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Geophysics in Oman

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ABSTRACT

To date Petroleum Development Oman has acquired approximately 200,000 kilometers of 2-D and 20,000 square kilometers of 3-D seismic data. Five 3-D and one 2-D crews are operated by contractors. For 3-D surveys PDO uses 2 vibrator source groups recording a "double zig-zag". The vibrators have GPS systems. The standard spread consists of 4 receiver lines of 120 active channels, spaced 200 meters apart, with receiver spacing of 50 meters. Bin size is 25 by 25 meters, multiplicity is 60 fold and the active spread is 6 kilometers. Most of the seismic data is processed inhouse by CGG. Additionally PDO uses proprietary software for bench-marking, training and attribute studies. Recent lines recorded with vibroseis, rather than thumper, and long offsets (4 to 6 km compared to 2 km) have improved both shallow (1 to 1.5 second) and deep reflections including sub-salt events (>2.5 second). Improved data quality has better imaged exploration targets (e.g. post-salt Haima and intra-salt Athel) and reservoir geometry (e.g. Alkhlata and Gharif). Proper imaging of the Athel silicilyte may require 3-D pre-stack depth migration. The application of other geophysical techniques including gravity, aeromagnetics, seismic attribute analysis and borehole geophysics has also proven useful, particularly where conventional seismic data quality is poor.

INTRODUCTION

Geophysics in Oman has a long history with records of seismic surveying going back to 1956. In the past four years PDO has applied strategic new technologies in key sectors of the geophysical business. This has resulted in a rapid improvement in seismic data quality combined with successful efforts to contain costs. This development has not only led to the identification of a number of promising new plays, but also opened up a new world of additional information hidden in the seismic data which can be related to reservoir characteristics and porefill. Also, the application of non-seismic techniques such as analysis of gravity and magnetic data has recently been revived.

This paper reviews PDO's latest geophysical technologies in Oman. First we discuss PDO's 3-D seismic acquisition techniques with an emphasis on quality versus cost. This is followed by representative cases which demonstrate PDO's data improvement strategy. Two cases are related to the two main exploration targets: the Haima gas play in North Oman and the Athel play in South Oman. In addition, we present some results of 3-D seismic surveys over two major producing fields: Nimr in South Oman and Fahud in North Oman. We then show how gravity and magnetic methods are again being utilized in support of exploration. The successful use of seismic attributes and borehole techniques is discussed in the final two sections.

SEISMIC SURVEY RESOURCES

PDO acquired the first 3-D seismic survey in 1984 over Suwaihat. Compared to other major operating companies, PDO was relatively late in employing this technology. However, once the advantages of 3-D became apparent, notably in the poor-data area of the Eastern Flank, 3-D proliferated rapidly. To date, some 20,000 km^2 of 3-D have been acquired, representing approximately 20% of PDO's present concession area (Figure 1).

PDO's current seismic acquisition resource base consists of six crews, five of which are dedicated to 3-D surveying. All major international geophysical contractors are currently represented: Western Geophysical, CGG and Geco-Prakla operate in total three 3-D crews and one 2-D crew; in addition, Rees Geophysical Oman (a fully Omani owned company) operates two 3-D crews.

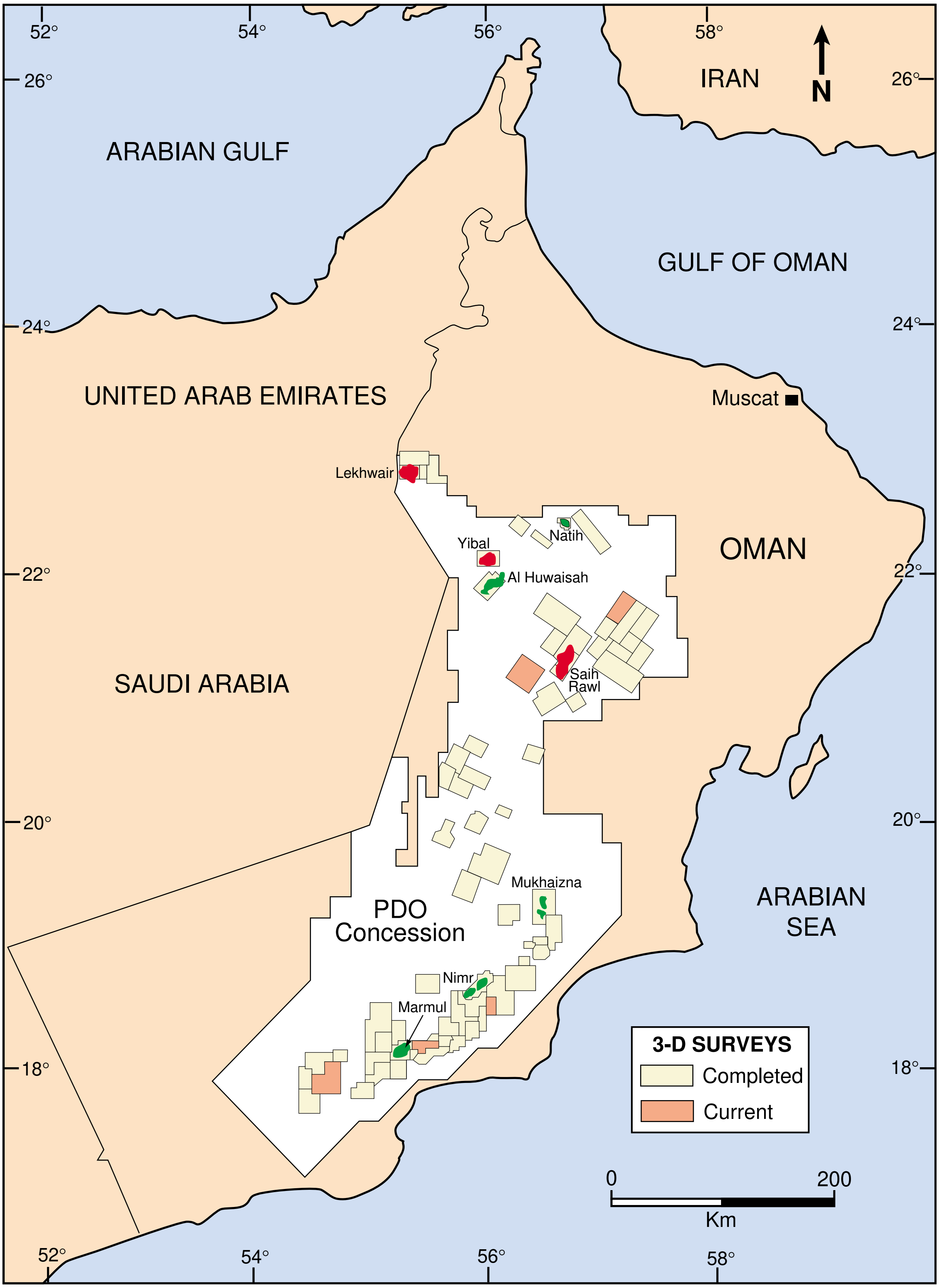


Figure 1: Map of PDO's 3-D seismic coverage.

All seismic data acquired by PDO are processed internally. The majority of the data are processed by CGG, PDO's in-house contractor since 1994, using a dedicated Convex 3850 computer and a series of IBM RS6000 workstations in a networked configuration. A separate dedicated processing group in the Geophysical Department process the remainder of PDO's 3-D and 2-D data using proprietary software. This group has a three-fold objective: (1) value-added processing in support of seismic attribute studies; (2) contractor benchmarking; and (3) transfer of expertise to, and training ground for, newly recruited Omani graduates.

The Cost - Quality Cycle

PDO's standard 3-D acquisition geometry consists of four receiver lines of 120 active channels spaced 200 m apart; receiver spacing is 50 m, yielding a total active spread length of 6 km. Four 50 m spaced source lines are acquired between the two central receiver lines in a zig-zag mode at 50 m intervals in-line (Figure 2a). Depending on the spread configuration, data are acquired with the source shooting off-end (6 km maximum offset), asymmetric split-spread (1.6 km - 0 - 4.4 km) or symmetric split-spread. Multiplicity and maximum offset can thus be balanced to produce the best possible results at different depths in case of multiple (shallow and deep) objectives.

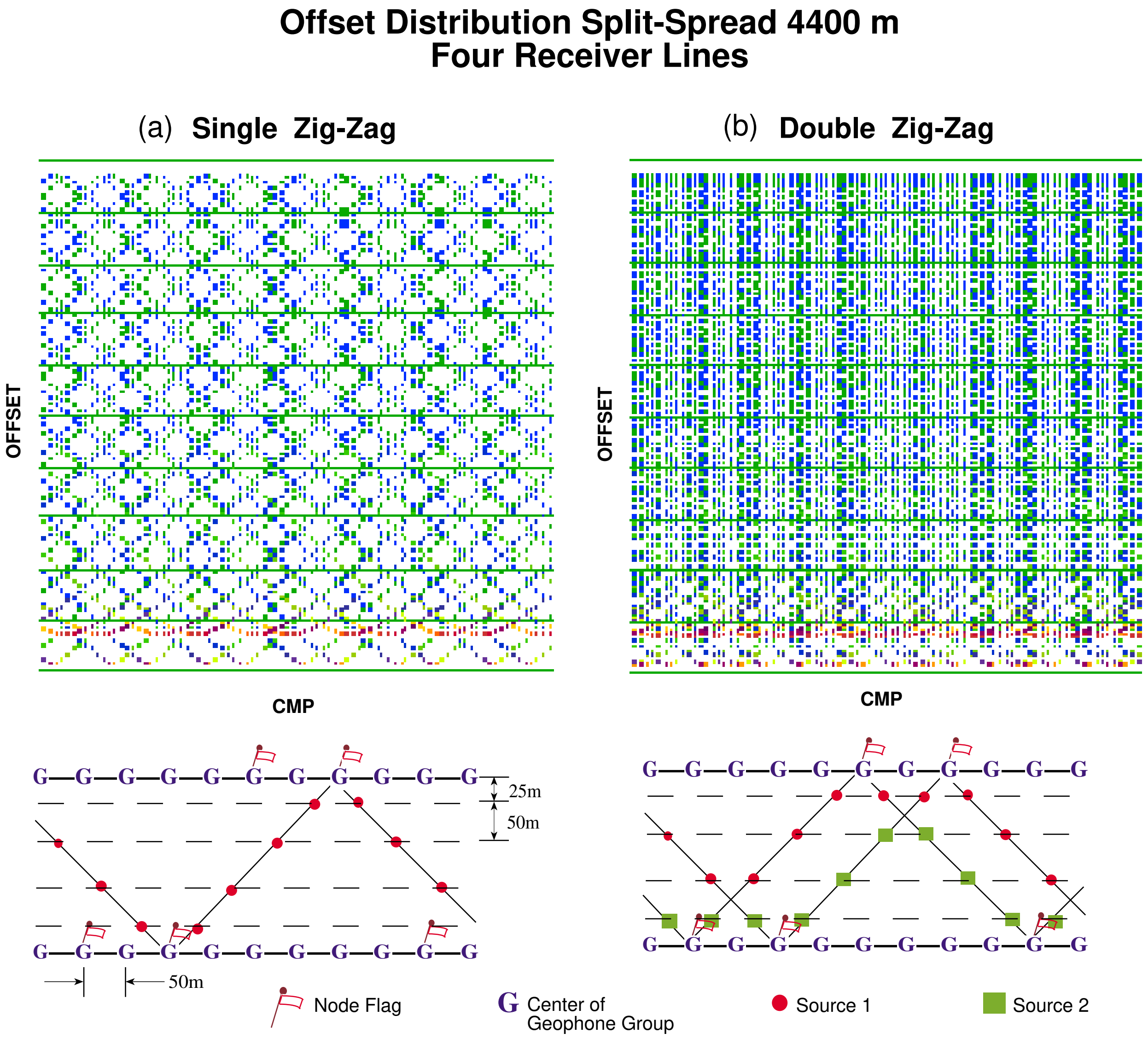


Figure 2: Standard 3-D acquisition geometry and resulting offset distribution: (a) single zig-zag, and (b) double zig-zag.

Data quality in Oman suffers from a number of problems associated with the shallow subsurface. Apart from shot-generated noise (ground roll) and poor coupling in soft-sand areas (sand dunes), intra-bed multiples generated in shallow carbonate layers constitute a major source of data contamination. Particularly when the acoustic impedance contrast between levels of interest is small, this contamination often leads to severe imaging deterioration at target level. Its effective suppression poses a considerable challenge to the acquisition and processing geophysicists.

Early 3-D surveys over the Eastern Flank in South Oman were acquired with 4 by 64 channels (1.6 km maximum offset in symmetric split-spread mode, nominal 16 fold bin multiplicity), later increased to 4 by 96 channels (2.4 km maximum offset, 24 fold data). This configuration proved efficient and economical, but the resulting data quality was poor, occasionally even inferior to 2-D seismic. The main reason is multiple contamination due to inadequate sampling. The limited offset range hampers multiple suppression in processing, which is based on differences in moveout between primaries and multiples.

Moreover, the zig-zag configuration described above results in an inhomogeneous stacking operator (uneven distribution of offsets) which in turn causes multiples to "leak through". This can be remedied by introducing a second zig-zag, 90 degrees (100 m) shifted with respect to the first, which fills the offset holes in the stacking operator (Figure 2b). This "double zig-zag" geometry is now the standard procedure for acquiring seismic data in PDO. In addition, the increasing interest in deep plays following the

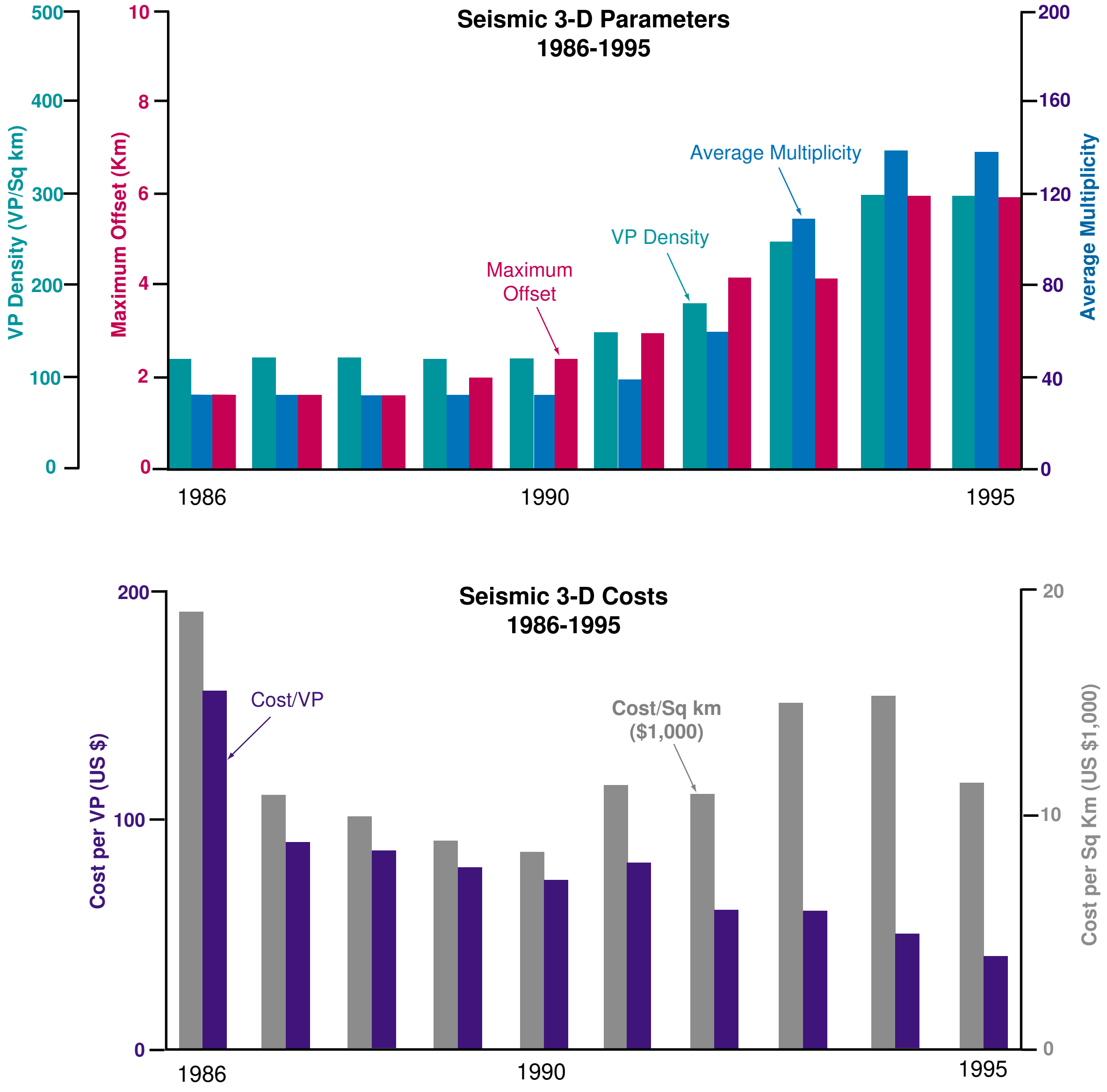


Figure 3: Seismic performance indicators 1986 to 1997.

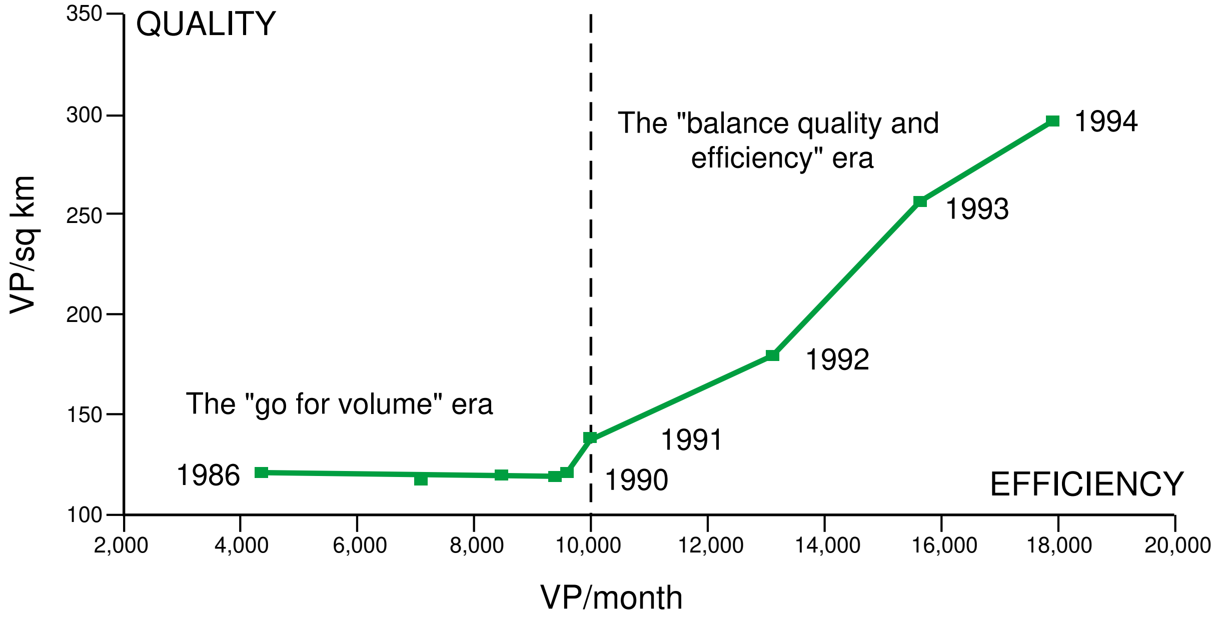


Figure 4: Seismic quality measured in vibrator point per square kilometer improved significantly after 1991. Efficiency measured in vibrator point per month increased nearly 500 percent over the decade.

discoveries of gas accumulations in North Oman resulted in extending the length of the active spread to the now standard 6 km. As a consequence, multiplicity per 25 by 25 m bin has gone up to a nominal 60 fold.

Straightforward implementation of the dual zig-zag using existing resources was not cost-effective as it would increase unit cost by 50 to 70%. By deploying a second set of vibrators on the second zig-zag, operating in tandem with the first, the same productivity rates could be achieved, resulting in improved data quality at only moderately increased unit costs.

It has been PDO's strategy over the past four years to balance quality improvement steps with investments in additional equipment in order to contain unit cost as much as possible. Other examples of such investments included the provision of additional channels. On the one hand, these have been deployed to increase maximum offset. On the other to harmonise block overlaps and maintain multiplicity and offset distribution in adjacent acquisition strips. This strategy has proved very successful, as is depicted in Figure 3. Quality indicators such as average multiplicity, maximum offset and vibration points per km^2 have shown a significant increase since 1991, while cost indicators such as US$ per km^2 and US$ per VP have stabilised or decreased.

Another way of depicting this history is by cross-plotting the number of VPs per km^2 (a measure of data density and hence a rough measure of data quality) versus number of VPs per party month (a measure of efficiency) for the period 1986 to 1995 (Figure 4). There is a clear break in the trend around 1991, marking the distinction between the "go for volume" era and the subsequent "balanced quality and efficiency" era. Since 1991 quality improvements have been achieved at the same time as increased efficiency as demonstrated by the upward trend in the curve.

Major improvements have also been achieved by the introduction of GPS on vibrators and intensifying quality control on shot/receiver geometry on the seismic crews rather than in processing. GPS on vibrators has enabled the identification of discrepancies between actual and pre-planned source positions, which can subsequently be updated if the error exceeds a predefined margin.

Most 3-D seismic crews now have Unix workstations and the necessary software which makes it possible to display LMO'ed shot and receiver gathers on a day-to-day basis and flag any remaining geometry errors at a stage when correction is still relatively straightforward. Other QC criteria are being reviewed for implementation, such as recording of the level of distortion of the vibrator sweep and displaying this in map mode for every VP. The resulting display correlates well with a satellite view of the area indicating potential areas of softer overburden which could create localised static anomalies (Figure 5).

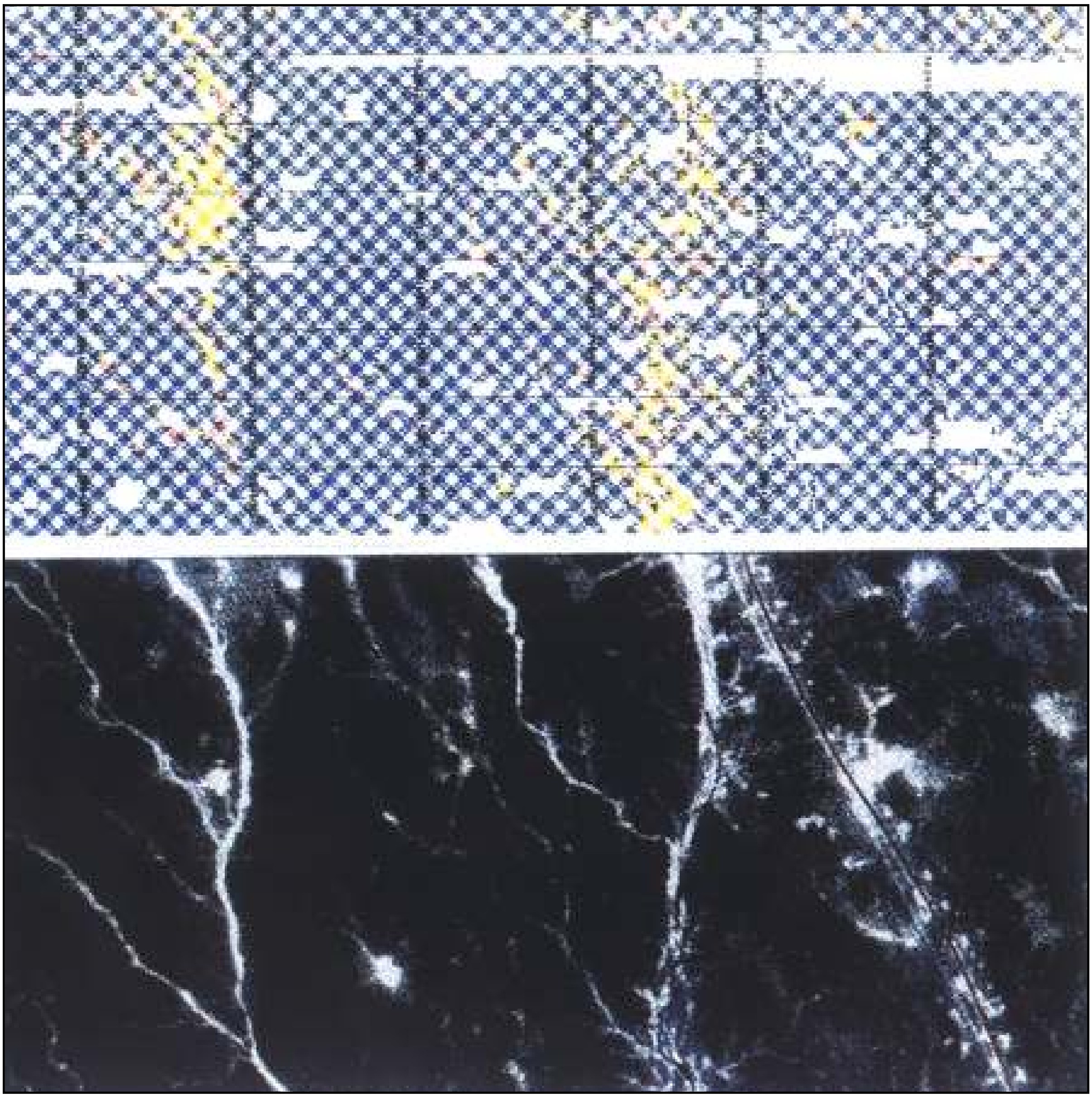


Figure 5: Plot of vibrator distortion level and satellite map of Qarat Kibrit area. The regions colored in yellow show the greatest average distortion and correspond to channels with soft overburden.

While investments in improved quality and efficiency limit or even reduce unit costs, they result in increased total costs. A decision, which is based on business requirements, must trade off quality and efficiency versus the reduction of total costs. In PDO it was felt that by mid-1996 one 3-D crew could be released as the remaining crews generate data of sufficient quality and quantity to meet business requirements. This is evident by the trend in performance figures. In 1996 four 3-D crews will produce roughly as much data, on a km^2 basis, as in 1991 at the same unit cost; however, with a considerably improved quality due to higher data density.

SEISMIC DATA EXAMPLES

Haima Play

Figure 6 is a comparison between old and new 2-D data over Saih Nihayda. To the right is a 1985 thumper line recorded which was reprocessed in 1990. The cable is an asymmetric split-spread configuration aimed at providing optimal multiplicity (24 fold) at the shallow targets between 1 and 1.5 sec. Maximum offset is 2 km. To the left is a vibroseis line over the same trajectory, acquired in 1992 with

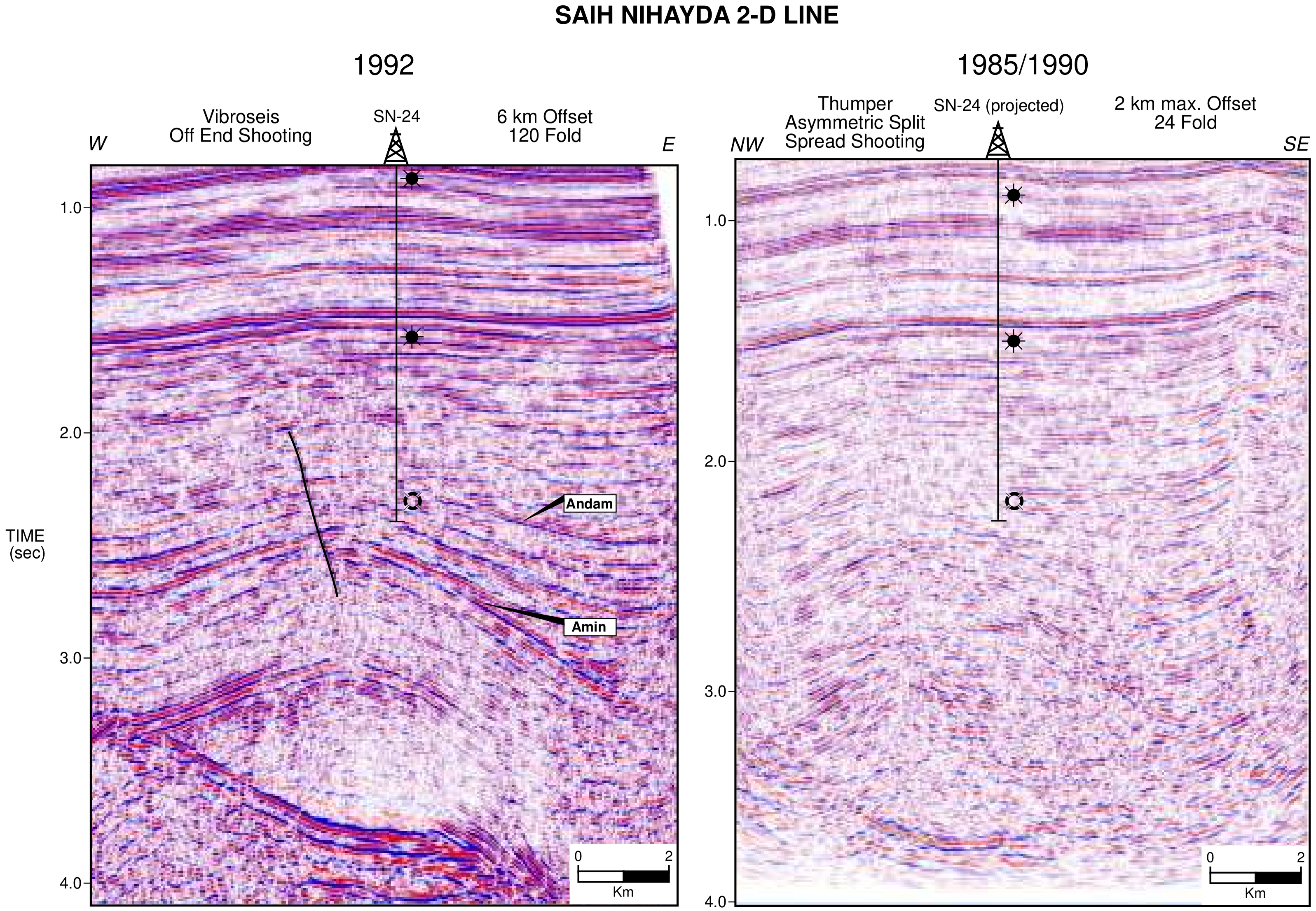


Figure 6: Data comparison (2-D), Saih Nihayda: (right) Thumper line, shot 1985, reprocessed 1990 (24 fold, maximum offset 2 km); and (left) Vibroseis line, shot 1992 (120 fold, maximum 6 km offset).

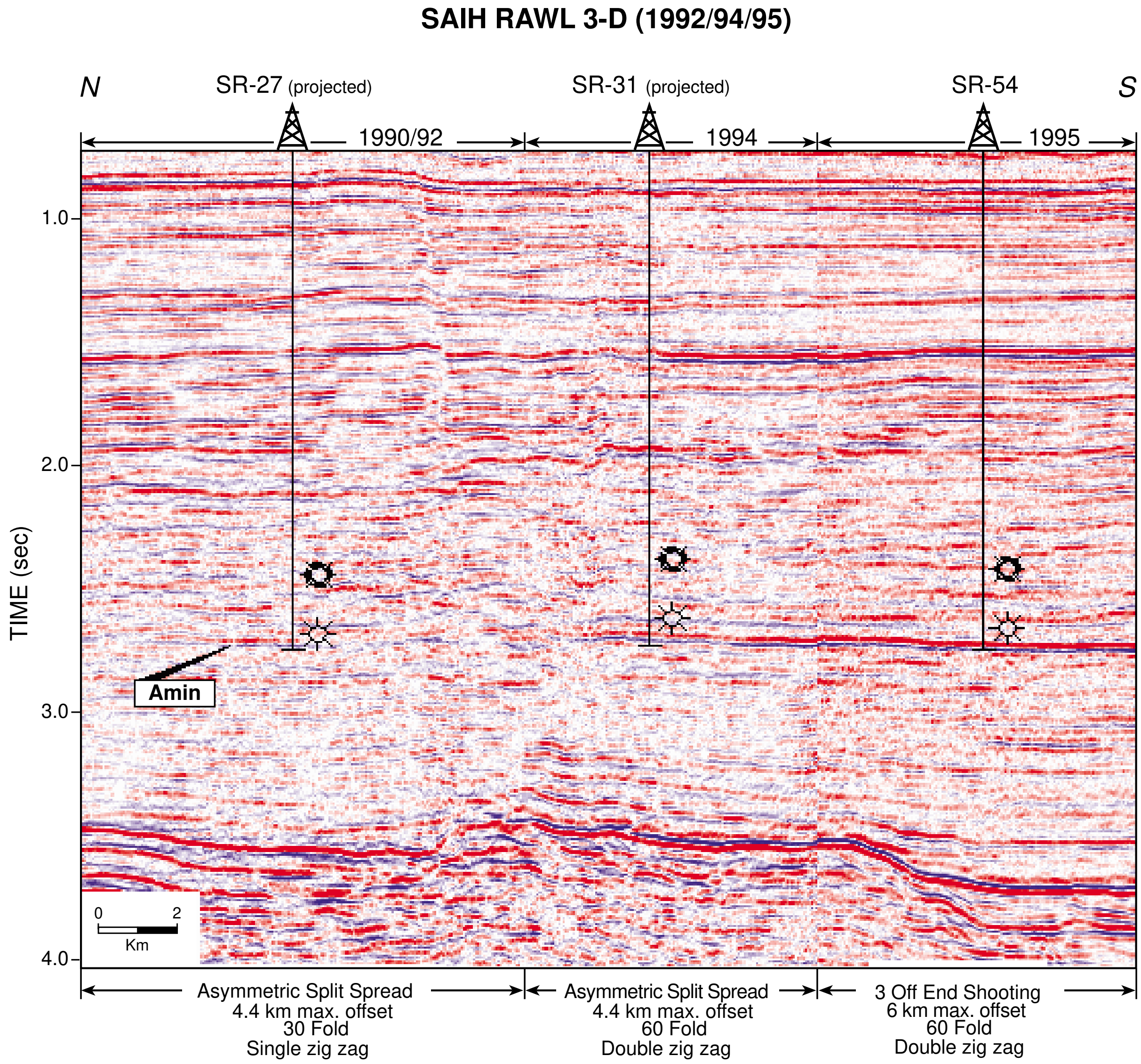


Figure 7: Data comparison (3-D), Saih Rawl. (1990-1992 left side) Asymmetric split spread, 4.4 km maximum offset, single zig-zag, 30 fold; (1994 center) Asymmetric split spread, 4.4 km maximum offset, double zig-zag, 60 fold; (1995 right side) Off-end, 6 km maximum offset, double zig-zag, 60 fold. Note the improved imaging of the gas-bearing top Amin at approximately 2.8 seconds. (Note: geological and/or porefill-related effects could contribute as well; this is currently being investigated.)

6 km off-end shooting yielding 120 fold multiplicity. The higher multiplicity gives overall better signal-to-noise ratio in the target zone between 1 and 2 sec, while improved multiple suppression leads to better continuity of events at top Shu'aiba and Gharif level (approximately 1 and 1.5 sec, respectively). The better acoustic source and the contribution of longer offsets result in a superior image of the Andam and Amin reflections around 2.5 sec and the base salt events between 3 and 4 sec.

The lessons learnt from improved 2-D imaging were subsequently implemented in 3-D acquisition. Figure 7 shows a comparison between three successive generations of 3-D imaging over the nearby Saih Rawl accumulation. The left (northern) part of the profile shows a track from the 1990/1992 survey which is single zig-zag, asymmetric split-spread, 4.4 km maximum offset, 30 fold data. The middle section is part of the 1994 survey, shot with similar parameters as the first but with double zig-zag, hence 60 fold multiplicity. The right (southern) section is part of the survey acquired in 1995 which differs from the first two in its off-end shooting geometry.

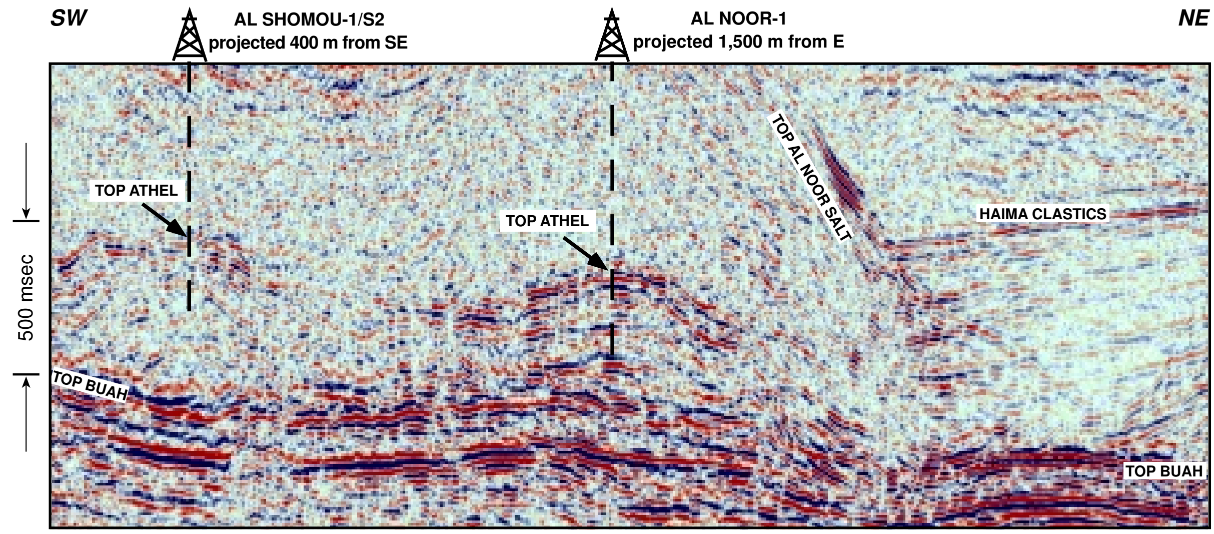
Note the improved imaging at the Amin level around 2.7 sec. However, other factors, such as geology and/or porefill, rather than acquisition parameters may also have affected the amplitude behaviour (AVO) which in turn results in a different expression on a full-offset stack. An analysis of such effects utilising near/far offset substacks is currently ongoing.

Athel Play

The Athel silicilyte is one of the most significant recent oil plays in Oman. It has therefore had an impact on PDO's seismic acquisition and processing strategy. Firstly, the geological setting is a challenge to geophysics. In addition to the traditional problems such as statics induced by sand dunes, multiples and weak acoustic impedance contrasts, the deep reservoir is encased in salt which varies rapidly in thickness. This variation results in non-hyperbolic moveout and ray-bending which further degrades the data. Secondly, there is a relative paucity of long-offset 2-D and 3-D seismic data over the area of interest.

ATHEL PLAY

NEW 2-D SEISMIC (6 km OFFSET; CGG PROCESSING 1995)



AL NOOR 3-D (2.4 km OFFSET; SIPMAP RE-PROCESSING 1994)

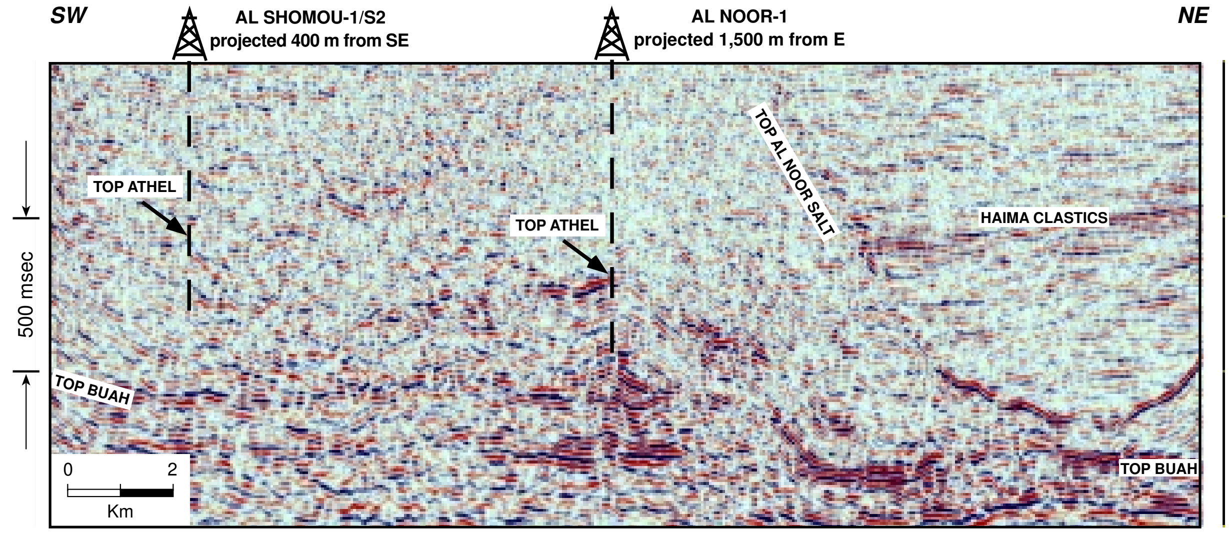


Figure 8: Data comparison, 2-D and 3-D, Al Noor: (top) 2-D section (1995), 120 fold, 6 km off-end; and (bottom) 3-D arbitrary line (1989) 24 fold, 2.4 km split-spread.

The exploration strategy called for a rapid succession of wells over the most attractive of the 30 identified Athel prospects. Due to insufficient time to acquire high-quality 3-D data over the extensive geographical area of the play, the relevant prospects were surveyed with a 2-D long-cable. In the case of a successful discovery a 3-D survey would follow. During 1994-95, the Al Mesbah and Al Fajr prospects were covered with 2-D, while the regional Waad, Aud and Asem surveys, acquired during the same period, led to the identification of additional opportunities. As far as 3-D is concerned, the only datasets currently available are the less than optimal Al Noor (1989), and the good-quality Dasimi/Andhur dataset (1994). A survey over the Katheer prospect in the northeast of the play area has recently been acquired.

Figure 8 compares modern 2-D data (top section, 120 fold, 6 km maximum offset) and a coincident arbitrary track of the Al Noor 3-D data (24 fold, 2.4 km maximum offset). While the 3-D imaging of terminating Haima sediments against the salt flank is clearly superior to the 2-D, the latter shows a much better overall signal-to-noise and continuity at the top Athel event, around 2 sec and below.

The geological setting of the play requires technologies which have rarely been used in PDO. Pre-stack depth migration is among the potentially most promising. PDO's processing group has embarked on an evaluation of 2-D pre-stack time and depth migration and velocity model building. Their expertise will be helpful in preparing for a full 3-D pre-stack depth migration project to be carried out in the first half of 1996.

Nimr Field

The 1993 Nimr survey is one of the first larger 3-D surveys which differed from the standard acquisition geometry described above. The requirements of this survey in the context of field development planning led to a unique design, tailored to achieve optimal coverage at acceptable cost. Objectives of this survey were twofold:

(1) to identify Alkhlata valleys (erosional features filled with Alkhlata non-reservoir rock cutting into the main producing Haima sediments) beneath the base Nahr Umr unconformity; and
(2) to obtain a better structural definition of the Gharif rim at the field's northern edge.

Figure 9 shows the structural geometry and describes the main intervals of interest. Note that the target depth, between 700 and 900 m subsurface, corresponds with reflection times between 500 and 800 msec. The area covered consisted of 100 km^2 over the eastern part of the field and was intended as a pilot for potential further high-resolution coverage.

The acquisition geometry adopted consisted of 4 receiver lines spaced at 100 m; receiver spacing was 25 m, with a total of 768 channels recorded. Tests were carried out to determine optimal shot patterns, resulting in the choice for areal shot arrays. As the narrow receiver line spacing did not allow implementation of areal shot patterns between two central lines without the vibrators crossing the spread, the survey was acquired off-end in crossline mode, symmetric split-spread in inline mode (maximum offset 2,400 m). Resulting fold was 96 per bin size of 12.5 by 25 m.

Figure 10 compares 1993 data to the 1987/88 survey. The Alkhlata valleys are indicated with the yellow marker between 600 and 800 msec. Although the outline of these valleys is still difficult to recognise on the newer data, it appears that their occurrence correlates with structural features at top and base salt level at 1,400 and 1,800 msec, respectively. These features were not recognised on the previous data (pink marker). This survey enabled better positioning of producing wells near the flank of the catchment areas.

An example of the second objective, the structural definition of the Gharif rim, is illustrated in Figure 11. The profile covers two flank wells, Nimr 206 and Nimr 251-H1 (horizontal). Also shown are two interpreted levels, the near base Nahr Umr (top) and the near base Alkhalata P1A (bottom), cf. Figure 9. The new data suggest the presence of a pre-Nahr Umr fault between the two wells which could not be recognised on the older data. Based on the much improved structural information provided by the new data, some 30 horizontal flank wells are planned to be spudded.

The encouraging results of the 1993 survey led to the decision to cover the remainder of the field with 3-D seismic using identical survey parameters. Acquisition of an additional 180 km^2 of high-resolution data has been completed at the end of September 1995.

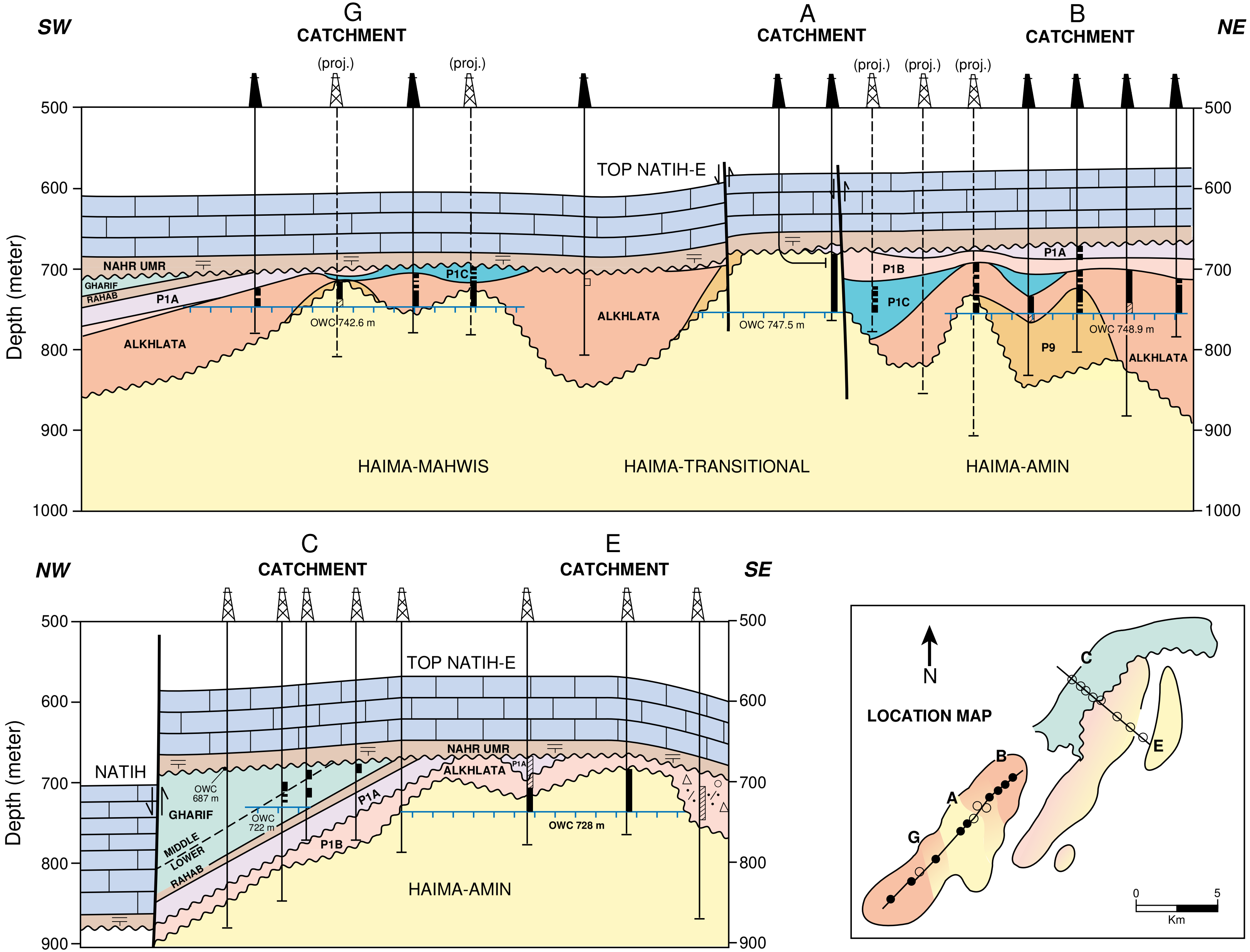


Figure 9: Nimr field, structural cross-sections. Layers P1 to P9 indicate different stratigraphic units of the Alkhalata Formation. These are based on palynological content with P9 the oldest and P1A the youngest.

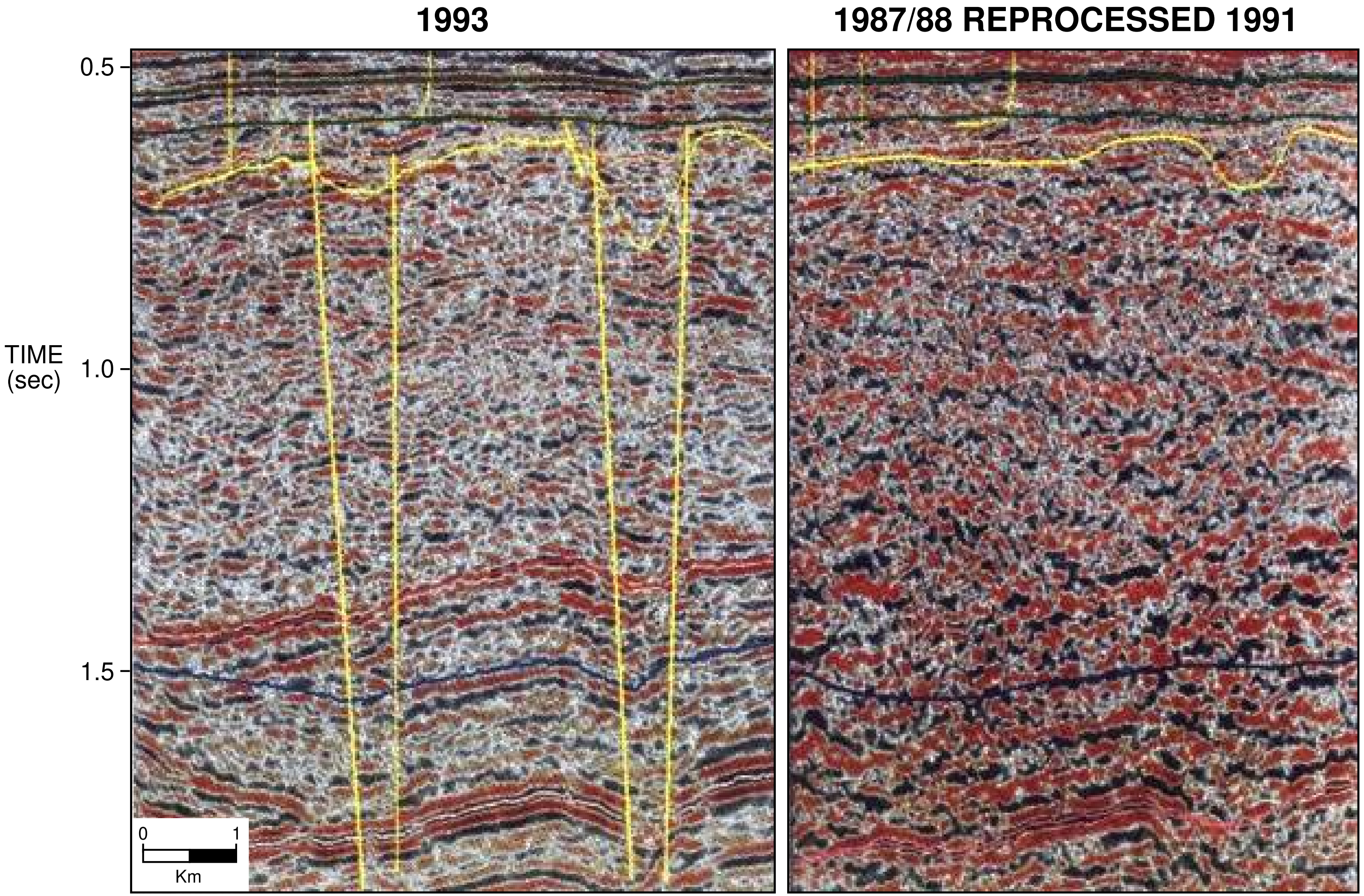


Figure 10: Data comparison (3-D), central part Nimr field: (right) 1987/88 data, reprocessed 1991 (16 fold, maximum offset 1.6 km); and (left) 1993 data (96 fold, maximum offset 2.4 km). Structural control of Alkhlata valleys (yellow marker) greatly improved due to better imaging at base salt (pink marker).

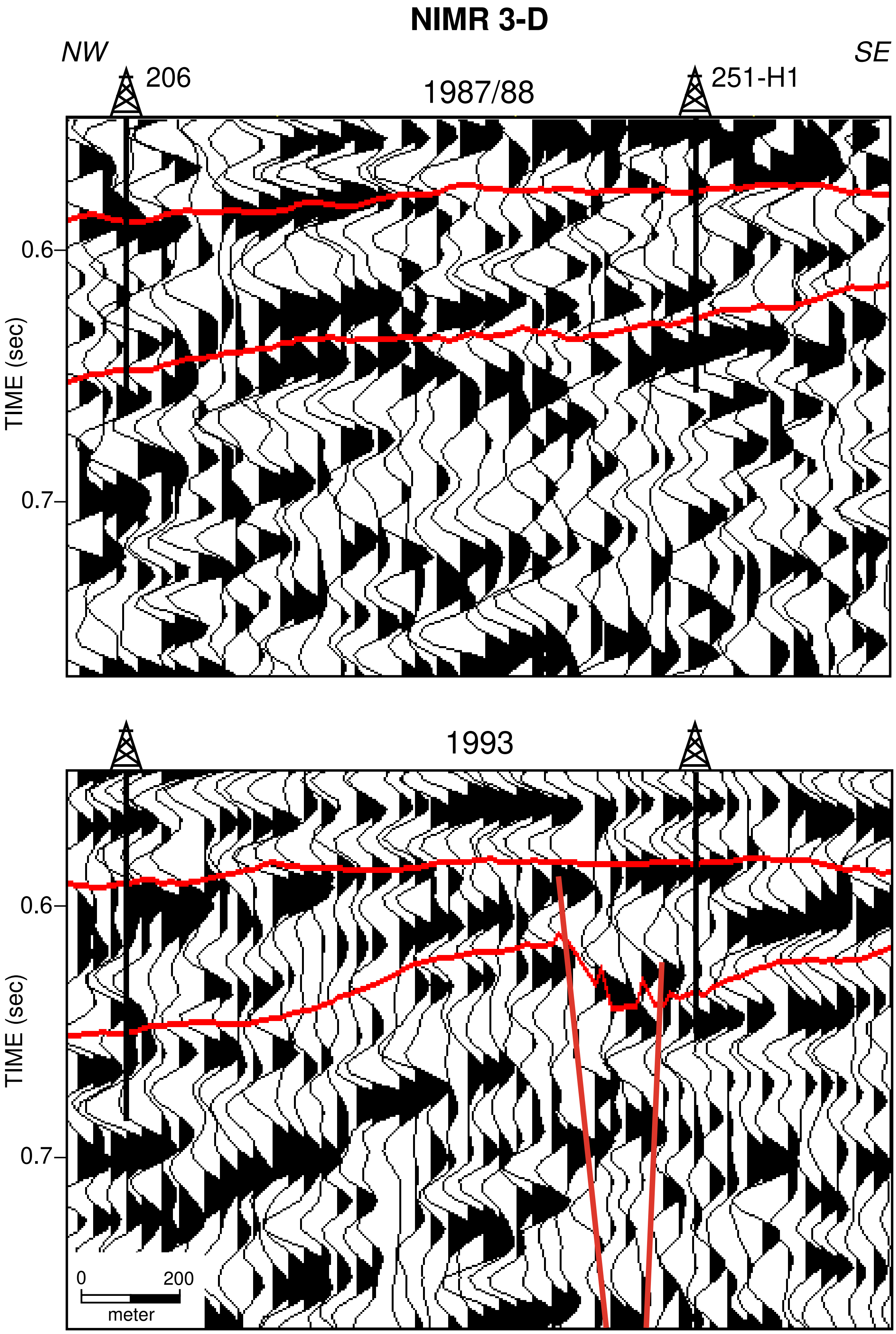


Figure 11: Data comparison (3-D), flank Nimr field: (top) 1987/88 data; and (bottom) 1993 data. Example of much improved structural control of Gharif reservoir unit, which appears as a simple monocline on (top), but is shown to be broken up by a fault (bottom).

Fahud Field

Fahud field was surveyed in 1994 to improve imaging of crestal fault blocks (slump features or "terraces") and the overall fieldwide structure. The survey would improve targeting of development wells, delineate the gas cap and optimise production. In addition, there was exploration interest in improved imaging of the deeper Haima and Gharif intervals. The top Natih-A culminates at approximately 50 m subsurface. The field oil-water contact is at 515 m. Main objective reflectors are found in the interval from 180 to 600 ms.

A map and structural cross-section of the field is shown in Figures 12a and 12b. A most prominent structural feature is the large northwest-southeast running boundary fault, hading to the southwest. At the surface a steep escarpment of locally 30 m height, a remnant of the eroded Tertiary anticline, overlies the field perimeter. This necessitated special operational and logistical provisions, such as a team of expert mountaineers to assist the seismic crew in the deployment of source and receiver equipment. The 120 km^2 area was covered in 1994 for US$ 4.3 million. Excellent planning by the contractor, Western Geophysical, and many PDO departments resulted in an accident-free operation.

The acquisition geometry chosen for this survey consisted of eight receiver lines spaced 100 m apart, receiver interval 50 m, with a total of 960 channels recorded. In view of the multiple objective, acquisition was done in asymmetric split-spread mode with maximum offset of 4.4 km. In contrast to the Nimr survey standard in-line shot patterns were deployed on two 50 m spaced shot lines between the two central receiver lines. Shooting was done in double zig-zag mode, 100 m source interval per zig-zag. This resulted in a nominal multiplicity of 120 fold per 12.5 by 25 m bin, with a nominal fold at top Natih of 15.

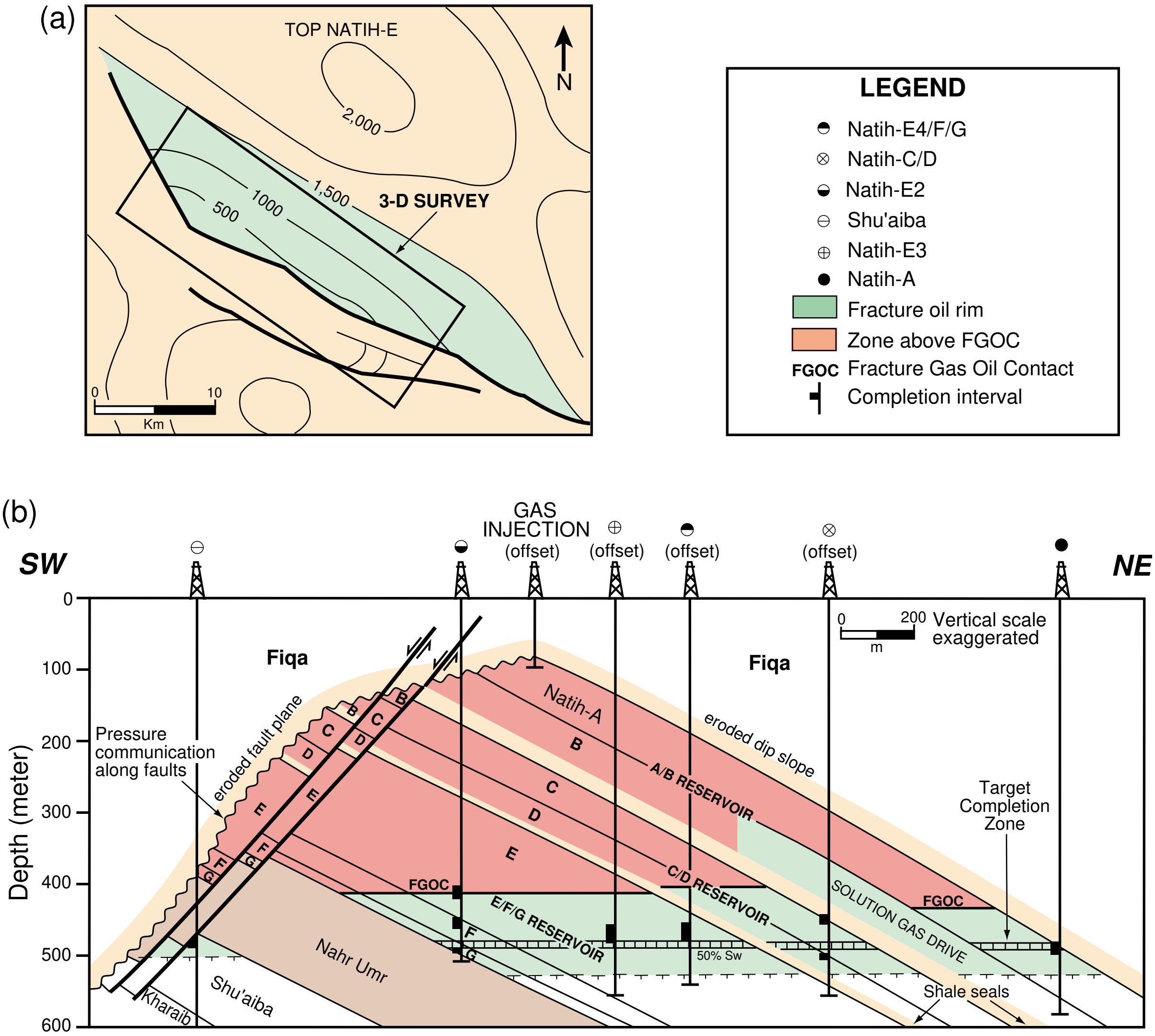


Figure 12: Fahud field: (a) map of top Natih E level showing area of 3-D coverage; and (b) cross-section over northwest segment.

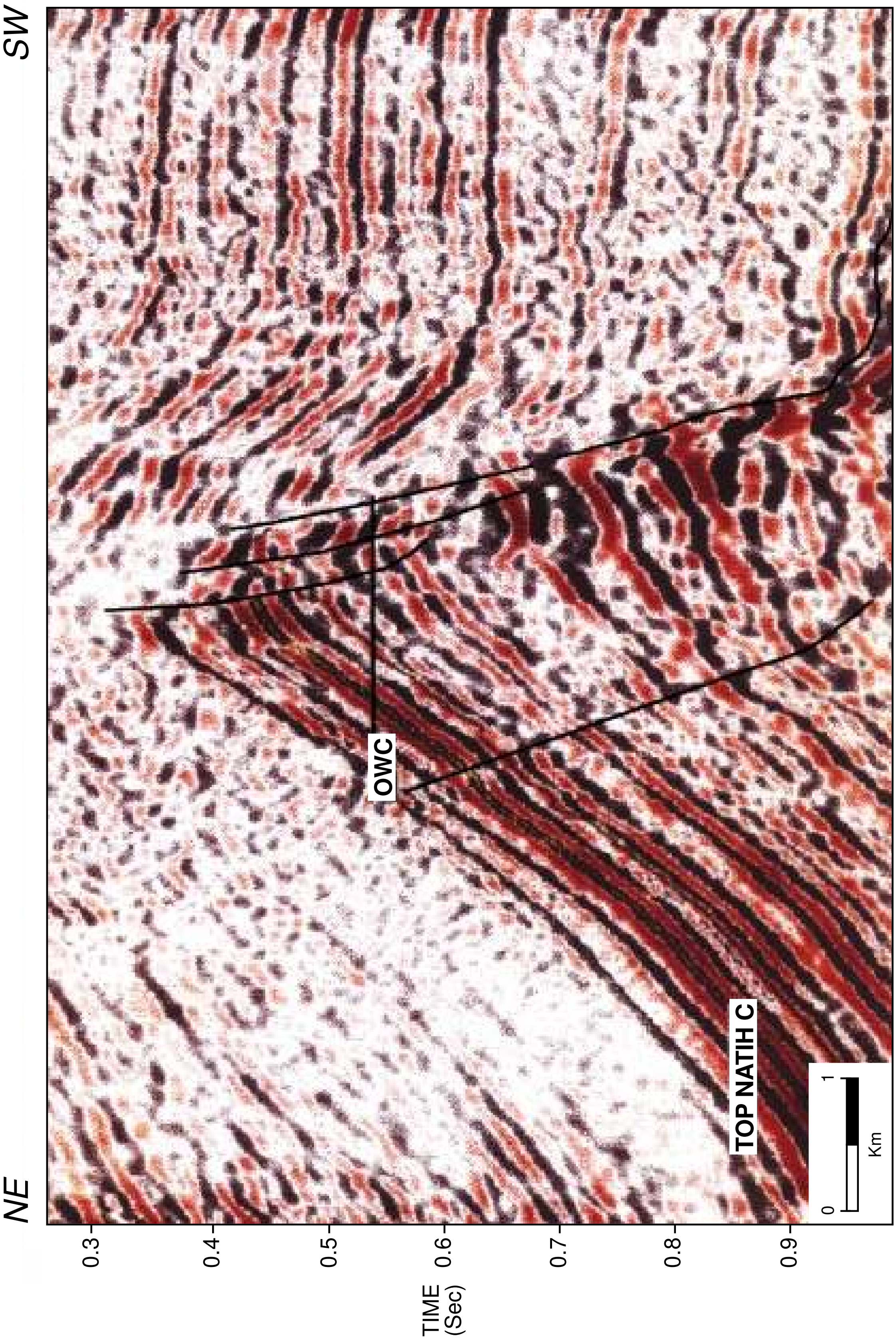


Figure 13: Cross-line over Fahud field.

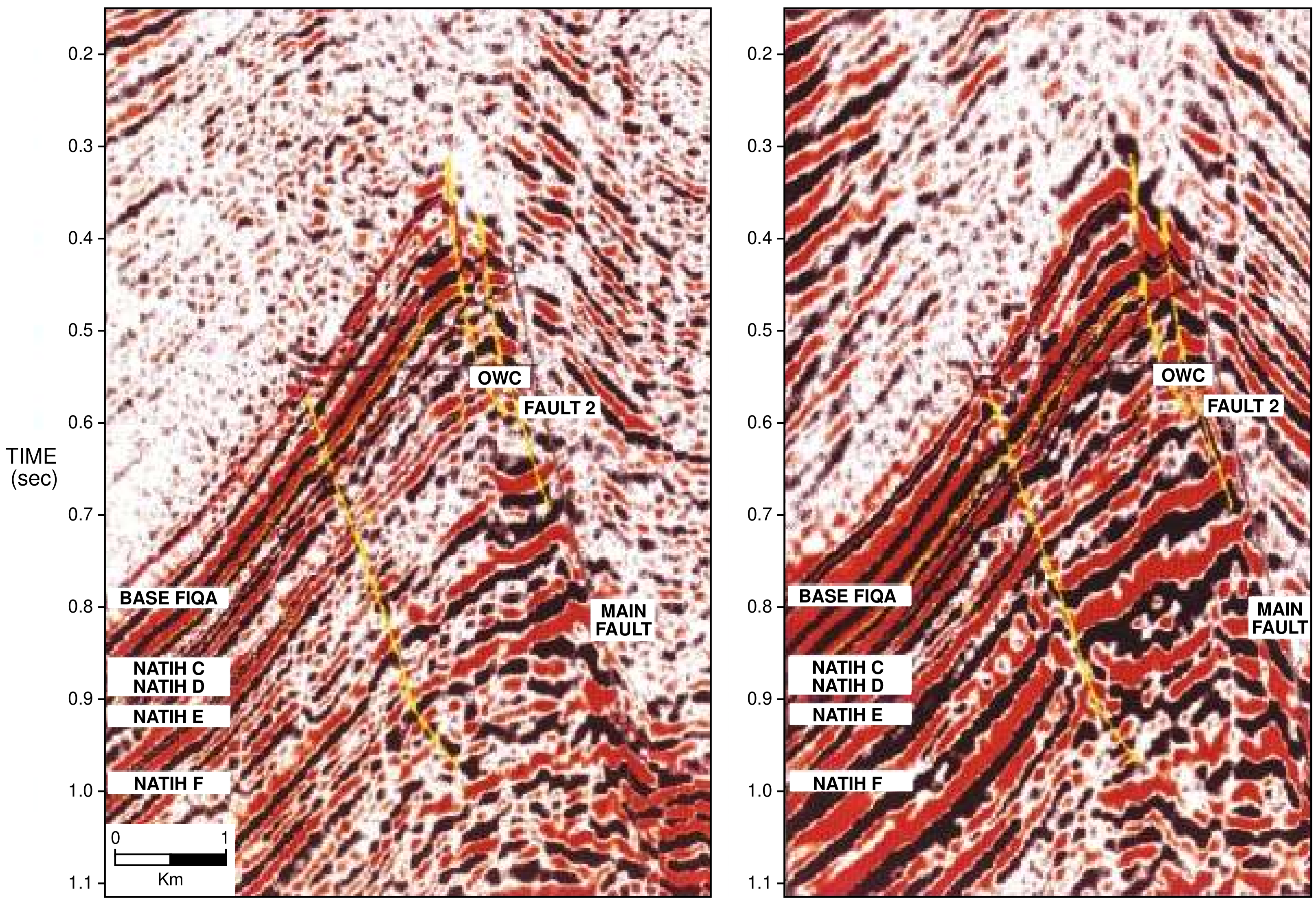


Figure 14: Same cross-line as Figure 13, but with near (left) and far (right) offsets only. Note the difference in expression of the Base Fiqa event on near and far offset sections.

As an example of the resolution achieved a crossline running northeast-southwest over the central part of the field is presented in Figure 13. The top Natih C reservoir unit and the approximate oil/water contact are indicated. Note also the slump blocks at the hanging wall of the major fault. To aid in the structural interpretation and to attempt to facilitate the recognition of porefill-related effects, separate near and far offset datasets were generated (for example Figure 14). Certain events (e.g. faults) appear more visible on the near-offset displays, while others are clearer on the far offset sections. Pre-stack amplitude (AVO) effects were modeled but turn out to be small in this setting, at least at top Natih-C level.

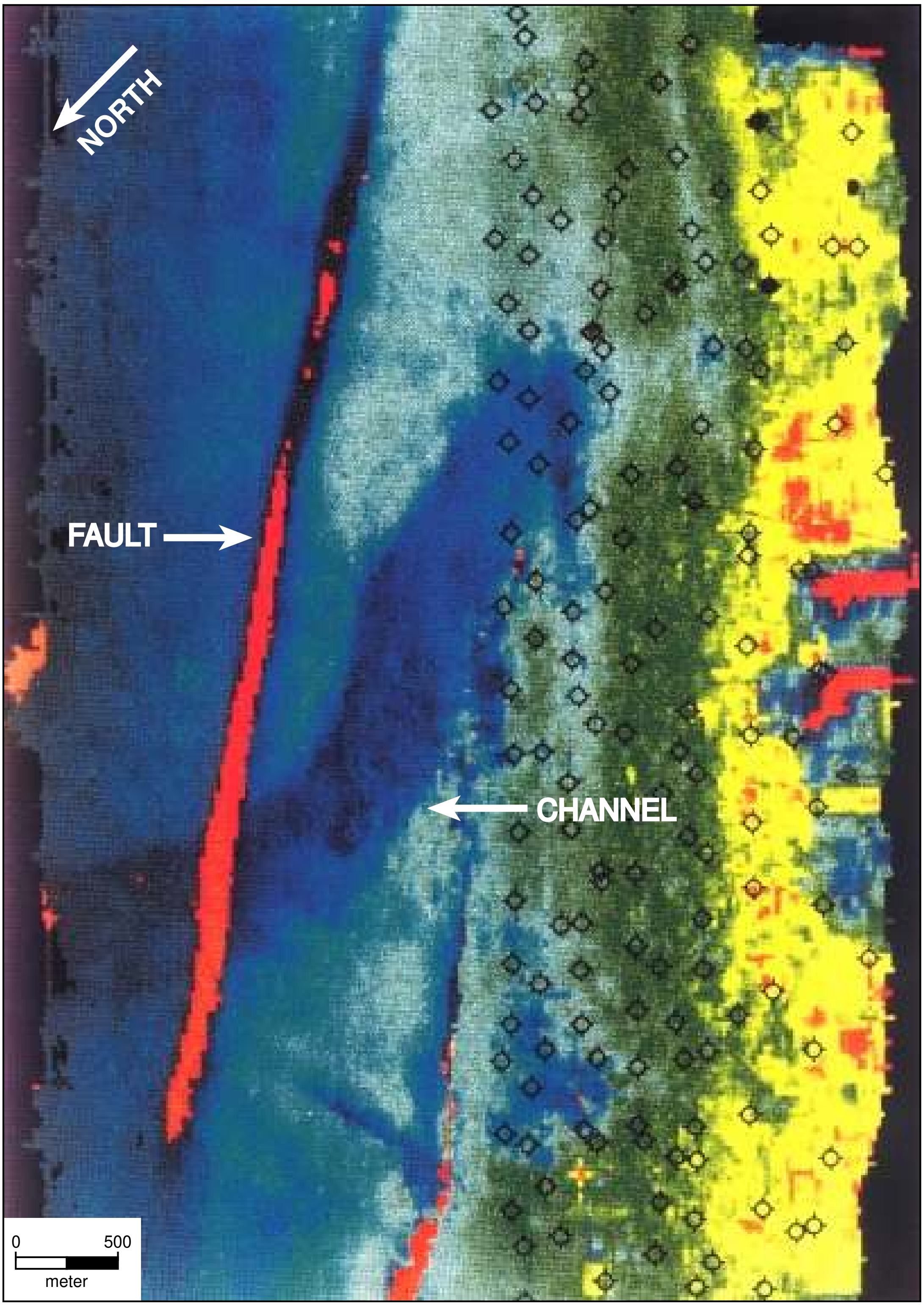


Figure 15: Time-dip map of Natih-E with channel feature. The channel is seen as a dark blue, S-shaped zone running from the lower left to the upper middle part of the figure. The red streak to the left crossing the channel is a fault. Note the orientation of the figure with respect to the structure map in Figure 12a.

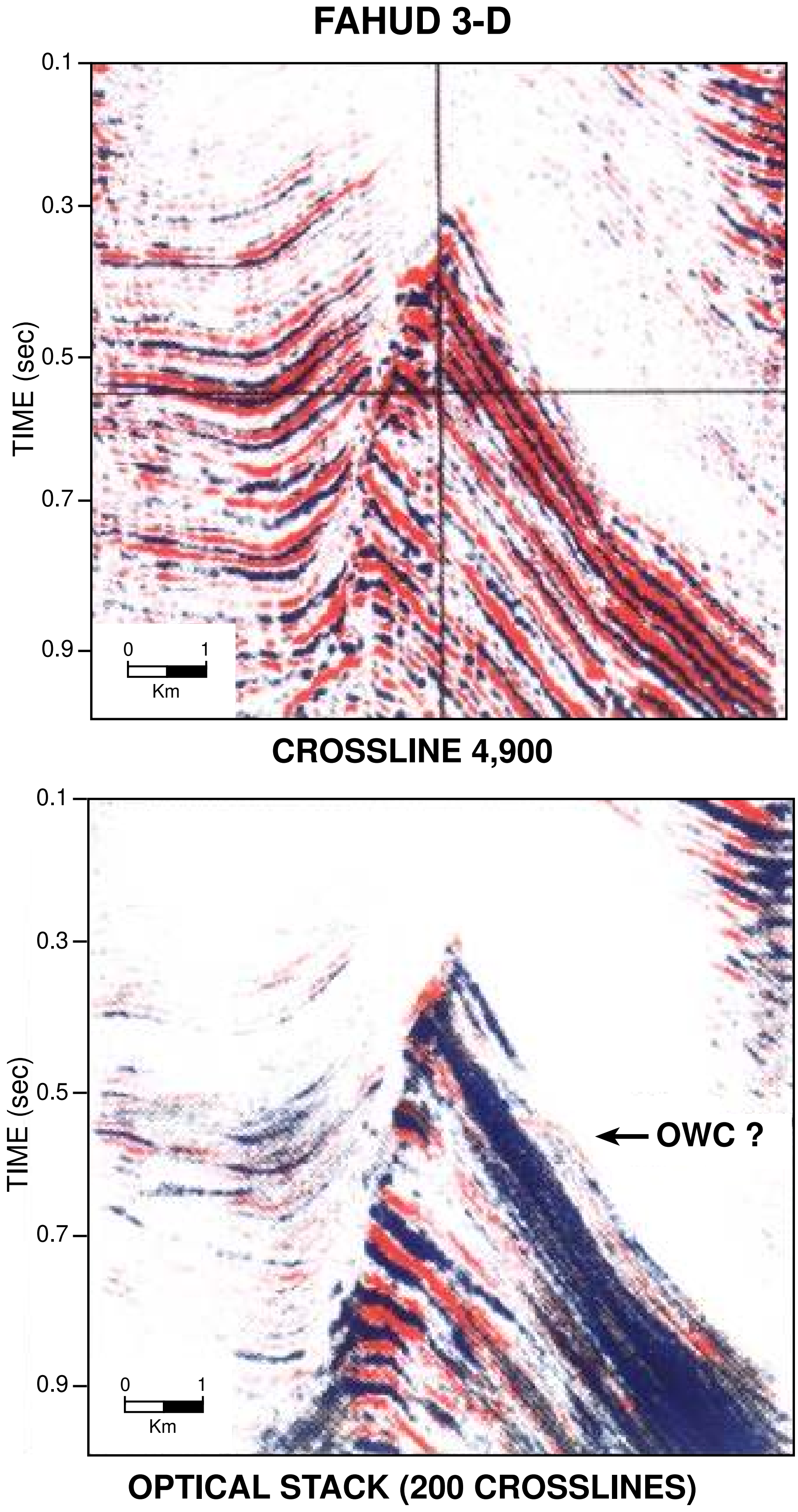


Figure 16: Conventional cross-line display (top) and "optical stack" of 200 cross-lines (bottom). The oil/water appears to show up as a faint, sub-horizontal event (see arrow); it is not visible on the conventional display.

An example of extracting information with special display techniques is shown as Figure 15, where a time-dip map at top Natih-E level is shown. The feature running diagonally across the display is a channel which had previously not been observed on seismic. Its presence confirms hitherto unexplained observations of differences in fluid levels and well performance.

A second example of the power of special display techniques is shown in Figure 16. The left panel shows a conventional crossline over the field's crest. The right panel is an "optical stack" of 200 crosslines around the first one. The image is similar to looking through the data volume in a strike direction, such that events which line up in the direction of observation predominate while others cancel out. A faint, near-horizontal event is visible left of the arrow, possibly corresponding with the oil/water contact.

While detailed analysis of the Fahud 3-D dataset has only recently started, the general conclusion is that the data quality is excellent and has led to a radically different image of the "terrace" area. A direct result of the survey has been the decision to sidetrack well FN-62 horizontally to appraise the terrace area and assess producibility from the slump blocks. Additional field appraisal opportunities have been identified and will be further pursued.

OTHER GEOPHYSICAL DATA

Geophysical methods outside the field of seismic reflection technology such as gravity and magnetic surveying have recently attracted renewed attention.

Gravity

Extensive gravity surveys have been acquired during the early exploration phase of Oman. PDO continued acquiring gravity data in subsequent years and now has excellent coverage on a 5 by 5 km grid with 500 m station spacing over most of the country. Recently this dataset was looked at again.

Figure 17 shows the result of recalculating the residual Bouguer anomaly map and displaying it using modern visualisation software. The result is a spectacular overview of rock density variations across the entire country. This map highlights the possible relationship between local tectonics and the regional geological setting. It also provides increased insight, particularly in areas where the seismic image is poor.

A specific application of gravity data is found in the developing silicilyte play in south Oman. Here it helps delineate areas with the thickest salt intervals and to check the seismic interpretation of salt and Haima pods. In addition, a modeling study was carried out to investigate whether intra-salt silicilyte slabs could be detected from gravity data. The gravity response of the Al Noor accumulation was calculated and its dependence on varying density and depth of the silicilyte was analysed. While the overall correlation between observed gravity response and seismic interpretation was good, the extent of the silicilyte slab and the presence of a second partially overlying slab could not be unambiguously resolved. This study has however rekindled interest in the technology as a useful supplement to seismic data, facilitated by powerful display techniques. Acquisition of additional gravity data in areas of interest is under consideration.

Aeromagnetic

Another outstep in a long established non-seismic geophysical technique has been the acquisition of high-resolution aeromagnetic data over part of South Oman. The objectives of this pilot project were twofold. Firstly, to investigate if such a dataset could assist in delineating subtle structural features in the poor-seismic-data area of the Eastern Flank. This idea is based on the possibility that a small difference in magnetic signature of Alkhlata and Haima sediments could be revealed by dense lateral sampling of magnetic data (an analogy would be small faults becoming visible on 3-D seismic timeslices). The second objective was to check the potential of delineating Haima sediments on the one hand, and salt and intra-salt silicilyte on the other, on a dense laterally sampled dataset. The data were acquired during the first quarter of 1996 and are being processed.

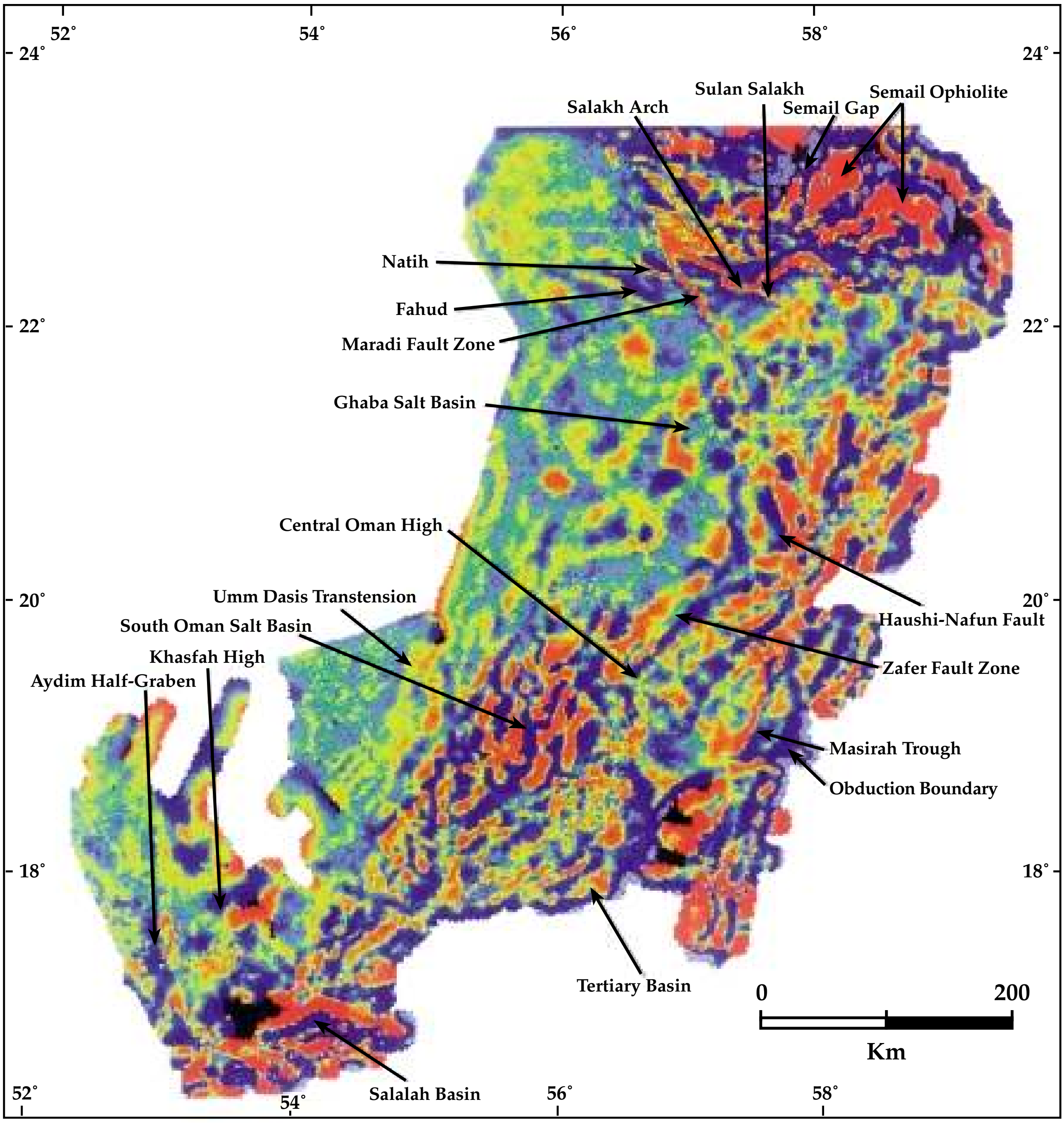


Figure 17: Residual Bouguer Gravity Map of Oman.

QUANTITATIVE SEISMIC INTERPRETATION

Improved data quality, together with increased seismic activity and expenditures, raised the question whether the seismic data contained more than the conventional (mainly structural) information. As is often the case with land seismic data from areas with a hard near-surface, detailed amplitude studies generally carry little information even with the present data quality. During the past few years it has become clear that amplitude and waveform studies can nevertheless fruitfully support both exploration and production. In addition, it became apparent that there is considerable potential for a more quantitative analysis of borehole seismic data, hitherto only utilised for depth-time matching.

Seismic Attribute Studies

The increased importance attached to amplitude and waveform analysis has been accompanied by a change in PDO's data processing philosophy. To facilitate seamless merging of 3-D surveys, standard data processing did not include zero-phasing. A break with this tradition was necessary for well matching. After extensive testing a deterministic version of time-variant de-absorption has been incorporated in PDO's contractor and proprietary processing. It removes the effect of wavelet dispersion with increasing travel time and is an obvious benefit for the many surveys in which there are shallow as well as very deep objectives. To help evaluation teams understand the motivation and implications of this new philosophy a tutorial-style introduction to the subject was prepared which enjoys great popularity.

The first attempt at an integrated project involving quantitative interpretation techniques was aimed at the Birba field in South Oman. An important observation was made that over the expected range of stringer porosity, seismic amplitude variations up to 35% should be observed enabling discrimination between good and poor reservoir. However, the seismic data contained amplitude fluctuations tantamount to completely obliterating this effect. Subsequent amplitude-sensitive re-processing improved the data but not sufficiently for porosity predictions. This and subsequent observations have led to an in-depth ongoing investigation into the causes and possible remedies for the problem.

In spite of these difficulties, detailed interpretive work which utilizes modern technology can produce further spinoffs. An example is the Haima gas exploration program. Here the very weak impedance contrasts at target level and the presence of strong multiples impedes the interpretation of the reservoir tops. Until recently this problem was compounded by the very poor quality of the well logs, particularly the density log. The routine generation of well synthetics had therefore failed to produce reliable seismic-to-well matches thereby limiting the accuracy of reservoir volume estimations.

While this problem can only be overcome with further improvements in seismic data quality, a partial solution is the introduction of the new Schlumberger tandem density tool. It significantly improves density measurements over the broken-out Mabrouk shale and Al Bashair claystone intervals overlying the reservoir units.

Figure 18 shows data from well Saih Rawl-54. The first six tracks are the (1) velocity log derived from sonic log, (2) density and gamma-ray, (3) acoustic-impedance, (4) resulting zero-phase well synthetic, (5) VSP corridor stack, and (6) seismic trace at the well location. Note that the VSP has been bandpassed down to the same frequency range as the seismic data. Track 7 is also a well synthetic with a 90-degree-shifted version of the wavelet in track 4. This wavelet corresponds approximately to the vibroseis wavelet of the seismic data (which was not zero-phased). Finally, track 8 is part of the inline across the well.

The quality of this match is sufficient for validating interpretations against the seismic response to determine whether the correct seismic loop is picked. Such validation is invaluable for confidence in reservoir maps. In addition to the better log quality the flexibility offered by modeling software on trace interpretation stations, which we have started to employ instead of fixed-scale black-and-white paper synthetics, turns out to provide a major impetus for loop-level studies. It turned out that three of the six wells studied had very good well matches, by far the best obtained in the area to date. The remaining three were still good enough to allow general statements about the seismic response to be made.

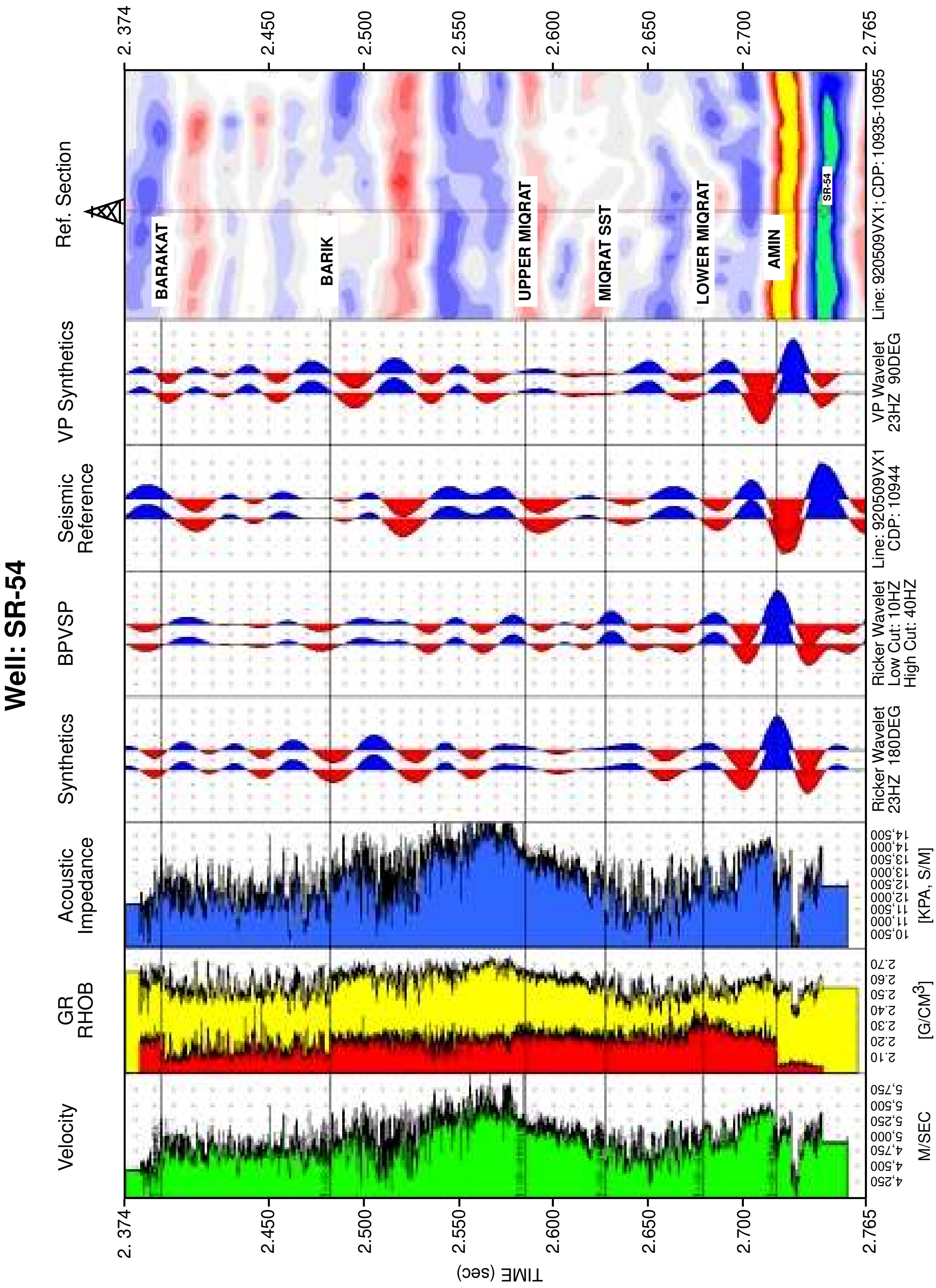


Figure 18: Seismic-to-well match Saih Rawl-54.

Borehole Geophysics

The interpretation of intermediate Vertical Seismic Profiles (VSP) has a direct operational impact, particularly for wells drilled as part of PDO's Athel exploration and appraisal campaign. These VSPs are taken to obtain accurate measurements of interface depths, but also to predict acoustic impedance ahead of the bit.

The first is a standard application linking the location of the drill bit to time on the seismic section. VSP-based prognosis of horizon depths has been found to achieve an accuracy of typically 10-20 m, compared with 100 m typically from surface seismic. This order-of-magnitude improvement is important for the determination of casing points. It could be achieved as a result of the higher frequency content and the fact that the base of the VSP is chosen close to the anticipated target level allowing the use of up-to-date velocity data.

The second application is acoustic-impedance prognosis. It has been applied as an experimental procedure in five wells. Its motivation derives from the fact that the planning of Athel wells requires additional information because casing levels depend critically on the lithology ahead of the bit. The prospective Athel silicilyte slabs are encased in salt that is known to contain potentially overpressured stringers. Drilling into an overpressured stringer before casing has been set several tens of meters into the salt carries a high risk of losing the well. It is therefore very important to establish how far one can drill into the salt before encountering a potentially overpressured stringer. This is an area where VSPs can be exploited as the receivers' proximity to the salt allows more reliable prediction of impedance ahead of the bit from VSP than from seismic data. It should not be mistaken for an attempt at predicting overpressure.

Instead one endeavours to predict whether a specific lithological unit should be anticipated in the salt ahead of the bit. Such a unit is known, from analogues in other wells, to be potentially overpressured but its pressure state cannot be derived from the VSP data. Ahead-of-bit prediction has been attempted in the past by crude interpretation of paper copies of the VSP, and here another example arises where PDO is resorting to more sophisticated methodologies. A standard procedure does not exist, the wells being in different environments, having different objectives, and requiring various operational issues to be addressed. The example is therefore only representative for the approach, not for the specific technology employed.

In the case of Well Dasimi-1 the question was posed as to the chance of encountering overpressured stringer a short distance below the top of the Ara salt. In the drilling proposal it was intended that casing be set at 50 m into the salt, a decision which would need revision if stringers were present. The Dasimi-1 VSP was acquired some 300 m above top salt with a high-bandwidth (8-120 Hz) vibroseis source. An enlarged portion of the data is shown in Figure 19. The strong peak at a time of 1.380 sec was interpreted to be the (soft) top salt reflection. Two potential stringer events slightly below top salt were identified as the troughs at 1.409 sec and 1.443 sec.

As at this point no logs of any kind were available, a calibration of the VSP traces with measured acoustic impedance was not possible. Based on regional information the Dhahaban formation which overlies the Ara salt was presumed to be a dolomite. Acoustic impedance values of 13,700 g/cc.m/s (gram/cm^3 meter/sec) for the Dhahaban and 9,600 g/cc.m/s for the Ara salt itself were assumed. This artificial log was then edited to match the VSP, under the assumption that two high-impedance stringers were present. It constitutes our a-priori acoustic-impedance model.

The next step is to run an inversion program on the data in an attempt to refine this estimate. The refined model, with the VSP traces superimposed, is shown on the left in Figure 20. In the background of predominantly low impedance (blue) the postulated stringers are easily recognized as the red streaks. The yellow band is the Dhahaban. On the right the VSP traces are superimposed on the synthetic seismogram corresponding to this inverted acoustic impedance model. This indicates the good correspondence obtained after inversion. At this point it is concluded that the presence of two stringers is consistent with the VSP data, which based on the salt velocity of 4,400 m/s are approximately 64 and 139 m into the salt, i.e. in excess of the drillers' 50 m minimum depth for an intra-salt casing point.

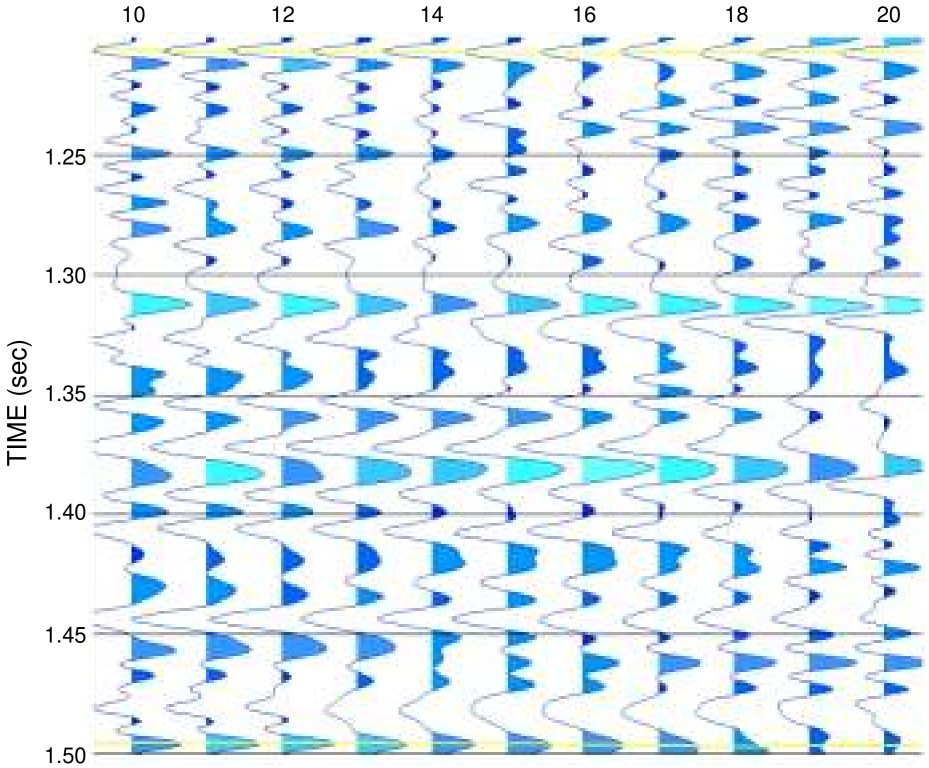


Figure 19: Dasimi VSP (enlarged part of dataset).

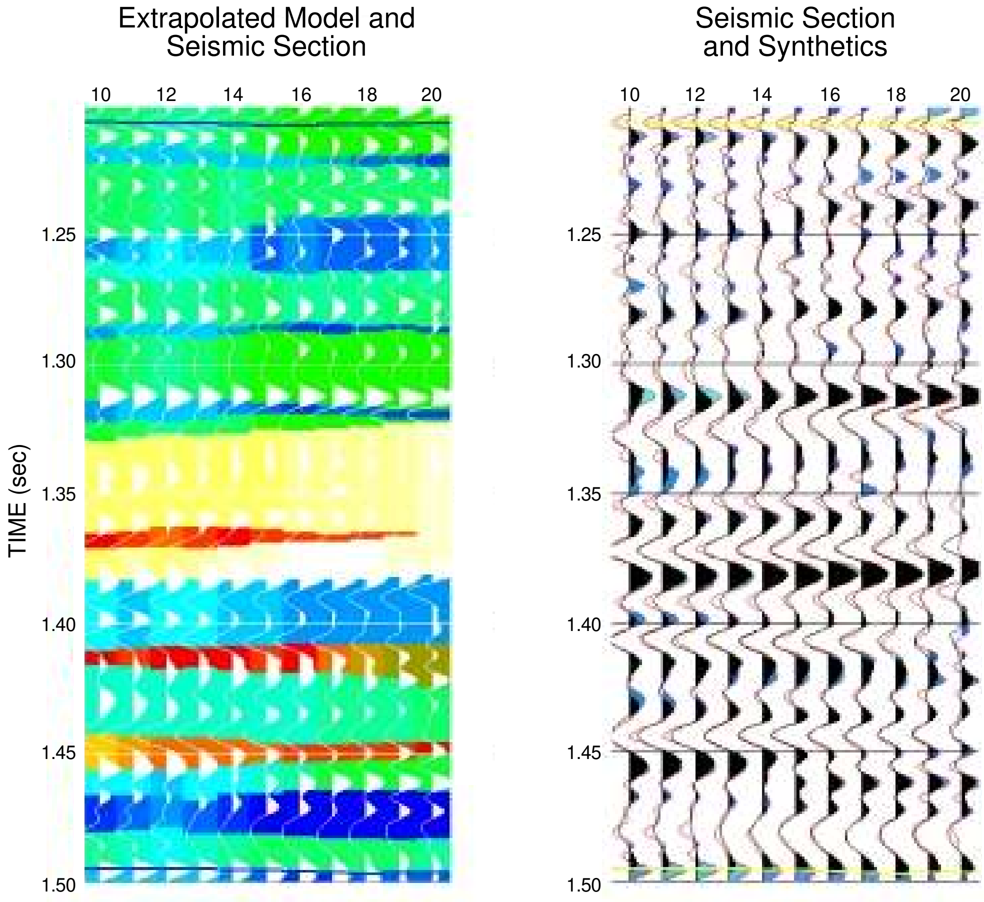


Figure 20: Dasimi VSP: (left) VSP data superimposed on inversion result; and (right) VSP data superimposed on synthetic traces derived from inversion result.

Wary of the inherent non-uniqueness of this type of inversion an attempt to prove an alternative was also considered. A stringer only 15 m below top salt was introduced in a second a-priori model and followed by an inversion. In this approach the stringer is effectively removed by reducing it to almost zero thickness. This indicates that a shallow stringer is inconsistent with the VSP.

Drilling then proceeded and casing was set at 40 m into the salt. Subsequent to these results examination of cuttings established that the Dhahaban was a shale and not a dolomite, contradicting the model. The predicted acoustic-impedance streaks were confirmed at depths of 62 and 152 m into the salt, well within the depth range of our prognosis. They turned out to be shale streaks instead of stringers, having a much smaller acoustic impedance.

The post-mortem of this and other VSPs indicates that lithology variations can be fairly precisely localised ahead of the bit but that the acoustic impedance estimate will be considerably in error in the absence of calibration by means of log data or regional rock properties. It has been successful where it is attempted to predict no further than a few hundred meters ahead of the bit. Longer-distance predictions have turned out highly unreliable and can only be used under extremely favourable circumstances.

CONCLUSION

Despite a late start in 3-D seismic data acquisition and various circumstances which have had an adverse effect on data quality, recent developments have seen major advances in quality improvement and therefore increasing opportunities for interpretation methodology which thus far have found application only in areas of superior data quality. At the same time, there is renewed interest in the potential of other geophysical technologies such as gravity, magnetics and borehole geophysics.

The application of new technology in an environment which is characterised by a continuously high exploration activity level poses a considerable challenge in terms of balancing opportunities and resources. It has been a consistent policy of PDO's Geophysical Department to apply new technology where its economical value could be justified on the basis of a rigorous cost-benefit analysis. The rewards of this strategy are now being realised in terms of cost savings and quality improvement.

Developments in seismic acquisition and processing technology will create further opportunities for progress. Notably the ever-decreasing cost of hardware creates a perspective of applications which at this time are still considered experimental and outside PDO's reach. An example of this are machine-intensive pre-stack imaging techniques which, if successful, could significantly contribute to PDO's Athel strategy. Successful quantitative studies would further the link between seismic and reservoir modeling. To promote the required advances a business improvement team composed of members of the department has been established. Once the results of their study have been field-tested and associated costs and benefits have been quantified, another exciting chapter of the history of Geophysics in PDO will begin.

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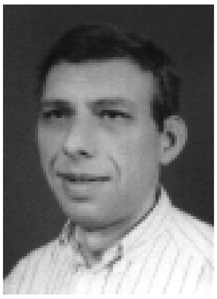

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