration phases were performed by ‘Contractor 1’, and the pre-migration and Pre-Stack Time Migration (PSTM) phases were completed by ‘Contractor 2’. Both contractor processing centres used the same processing software. During this initial seismic processing effort, two main issues impacting the processing results were identified:

- The very shallow water depth causing low S/N mainly due to surface waves, especially in the eastern part of the survey where the water depth was shallowest (3-4 m).
- The presence of a shallow high-velocity layer at 100-200 ms TWT, generating strong peg-leg multiples.

A close investigation of the end results revealed the following data quality shortcomings (Figure 3):

- The presence of steeply dipping (cross-hatch) residual noise in the post-salt interval. This cross-hatch noise is likely to be a direct consequence of the sparse acquisition geometry. The wide acquisition line spacing (450 m x 600 m) creates a lack of near-offset data and limits the effectiveness of denoise processes. Both acquisition-related footprint and cross-hatch noise can be tracked quite deep through the seismic volume.

Recording spread geometry	
Spread type	Split spread, no gap
Receiver line length	9000 m
Receiver line spacing	600 m
Active stations per line	180
Station interval	50 m
Receiver line orientation	South-North
Type of detectors	Dual sensor: 1 hydrophone and 1 geophone
Source line geometry	
Source type	Airgun
Source line spacing	450 m
Source line length	9000 m
Source point spacing on source line	50 m
Source line orientation	West-East
Patch swath design	
Active receiver line length	+/-4500 m from source line position
Number of receiver lines	4
X-line offset limitation	3600 m
Patch roll (inline)	450 m (source line spacing)
Path roll (crossline)	2400 m
CDP bin dimension	
Bin width	25 m
Bin length	25 m
Nominal CDP fold	60

Table 1 Summary of key acquisition parameters.

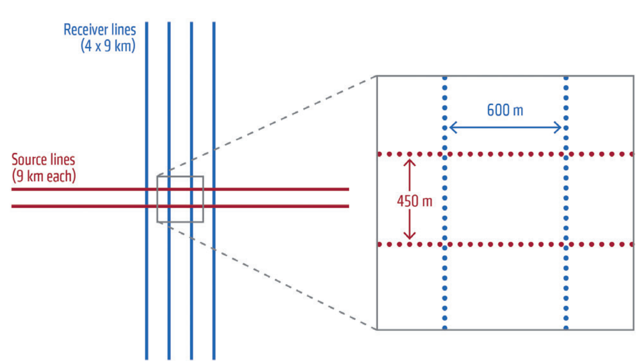

Figure 2 On the left – the standard acquisition patch (template), on the right – source/receiver location map (zoomed).

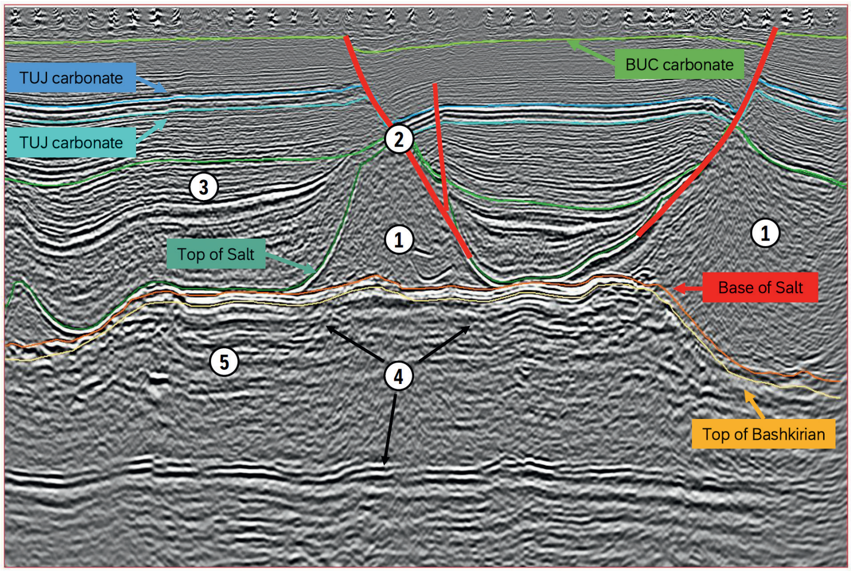

Figure 3 1) Salt diapirs and 2) Shallow faults make difficult interpretation in pre-salt; 3) Cross-hatch noise due to sparse acquisition geometry; 4) Salt flank multiples and deep migration sweeps cross-cut the reservoir and can create false lineaments; 5) Peg-leg multiples.

- Remnant multiples of salt-flanks and intra-reservoir (peg-leg) multiples have high amplitudes and very often mask weak primaries of carbonate reservoir stratigraphy.
- Poor illumination in some areas due to the complex overburden (shallow faults and salt diapirs).

The Kashagan East seismic reprocessing project was designed and implemented with the aim of obtaining a high-quality seismic dataset which provides a step-change in interpretability at the reservoir level relative to the vintage processing efforts. This new high-quality seismic data was needed to: 1) Perform further interpretation of the geological structures across the block, and 2) Prepare for further production drilling. The reprocessing project consisted of two main phases: 1) Processing in time domain, including PSTM, and 2) Velocity Model Building (VMB) and Pre-Stack Depth Migration (PSDM). The first phase took approximately 18 months, from December 2018 to May 2020, and was performed in a collaborative team effort by several companies, namely:

- PGSK (Almaty, Kazakhstan) – Processing in time domain and data preparation for PSDM
- PGS (Oslo, Norway) – Technical support, principally during the demultiple stage
- ExxonMobil (Houston, USA) – Technical supervision, evaluation of tests and QC of intermediate results
- NCOC (Atyrau, Kazakhstan) – Assistance with evaluation and interpretation of tests and intermediate results

Very thorough testing and QC procedures were followed at each processing step. QC products consisted of a set of cross-spread gathers over the entire survey, volumetric QC of amplitudes and dominant frequencies over the three time intervals, NMO full-fold stacks, near-trace stacks, and post-stack time migrations for the whole volume and pre-stack time migrations for selected lines. The work was performed at the PGS Kazakhstan LLP Seismic Data Processing Centre utilizing SPArk 1.5 software package, developed by PGS (headquarters in Oslo). The implementation of new technologies in OBC processing, such as 3D wavefield extrapolation demultiple and 3D SRME were critical in obtaining the step change in data quality required for future field development. Other methods such as 2D IME were performed alongside these methods but are not the focus of this paper.

One of the key technologies applied by PGSK that led to significant improvement in resulting data was SWIM (Separated Wavefield Imaging). SWIM enabled the use of the multiple wavefields to image the very shallow part of the section, which can then be used to predict multiples (Oukili *et al.*, 2015). SWIM can also assist in the validation of velocity model updates in the VMB and PSDM processing, in the absence of primary reflections at shallow depths in conventional imaging.

Demultiple flow

The Kashagan East area was affected by several types of multiples which presented a formidable challenge for multiple attenuation algorithms. Due the very shallow sea-bottom depths, in the range of 3-10 m, the water-bottom reverberation cannot be meaningfully separated from the source signature. Shallow carbonate layers below the water bottom create the next set of strong multiples. Moving deeper, thick, faulted Cretaceous and Jurassic carbonate layers are present throughout the survey, creating longer period multiples.

Furthermore, the sparsity in the acquisition geometry created additional problems for data regularization required in the application of SRME and for the generation of a reflectivity cube for 3D Wavefield Extrapolation techniques.

Numerous attempts were made to address this complexity during previous rounds of processing and included application of deconvolution, Radon demultiple, and SRME. Given that these previous efforts were only partially successful, the goal of the reprocessing project was to bring to bear the latest advancements in multiple prediction and subtraction, in order to produce a step change improvement in S/N at the target.

Taking these challenges into account, the demultiple flow was split into three stages designed to target surface multiples with different multiple periods. Short-period multiples with periods less than 48 ms were attenuated during designature using pre-stack wavelet deconvolution. Multiples with a period

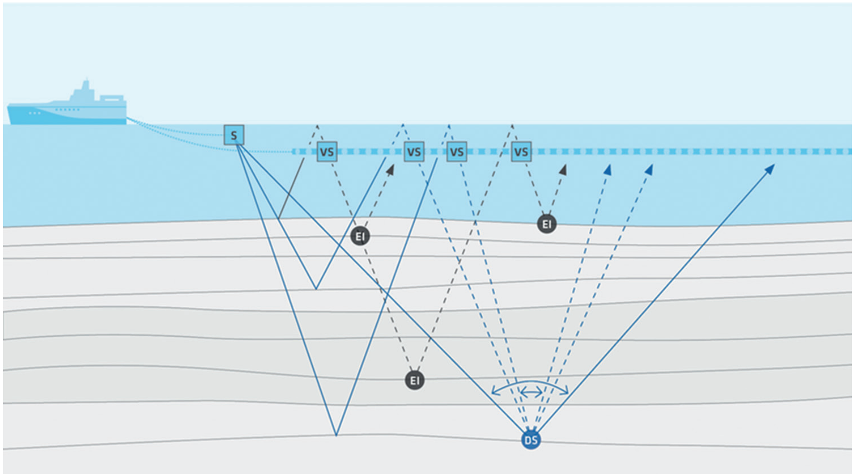

Figure 4 Schematic of SWIM showing how recorded downgoing waves (S) become virtual sources (VS) at receiver locations allowing reconstruction of near angle information.

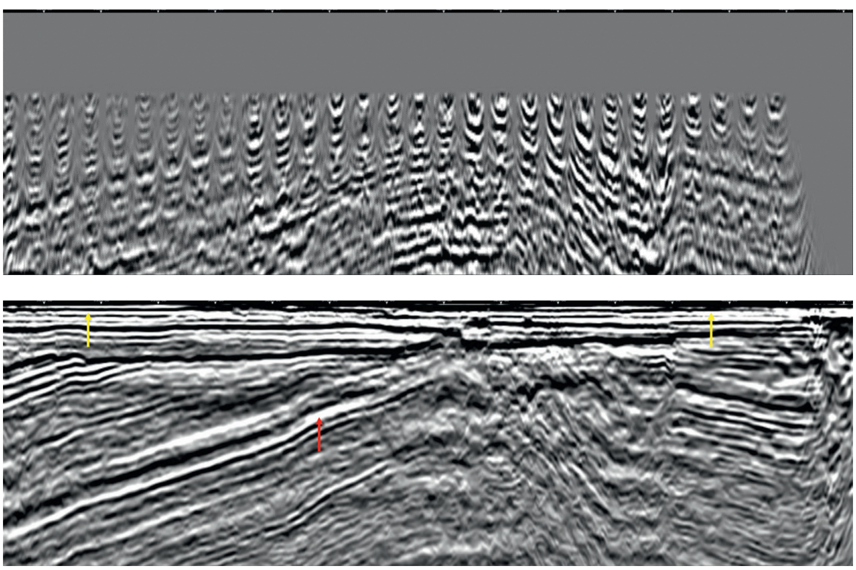

Figure 5 Comparison of SWIM reflectivity cube (bottom) with the legacy PSTM volume (top).

of 48-500 ms were modelled with a 3D Wavefield Extrapolation technique and multiples with a period longer than 500 ms used True Azimuth 3D Convolution SRME (Barnes *et. al.*, 2011). The latter two techniques are the focus of this paper.

3D wavefield extrapolation modelling

The wavefield extrapolation technique adds one round trip through the earth by downward- and upward- extrapolating receiver gathers through a reflectivity cube using the one-way wave equation. Traditionally this reflectivity volume is obtained by imaging near-offset data, but due to the limited acquisition geometry of the Kashagan OBC survey this was achieved instead by using Separated Wavefield Imaging (SWIM) technology (Lu *et. al.*, 2014). This advanced imaging capability was not available during the legacy processing and proved pivotal in creating a reflectivity volume of sufficient quality to generate a good surface-related multiple prediction. Figure 4 shows a schematic of SWIM working on towed streamer acquisition to improve angular diversity.

Using SWIM on the Kashagan East survey, receiver gathers are migrated assuming reciprocity as a downgoing source wavefield and each source position becomes an upgoing wavefield at virtual receivers (Lecerf *et. al.*, 2015). Free-surface multiples are treated as signal and imaged using a deconvolution imaging condition between the two wavefields, improving near-surface illumination and allowing the reconstruction of the very shallow overburden. Unlike mirror migration techniques, there is no strict assumption on the order of multiples nor the water depth. Furthermore, the deconvolution removes the source signature present in both wavefields, and the migrated image is intrinsically zero-phase with no bubble effect. Due to the ultra-short multiple periodicity (starting with 48 ms), the SWIM-derived reflectivity volume contained a number of false reflectors which were the result of undesirable cross-talk (Lu *et. al.*, 2014).

Therefore, this SWIM image was then post-processed using a simple flow of denoise, footprint attenuation and cross-talk removal before its use as a reflectivity cube in the demultiple flow. Some cross-talk remained, causing areas of inaccurate amplitudes but this was accounted for in the adaptive subtraction step. Figure 5 shows a comparison of the SWIM reflectivity cube with the legacy PSTM volume. Notice that SWIM has reconstructed near-angle information needed to image both the water bottom (yellow arrow) and the Cretaceous carbonate layer (red arrow). The highly reflective near-surface geology is the source of many short-period multiples which have historically been poorly represented, although they affect the entire seismic section in the form of high-order reverberations and peg-leg multiples. The example also illustrates spatial variability in this reflectivity series which emphasizes the need for accurate information in order to minimize the risks associated with adaptive subtraction for multiple suppression.

After wavefield extrapolation, the multiple model was subtracted in cross-spread domain using a multi-dimensional adaptive subtraction technique (Perrier *et. al*., 2017). Figure 6 shows a comparison of the input data, multiple model (raw and adapted), and subtraction on a stack section. Peg-leg multiples of the Base of Salt are clearly interfering with the reservoir primary reflections and are attenuated in this example.

3D SRME

After subtraction of short-period multiples with wavefield extrapolation modelling, 3D convolutional SRME was performed as the need for recorded very short offset information for multiple prediction rapidly diminishes at greater depth. Using the whole dataset, data regularization in four dimensions (subline, crossline, time, offset) was performed to a density of 12.5 x 12.5 m spatial grid and 50 m offset spacing, extrapolated down to zero-offset. This intermediate regularized data was then muted at 500 ms to prevent modelling of multiples already removed with earlier procedures. For SRME, reconstruction of densely sampled shot and receiver gathers before convolution within a true-azimuth shot-receiver azimuth aperture was performed to create the multiple model. This model was then adaptively subtracted in the same manner as the wavefield extrapolation technique applied earlier in the sequence.

Long-period multiples modelled with this process are not obvious on the full-stack due to high fold of coverage but are present on near-angle stacks. An example of input, model (raw and adapted), and subtracted result on an unmigrated near-trace cube is shown in Figure 7.

Demultiple evaluation

Evaluation of demultiple efficiency was performed after each intermediate step by interpreters, using post-stack time migrated

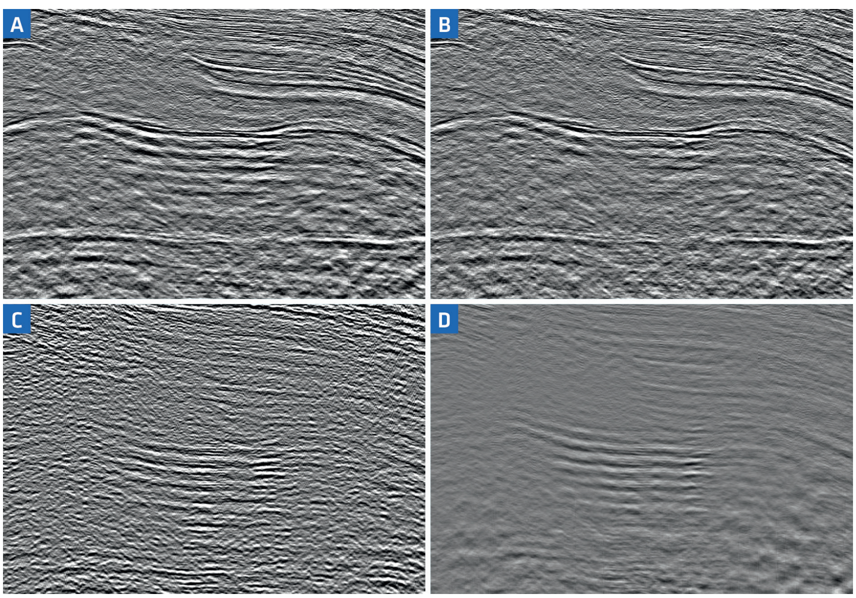

Figure 6 Stack section of input data (A), adaptive subtraction (B), wavefield extrapolation model (C) and adapted model (D).

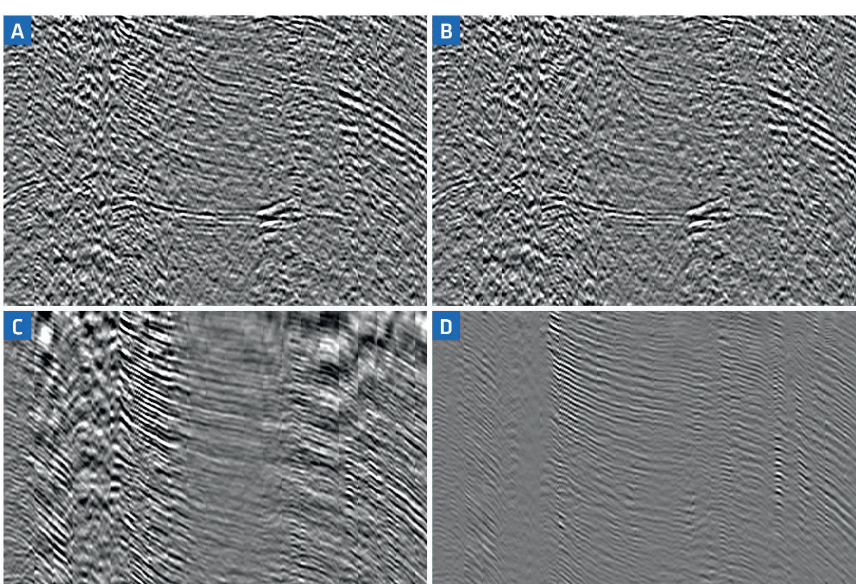

Figure 7 Near-trace section of input data (A), adaptive subtraction (B), 3D SRME model (C) and adapted model (D).

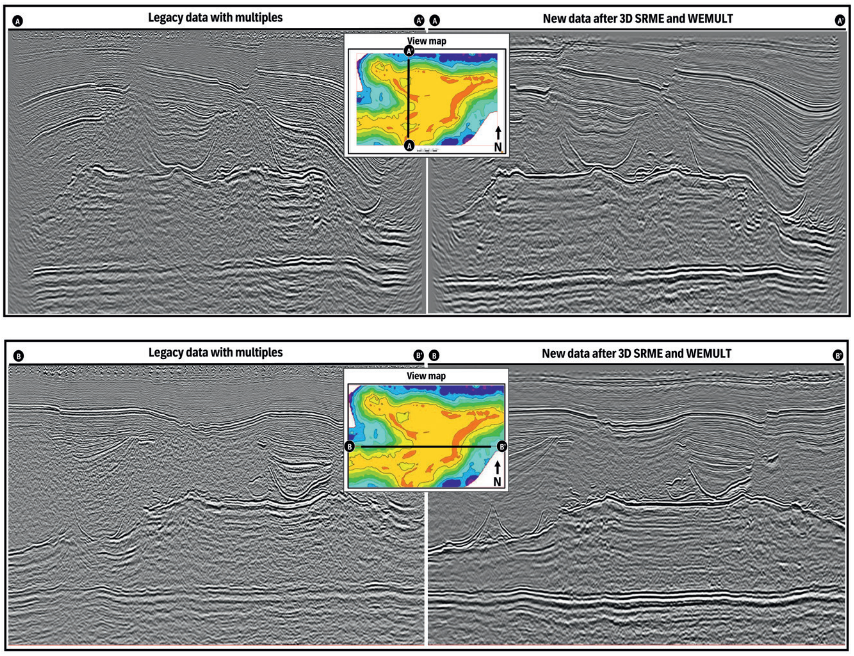

Figure 8 Comparison of legacy (left) and reprocessed (right) final PSTM stack images.

volumes and cross-correlations between input/subtraction and model. This ensured a 3D, reservoir-focused analysis of the results, assessing both multiple attenuation and preservation of geobody structures (e.g., karsts) beneath the salt.

Final results and interpretation

Comparisons to legacy pre-processed data (Figure 8) showed that the recent reprocessing results contain significantly fewer multiple events, while at the same time preserving primary reflections. Consequently, final Kirchhoff and RTM least-squares migrations utilizing the newly pre-processed data have led to significant improvements in S/N, resolution and reflector continuity, throughout the seismic volume. Of particular interest are the observations around the reservoir interval: images of previously challenged seismic features (such as depositional geometries, karst bodies and fracture networks) have become more focused, geologically more consistent and easier to interpret. The correlations of synthetic well ties have improved throughout the volume (Figure 9). The enhanced demultiple results paid dividends in more ways than one; in addition to generating higher S/N images, they also enabled more accurate velocity model-building (e.g. through higher-quality residual depth error picking, and more accurate horizon interpretation – including previously unresolvable salt geometries). The newly imaged products have the potential to improve the placement of future wells to target high-permeability features, as well as to better explain the existing well data. The new seismic images are also expected to help improve the conditioning of geologic models; in turn, such improvements can lead to more accurate field production simulations and operational efficiency gains.

Conclusions

Partners of the Kashagan field were faced with the option of acquiring and processing a new seismic survey or using more advanced modern techniques to reprocess the existing data, which was an OBN dataset acquired back in 2001/2002. The decision

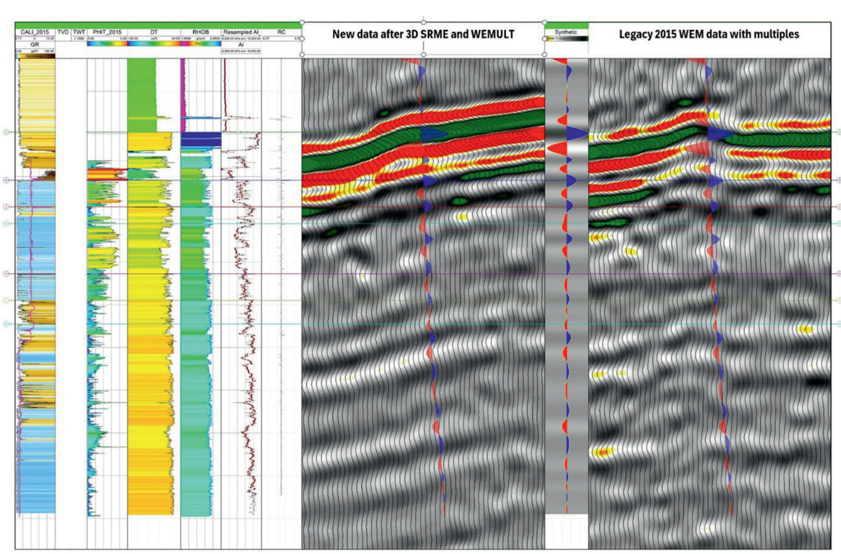

Figure 9 Comparison of well logs alongside reprocessed (left seismic image) and legacy (right) well/seismic tie.

was made to proceed with reprocessing as acquiring new data would have added another two years to the project timeline. The objective of the reprocessing was to deliver a step change in seismic data quality to conduct further field development activities and plan production wells.

Modern reprocessing techniques such as SWIM, 3D SRME, 2D IME and wavefield extrapolation demultiple helped to provide significant improvements in signal-to-noise and image quality, largely due to advanced multiple attenuation. In addition to the improvements in the PSTM processing, modern techniques such as FWI and least squares Kirchhoff and reverse time migrations provided even greater enhancements to the image in the PSDM processing flow.

These new seismic volumes have led to improved seismic interpretations providing higher confidence structural maps as well as better seismic attribute maps. They have also enabled the employment of more advanced techniques such as diffraction imaging and seismic inversion, all of which help to define the matrix porosity distribution away from well control and the non-matrix porosity distribution of fractures and karst features.

Undoubtedly, acquisition of new modern seismic data would have been preferable, but given the time and budget constraints, the reprocessing of the existing seismic data proved to be the right decision and provided the required step change in seismic image quality to meet the business objectives.

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